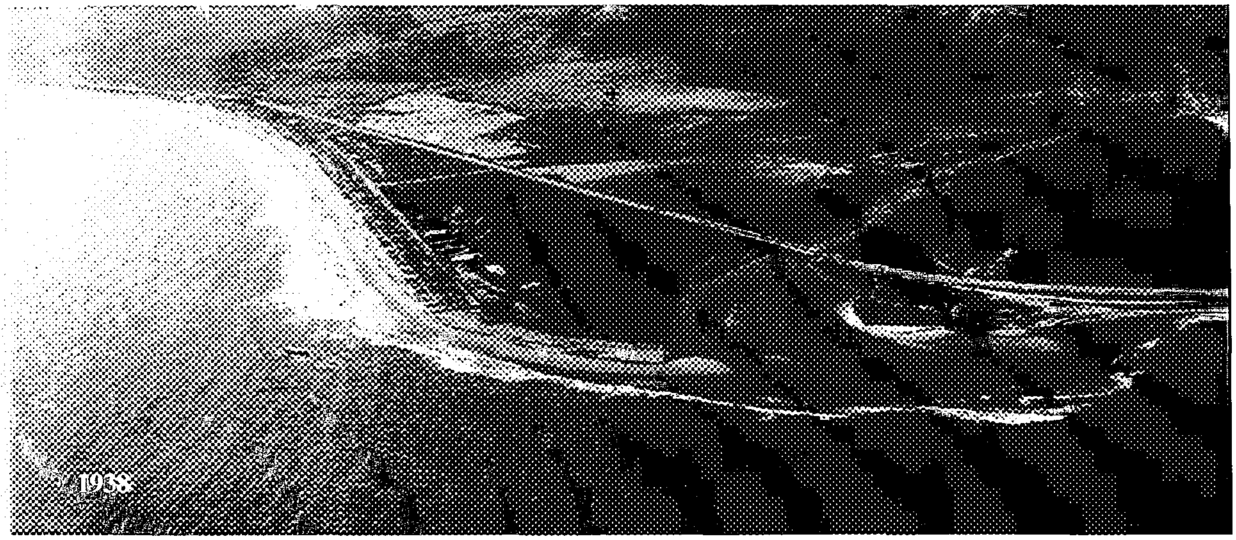
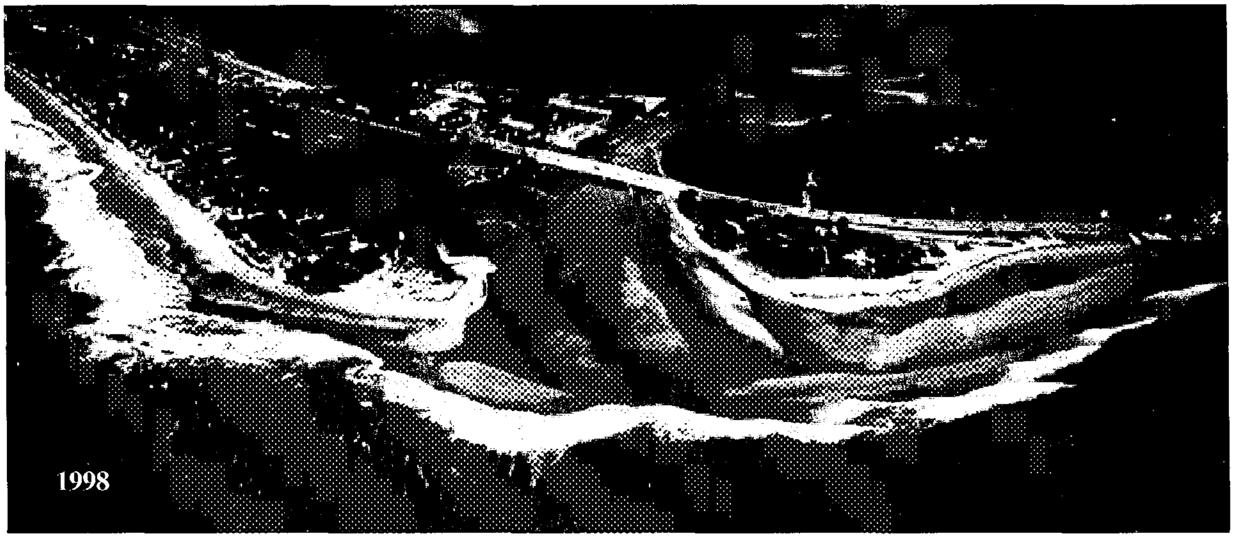
Lower Malibu Creek and Lagoon Resource Enhancement and Management





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Principal Investigators

University of California, Los Angeles

Final Report to the
California State Coastal Conservancy

May 2000

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Executive Summary

During 1997-99, an investigation of Lower Malibu Creek and Malibu Lagoon was conducted by a multidisciplinary research team from the University of California, Los Angeles and University of Arizona, under the general direction of Richard Ambrose and Antony Orme The purpose of this investigation was to understand better the natural system and human impacts on this system, and to develop strategies for the long-term management of the lower watershed

Based on the original proposal, as expanded for this report, the study involved eight major objectives for the lower watershed, namely an analysis and interpretation of (1) evolution and historical development, (2) hydrology and morphodynamics, (3) biological and water quality objectives and habitat associations, (4) vegetation, (5) eutrophication, (6) pathogens, (7) hydrologic alteration and human disturbance, (8) management alternatives, and (9) wetland restoration The Final Report is organized under these categories, together with (10) a summary of management and restoration alternatives, and (11) a concluding perspective

(1) Evolution and Historical Development

Historical reconstruction of Lower Malibu Creek and Malibu Lagoon was based on field investigations and documentary sources, including historic maps and photographs For southern California, first contact between native Americans and Europeans occurred in 1542 but the historic period *sensu stricto* began in 1769 when Spanish colonization began, although there is little useful information on the local area before 1870

The prehistoric evolution of the lower watershed is reconstructed from surface and sub-surface evidence Malibu Creek originated among distributaries of an early Pleistocene drainage system that was dismembered by transpressional tectonics in the western Transverse Ranges The creek was able to maintain its course through the rising Santa Monica Mountains and by late Pleistocene time had incised a significant canyon, cutting its channel at least 32 m, and possibly up to 100 m, below present sea level near the coast The Flandrian transgression (18-6 ka) later drowned this lowest reach to form an estuary, partly impounded seaward by a 1 5 km barrier beach This estuary was in turn progressively confined by fluvial, lagoonal, estuarine and marine sedimentation whose facies are well revealed by sub-surface investigations Meanwhile, the impounding barrier beach transgressed upslope, burying earlier lagoons to partially stabilize on bedrock foundations

By 1900, the distributary fluvial system was restricted to a corridor that broadened into an estuarine lagoon near the coast The system varied from an open estuary under high fluvial discharge to a closed lagoon under minimal discharge and constructive, barrier-forming, wave action Since 1900, the estuarine lagoon has been impacted by railroad and highway construction, erratic reclamation, and housing and commercial development, with concomitant changes in hydrology and fluvial-marine exchange scenarios Human activities have transformed the once natural system into a dysfunctional physical system characterized by widely fluctuating biological conditions, although stream floods and storm wave activity may temporarily recreate quasi-natural river-mouth dynamics during wet winters Neotectonic movement in the Malibu Coast fault zone and continuing relative sea-level rise of around 18 cm per century are ancillary issues for coastal management

(2) Hydrology and Morphodynamics

Under restorative gravitational forcing, the morphodynamics of lower Malibu Creek and Malibu Lagoon are conditioned by hydrologic inputs and wave climate, and resisted by rock and sediment properties During 1997-98, Agoura in the upper basin received 1007 mm of precipitation from 72 rain days associated with 50 discrete storms Although precipitation fell on and off from November through June, February was the wettest month (85 mm on February 3, 110 mm on February 23) Total precipitation was more than twice the 59-year annual average of 459 mm but comparable to prior wet years in 1940-41 and 1982-83

Frequent precipitation led to erratic but persistent stream discharge down Malibu Creek, varying from <0 1 $m^3 s^1$ in October 1997 to >100 $m^3 s^1$ in February 1998 During peak flows, Malibu Canyon's channel scoured but longitudinal bars later reformed The coastal barrier, which had closed the lagoon by August 1997 (although later breached artificially), was removed along a 250-m front by February storm discharge and remained open for several months This transformed the lagoon into a friction-dominated estuary with middle-ground bars The breach was gradually sealed by onshore bar migration in July, but reopened by lagoon overspill in August 1998 Wave climate generated significant waves of 0 2-1 8 m with periods of 6-20 s Storm waves and constructive swells with 12-16 s periods effectively reconstructed the barrier during summer 1998 During the course of the water year, the barrier beach passed through seven morphodynamic states involving stationarity, onshore migration, longshore migration, seaward progradation, beach-face erosion, partial breach, and wholesale removal

The measured responses of the creek and lagoon to these events, though associated with an unusually wet year, allow formulation of an interactive process-response model for a variety of conditions Significant bank scour occurred between the bedrock throat and Pacific Coast Highway bridge, with bank retreat of 15-30 m on the east bank and 5-10 m on the west bank, the latter countered by riprap protection Little bank erosion occurred seaward of the bridge but the lagoon bottom was widely scoured and reorganized into longitudinal bedforms These bars in turn constrained later reconstruction of the barrier and the location of the migrating tidal channel prior to closure Lagoon volumes varied as a semilogarithmic function of lagoon stage, a volume of 50,000 m^3 occurring at the 1-m stage, 150,000 m^3 at 2 m, and 220,000 m^3 at 2 2 m, the highest stage during 1997-98 Although flood discharge and tidal prism were just retained within existing banks during the highest stage, a further stage rise would vastly increase water volume and area as waters would overtop retaining levees Lagoonal response reflects a complex interaction between variable stream discharge and tidal water, lagoon bathymetry, and bar and breach morphology and migration rates Predictions for future lagoon behavior are constructed for a range of possible hydrologic scenarios The most probable scenario under existing climatic conditions is increased runoff, higher, more flashy flood peaks, and accentuated barrier-lagoon instability attributable to urbanization in the upper Malibu drainage basin and continued human interference with the estuarine lagoon system

(3) Biological and Water Quality Objectives and Habitat Associations

With respect to biological and water quality objectives, the requirements of ten indicator species were evaluated in order to determine the conditions necessary for a healthy ecosystem Two of these were endangered species of fish, the tidewater goby and steelhead trout Six of the remaining species were native fish that use estuaries during at least part of their life cycle, namely California killifish, topsmelt, arrow goby, staghorn sculpin, diamond turbot, longjaw mudsucker, and opaleye, all of which occur in Malibu Lagoon The last two species were invertebrates jackknife clam and mudflat crab In addition to these positive indicators, four negative indicator species were reviewed, namely western mosquitofish, yellowfin goby, oriental shrimp, and the polychaete worm *Polydora nuchalis* Virtually all the estuarine species tolerate very low salinity, since the normal seasonal cycle of southern California estuaries includes periods of very low salinity during high rainfall/runoff events Where upper limits to salinity have been determined, they are typically >40-50 ppt, higher than occur usually in Malibu Lagoon However, several species, such as tidewater goby, prefer much lower salinity of 10-15 ppt To protect these species, some low-salinity habitats must be available which, for the tidewater goby typically occur where freshwater enters the upper lagoon For most indicator species, temperature is not a particular concern For steelhead trout, temperatures should not exceed 15°C during spawning and incubation, or 26-28°C at other times There are few data about tolerated limits to ammonia in the target species, but the recommended upper limit for steelhead trout is 0 45 mg/L of unionized ammonia Neither is there much information about the tolerated limits to pH in the target species The preferred range for tidewater goby is 6 8-9 5 pH, and for steelhead trout is 7 0-8 0 pH, although the latter tolerate values as low as 4 0 and an high as 9 5 pH The minimal value of dissolved oxygen for most target species is 4 mg/L, but steelhead trout require

>7 mg/L There is little information about the tolerance of target species to nitrate, nitrite, and sulfide Steelhead trout reportedly tolerate up to 1300 mg/L of nitrate, up to 0 39 mg/L of nitrite (<0 15 mg/L is best), and up to 0 4 g/L of sulfide (the EPA recommended limit of 0 2 g/L would be more protective)

Habitat associations of target species in the lower Malibu Creek watershed were also assessed The target species included two aquatic invertebrates, eleven fishes, two reptiles, five birds and 2 plants Not all of the species currently occur in the Malibu Creek watershed or Malibu Lagoon, those species that do not occur there were included because they are thought to have occurred there historically or could potentially occur there The habitats in which the target species are found include lagoon/subtidal, intertidal mudflat, salt marsh, stream, riparian, and sandy beach and islands The most common threats to indicator species in the lower Malibu Creek watershed are loss and degradation of habitat, hydrological alterations, invasion by competitors and predators, eutrophication, and erosion

(4) Vegetation

Riparian habitats such as those of lower Malibu Creek support unusually high levels of both plant and animal biodiversity A small number of woody riparian trees and shrubs are keystone species in influencing microhabitat conditions along riparian corridors and providing a variety of ecosystem services Field studies of habitat conditions along lower Malibu Creek found that most of this riparian corridor exhibits good community structure but that significant human impacts are evident in many places Attempts to classify riparian community structure using either the Holland or Sawyer/Keeler-Wolf systems of community classification were unsatisfactory because such static systems performed poorly in characterizing vegetation structure in such a dynamic environment

Human activities have produced profound changes in the riparian corridor through both direct and indirect impacts Direct disturbance to the riparian zone has greatly degraded the structure and ecosystem function of this community at several places along the corridor These include areas in and around the Tapia State Park, the Rindge Dam, and the Cross Creek shopping center There is a need for active revegetation efforts in these areas Indirectly, physical disturbance to riparian habitats has had the effect of promoting invasions by exotic plant species Several of these have increased their range dramatically in recent years The most threatening of these invasions is that of *Arundo donax*, a large bamboo-like grass that promotes the incursion of fire into riparian areas, reduces biodiversity, and alters hydrologic flow and sedimentation patterns

(5) Eutrophication

The Malibu estuarine lagoon system is subject to eutrophication, namely excessive nutrient concentrations in the water, the effects of which include periods of algal blooms, mainly during summer months Nutrients enter the lagoon by transport in surface and groundwater flows, primarily from Malibu Creek Surface flows associated with normal storm runoff and accelerated urban runoff, septic seepage to ground and surface waters, and discharge from the Tapia wastewater treatment plant are important sources, though the amount from each varies by season The Tapia plant is the only point source determined in this study, the remainder being non-point sources whose exact input points along the creek are difficult to determine

There is greater nutrient loading to the lagoon during wet winters than during dry summers, but algal blooms and other effects may not develop during winter when the estuarine barrier is breached by flood discharge and nutrients are transported to the open ocean Conversely, when the barrier is closed during summer, eutrophic conditions and algal blooms are likely to occur The behavior of the barrier beach is thus critical to explanations of eutrophication The mass balance model employed in this study can be used to demonstrate this relationship Therefore source-control strategies concerned with algal bloom reduction should focus on conditions that occur when the barrier is closed, which is normally during the dry season

Nutrient-control strategies must take into account the limiting nutrient, which for an estuarine lagoon can be either nitrogen (N) or phosphorus (P) This study showed that the N P ratio delivered to Malibu Lagoon during the dry season was about 3 1 Thus nitrogen load reduction is the most efficient means of achieving algal bloom reduction Further studies are needed to evaluate details for the creek, especially because in-stream removal processes may lower the nutrient load from some sources en route to the lagoon Sediment delivered by winter storm discharge down Malibu Creek is a major contributor to phosphorus loading in the lagoon during the ensuing dry season Effective soil conservation measures in the drainage basin could reasonably reduce this source of nutrients Relative to Malibu Creek, sources adjacent to the lagoon are insignificant contributors to nutrient loading

(6) Management Pathogen Survey

This survey sought to assess the occurrence of pathogenic protozoan parasites and enteric viruses in lower Malibu Creek and the surf zone near the creek's discharge into the ocean Risk of infection from enteroviruses appears not to be significant in lower Malibu Creek and the surf zone Infectious enteroviruses were only detected in one sample - the wastewater from the discharge of the Tapia plant These viruses were detected by the animal-cell culture method where the polymerase chain reaction is used to detect viruses growing in the cell culture The Tapia treatment plant appears to be the source of *Cryptosporidium* and increased levels of *Giardia* observed in lower Malibu Creek *Giardia* was detected at all sample locations (before the Tapia discharge, in the Tapia discharge, in Malibu Creek below the discharge, and in the surf zone) *Cryptosporidium* was detected only below the discharge from the Tapia plant However average concentrations of *Giardia* were greater below the discharge from the Tapia plant Both parasites were detected in the surf zone near the discharge of Malibu Creek Recreational risks of *Giardia* and *Cryptosporidium* infection appear to be greater below the discharge from the Tapia plant, but are at levels which may present acceptable levels of risk *Giardia* appears to pose the greater risk of infection to bathers because it was found in greater average concentration than *Cryptosporidium* To quantify these risks better, it is recommended that monthly sampling of the protozoa be conducted for at least one year at the same sites and that the effectiveness of disinfection against *Giardia* cysts at the Tapia plant be assessed

(7) Hydrologic Alteration and Human Disturbance

The waters of lower Malibu Creek and its estuarine lagoon were analyzed of linear alkylbenzenes and fecal sterols, which are markers of household laundry detergents and sewage carbon respectively If present, these compounds would indicate a likely hydrologic connection to the creek and lagoon from storm drains and septic systems Coprostanol and other fecal sterols could also be considered innovative chemical tracers for human pathogens Both classes of compounds were therefore measured in water samples collected from different wells in the Malibu region, from different points within lower Malibu Creek, and from Malibu estuarine lagoon and the ocean

As expected, the sample from the Tapia treatment plant contained fecal sterols Water from C2, P7, Malibu Colony drain, and the lagoon exhibit significant human fecal contamination Waters from the Salvation Army Camp contain low levels of fecal sterols, while those from the Arizona Crossing and the ocean contain the least, and the available data do not indicate if they are of human origin Samples from the other three locations, P1, C1 and below Tapia, did not contain fecal sterols In addition, a suite of linear alkylbenzenes was detected in high amounts in the Salvation Army Camp sample, which must have originated from untreated domestic wastewater This sample also contained petroleum hydrocarbons The limited available data establish hydrologic connections to the creek and lagoon from storm storms and septic systems only in some locations More intensive sampling is required to address this issue in greater detail

(8) Management Alternatives

The environmental problems of Lower Malibu Creek and Malibu Lagoon, categorized in terms of biota, habitat and water resources, have a variety of causes Biotic and habitat problems include loss of aquatic and riparian habitat, proliferation of exotic species, reduced native populations of benthic invertebrates, fish, birds and plants, and endangered populations of birds and fish Water resource problems include eutrophication, high pathogen concentrations, erratic basin discharge and seasonally high lagoon water levels

Thirty-eight alternatives for managing these problems were evaluated according to 5 criteria feasibility, cost, effectiveness, environmental impact, and potential for controversy Eight alternatives for addressing impacts to biological resources were reviewed These comprised 2 alternatives for controlling the proliferation of exotic species, 2 alternatives for enhancing endangered fish habitat 2 alternatives for eliminating barriers to anadromous fish migration, and 2 alternatives for protecting birds Two alternatives, removing non-native plants and erecting signs to protect bird nesting areas, were assigned high priority

Thirty alternatives for addressing water resource issues were evaluated These included 10 alternatives for reducing dry season nutrient and pathogen inputs, and, for the lagoon, 5 additional alternatives for reducing only dry season nutrient concentrations, 1 alternative for reducing dry season pathogen concentration, 3 alternatives for reducing dry season algal growth, 2 alternatives for enhancing water circulation, 4 alternatives for reducing dry season freshwater flows, and 5 alternatives for preventing dry season lagoonal water levels from becoming problematic Ten alternatives were assigned high priority, including (1) treating creek flows, (2) treating urban runoff, (3) eliminating illicit discharges and connections, (4) implementing Best Management Practices (BMPs), (5) retrofitting the storm drain system, (6) reducing nutrients in Tapia's discharge, (7) diverting excess creek flows, (8) eliminating Tapia's discharge in dry months, (9) reducing water use in the watershed, and (10) implementing a modified mechanical breaching regime Three alternatives were assigned medium priority (1) eliminating Malibu Colony and Civic Center septic systems, (2) retrofitting septic systems, and (3) constructing a water level and/or disinfection facility Although we have separated high and medium priority alternatives, medium prioritization should not disqualify these alternatives from further consideration More detailed engineering and cost analysis should be conducted before some of the high priority alternatives are implemented, and the medium alternatives would also benefit from more detailed analysis

It is not necessary to implement all of these alternatives The ideal suite of management actions would focus on source reduction Some treatment, diversion and breaching alternatives are included among the hig-priority alternatives in recognition that source reduction alternatives alone may not be sufficient or successful enough in the short term

Although our analysis of water resource management alternatives was restricted (by the scope of the contract) to the lower watershed, any serious effort to solve the environmental problems in Malibu Creek and Malibu Lagoon must focus on the upper watershed as well

(9) Wetland Restoration

Potential restoration sites in Lower Malibu Creek and Malibu Lagoon were identified and assessed Because the comparatively narrow reaches of Malibu Creek near Tapia and the lower canyon experience high velocity discharges of water and sediment during flood events, vegetation on the floodplain and floodplain terrace is prone to frequent disturbance by events of modest return interval and, as a consequence, is dominated by riparian species Enhancement and restoration of this riparian vegetation would inhibit channel erosion and enhance instream habitat, and should be undertaken where feasible There are relatively few locations that would be appropriate for riparian restoration along the Creek, however Watershed management should also include reduction in landslide and debris-flow occurrence attributable to changing fire frequency and human activities such as road maintenance Although small ponds may survive into the dry season in these reaches, few wetland species persist in this dynamic environment Wetland restoration for these reaches is thus inappropriate

The Malibu Lagoon area has been substantially alterred by human activities, including infilling and construction of commercial and residential buildings Paxt activities have reduced the area of wetland and associated habitats and interfered with the natural physical processes that shaped the lagoon area For example, Malibu Creek would normally change its course in response to variable fluvial processes, but is now restricted to a narrowly defined area because of bank stabilization to protect commercial buildings The Malibu Lagoon Ecosystem Restoration alternative is presented as a model for restoring much of the original habitat types and processes to the lagoon area Although this alternative would not restore the lagoon area completely back to the condition is was in 200 years ago, it would restore the basic form of the lagoon, allow the development of some associated habitats, and remove some of the most serious impediments to natural physical processes Implementing this alternative would require the removal of commercial buildings west of the lagoon, removal of residences in the eastern portion of Malibu Colony, and removal or redesign of the Pacific Coast Highway bridge to allow natural physical processes to operate over an extended portion of the lagoon area Although this ecosystem restoration alternatives provides by far the greatest ecological value of all alternatives considered in this report, it also would be by far the most costly, as well as providing the greatest legal and logistic challenges

To consider other restoration alternatives, Malibu Lagoon may be divided into three distinct landscape units based on hydrogeomorphic characteristics Zone A, the estuarine lagoon south of Pacific Coast Highway, is fronted seasonally by the barrier beach extending westward into the more permanent physical structure beneath Malibu Colony Zone A is essentially a transitional environment between Malibu Creek and Santa Monica Bay, an interface between freshwater and marine systems Although it has suffered much loss of original habitat, Zone A contains the most extensive wetland in the area and offers most possibilities for effective restoration and management The highest priority restoration project would incorporate the existing salt marsh, the golf course, and vacant lot farther west into a larger, more effective estuarine lagoonal system Such restoration could closely mimic the natural diversity of wetland habitats and functions found in prehistoric Malibu Lagoon Alternatively, the salt-marsh area restored in 1983 could be modified to increase its wetland functions and values

Zone B is the riparian corridor that extends 1 km upstream from Pacific Coast Highway to the bedrock narrows at the lower end of Malibu Canyon Zone B, essentially the now constricted distributary interface between creek and lagoon, has little need for restoration but should be carefully managed to maintain its transitional habitats

Zone C, the Civic Center area, is the most extensively modified zone and poses the greatest challenge Certain developments here should never have been allowed, impinging as they do on the functions of the original natural system and creating in the process new artificial systems that are variably incompatible with the natural system Assuming, however, that such developments will remain, there are several opportunities for enhancement Water management, both of natural floodwater and wastewater, is the most critical element from which stem a range of dependent possibilities, including wetland restoration A packet wastewater treatment plant could be developed here to the benefit of the existing lagoon and in association with expanded wetland and riparian restoration

(10) Summary of Management and Restoration Alternatives

The findings from **(8)** and **(9)** are reviewed with respect to identification of critical issues for the pursuit of future management and restoration options, the resolution of inconsistencies, and the development of clear directives for agencies and stakeholders

The evaluation of alternatives and assignment of priorities was complicated by four issues (1) uncertainty about nutrient inputs from some sources, (2) uncertainty about pathogen inputs, especially from septic systems, (3) uncertainty about the disposition of Rindge Dam, and (4) lack of detailed engineering feasibility and cost analyses for some of the construction/management alternatives, including a water level management facility and creek flow diversion These uncertainties should not preclude action to solve Malibu's environmental problems For some alternatives, these uncertainties have little effect on our conclusions However, information removing these uncertainties might simplify the choice of which alternatives to implement, and could change the priority ranking of some alternatives In addition, more detailed engineering and feasibility studies must be conducted before any of the construction-intensive alternatives are adopted Although our prioritization is based on our best judgement about the advantages and disadvantages of the alternatives, we have not attempted the type of detailed studies that would be needed to confirm our assessments We recommend that a planning/engineering study be conducted to compare the different engineering alternatives

(11) Concluding Perspective

There are no easy solutions to the problems of Lower Malibu Creek and its associated estuarine lagoon and barrier system. Management and restoration alternatives are constrained by several natural and human factors. Lower Malibu Creek feeds the lagoon seasonally with a large volume of natural creek flows and human waste from both treated discharges and leaky septic systems, flushing the lagoon and its residual contents seawards through a variable breach in the barrier. Under natural conditions, in early historic time, this lagoon probably occupied two to three times its present area during the rainy winter season. During the dry summer season, however, the lagoon lost abundant water to evaporation and seepage, and was at times an odorous marsh and salt flat subject to occasional breaching by superelevated lagoonal waters and wave action. Under human impact, the lagoon has become smaller and more odorous, more eutrophic and contaminated with pathogens for longer periods, much manipulated by human activity but still prone to seasonal flushing by winter floods and summer breaching. Development along the barrier beach, however, has constrained breaching and flushing possibilities. Prior reclamation and restoration within the lagoon have created an imperfect system. Developments inland, especially successive iterations of the coast highway, construction along lower Cross Creek Road and in the Civic Center area, and widespread use of fill, have transformed a quasi-natural landscape into a dysfunctional artificial system.

Within a scientific context, there is a spectrum of options available for the future management of the system, ranging from one extreme of doing nothing beyond present controls to the other extreme of seeking to return the system to its natural state. Neither extreme is wholly appropriate or feasible. Instead, this study recommends action on several fronts, but particularly on such issues as water quality and public health, removal of non-native plant species, habitat management, and selective wetland restoration. As scientists we recognize, but do not enumerate, the economic, political and legal constraints of seeking to impose change on the present dysfunctional system. Possible solutions to the problems found at Malibu are readily identified but not easily implemented.

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May 2000

Preamble

Antony R. Orme and Richard F. Ambrose

Malibu Creek drains a 284-km^2 basin southward through the Santa Monica Mountains to the sea at Malibu on the north shore of Santa Monica Bay. The basin may be divided broadly into two parts: a large, relatively open upper section and a rugged lower or canyon section through the Santa Monica Mountains. The basin has a Mediterranean-type climate with warm dry summers and cool wet winters, thermal conditions and available moisture depending on location and elevation. Under natural conditions, the basin was probably clothed in chaparral, a fire-adapted evergreen sclerophyllous plant community, merging locally into coastal sage scrub, oak woodland, and native grassland, with riparian woodland and wetland plants in more specialized habitats, all of which in turn supported a variety of wildlife.

In recent times, the Malibu Creek basin has been much affected by human activity, initially by native Americans who used fire to drive wildlife and also lived off the coast's ample marine resources, later by Spanish, Mexican and American cattle ranchers whose impact further changed the native vegetation and led to the intrusion of alien species, and most recently, since 1900, by railroad and highway construction and residential, commercial and industrial development. Recent activities have focused particularly on the upper basin, along the transportation corridor provided by US Highway 101, but also occur in the narrow coastal strip along California Highway 1, the Pacific Coast Highway. The intervening canyon section, though used by Los Angeles County Highway 1, Malibu Canyon Road, has remained more pristine, except for the completion of Rindge Dam in 1928 and the inevitable downstream impacts of activities in the upper basin.

Concerned with the downstream impacts of continuing human activities on the natural system, the California Coastal Conservancy approved a contractual arrangement with the University of California, Los Angeles, for research entitled **Lower Malibu Creek and Malibu Lagoon: Resource Enhancement and Management**. The contract was approved on August 15, 1997, for completion by December 1999. For the purpose of this project, Lower Malibu Creek was defined as that portion of the creek south of the Salvation Army Camp in the Tapia unit of Malibu Creek State Park. Richard F. Ambrose, Professor of Environmental Science and Engineering, and Antony R. Orme, Professor of Geography, served as Principal Investigators for the project.

The Coastal Conservancy's original Request for Proposals (RFP) outlined a workplan comprising nine tasks. The main thrust of the research was contained in six tasks (Tasks 2 through 7); the remaining three tasks (Tasks 1, 8, 9) concerned meetings with the Malibu Lagoon Task Force, and preparation of draft and final reports. In consultation with the Coastal Conservancy and the Malibu Lagoon Task Force, the workplan was revised and expanded in order to accomplish project goals in the most appropriate manner. The following report addresses these tasks as follows:

Chapter 1: Evolution and Historical Development by Antony Orme. For reference, Task 7 in the original RFP called for an evaluation of historical conditions in Malibu Lagoon and adjacent areas. The investigator considered it desirable to evaluate briefly the prehistoric evolution of the area and to advance this discussion to the beginning of the report so as to set the scene for subsequent chapters.

Chapter 2: Hydrology and Morphodynamics, 1997-98 by Antony Orme, Kenneth Schwarz, Priya Finnemore, Mark Kuhlman and Johannes Feddema. Task 2 of the original RFP sought a comprehensive hydrologic evaluation of Lower Malibu Creek and Lagoon. Again, the investigators considered it appropriate to expand this research into the realm of estuary-lagoon-barrier morphodynamics, namely the specific interaction between hydrologic and marine forcing and the changing morphometry of the system. This study was conducted intensively over one water year, beginning October 1, 1997 and ending September 30, 1998, with continued monitoring to the close of the project.

Chapter 3: Biological and Water Quality Objectives and Habitat Associations by Richard Ambrose and Tonatiuh Trejo. Tasks 3, 4A-2 and 4A-3 in the original RFP were combined into Chapter 3. These tasks involved an extensive literature review of water quality factors influencing target species in the Malibu Creek watershed. In addition, habitat associations for target species are discussed.

Chapter 4: Vegetation by Philip Rundel. This was Task 4A-1 in the original RFP, which requested an assessment of biota, including non-indigenous species, in Lower Malibu Creek and Malibu Lagoon.

Chapter 5: Eutrophication by Mel Suffet and Shelby Sheehan. This was Task 4B in the original RFP.

Chapter 6: Pathogen Survey by Charles Gerba, Jaime Naranjo and Patricia Orosz-Coghlan, subcontracted to the Department of Soil, Water and Environmental Science in the University of Arizona. This was Task 5 in the original RFP.

Chapter 7: Hydrologic Alteration and Human Disturbance by Indira Venkatesan. The analysis of linear alkylbenzenes and fecal sterols was optional Task 4A-3a in the proposal.

Chapter 8: Management Alternatives by Richard Ambrose and Jonathan Lilien. This was included in Tasks 7 and 9 in the original RFP, which called for a discussion of a management plan within the Comprehensive Final Report. It is expanded to provide a comprehensive review of possible management techniques for resolving the environmental problems in the lower Creek and Lagoon. Previous studies and management actions in the region are reviewed and the causes of environmental problems summarized Management alternatives for biological resources and water resources are evaluated and prioritized

Chapter 9: Wetland Restoration by Richard Ambrose, Jonathan Lilien and Gretchen Coffman This was also included under Tasks 7 and 9 in the original RFP, which called for an evaluation of habitat restoration options within the Comprehensive Final Report Potential restoration sites in the lower Malibu Creek are assessed based on field surveys, and possible restoration activities evaluated In the Malibu Lagoon area, potential restoration sites are assessed in terms of site opportunities and constraints Conceptual plans are presented for a number of restoration alternatives

Chapter 10: Summary of Management and Restoration Alternatives by Richard Ambrose and Jonathan Lilien This chapter provides an overview of the management alternatives and restoration plans presented in Chapters 8 and 9 Because management alternatives and restoration plans are related, this chapter also provides a synthesis of management actions that could be taken to resolve the environmental problems in lower Malibu Creek and Lagoon

Chapter 11: Concluding Perspective by Antony Orme emphasizes the natural and human constraints within which the Malibu system functions, and evaluates, from a scientific viewpoint, the spectrum of options available for its future management

References and **Appendices** are given as necessary at the close of each chapter

In a multidisciplinary project of this nature, large volumes of data are acquired and analyzed, interpreted in the text and accompanying figures, but not reproduced in their entirety in the report The results also generate new scientific questions and implications for further research Persons interested in these data and their implications should contact the authors of individual chapters

Chapter 1: Evolution and Historical Development

Antony Orme

Chapter 1: Evolution and Historical Development

Antony Orme

The mainstem of Malibu Creek rises on Sandstone Peak (948 m) on the northwest flank of the Santa Monica Mountains and drains eastward for 35 stream km to its confluence with Cold Creek, whence it descends a further 7 stream km through Malibu Canyon to the Pacific Ocean east of Malibu Point on the north shore of Santa Monica Bay.

The 284 km^2 drainage basin of Malibu Creek may be divided into upper and lower sections by the Cold Creek confluence (Figure 1-1). The upper section comprises 272 km^2 of mostly rolling country containing several sub-basins draining southward from the Simi Hills to join the mainstem as it incises along its eastward path. Like other regional drainages, Malibu Creek has gravitated southward in its basin in response to tectonic forcing, causing south-flowing tributaries to lengthen at the expense of now insignificant north-flowing streams. The mainstem in this section has a mean gradient of 0.024. The lower or canyon section of the basin below Cold Creek covers only 12 km^2 and has no major tributaries. The mainstem here has a mean gradient of 0.017, reflecting a higher erosion:uplift ratio than upstream.

For this project, Lower Malibu Creek comprises the lowest portion of the upper basin, the 4.7 km^2 Tapia section between the confluences of Las Virgenes Creek and Cold Creek with the mainstem, and the lower basin which is in turn divided into a 9.6 km^2 Canyon section and a 2.4 km^2 Estuary section (Figure 1-2). The small Estuary section is distinguished from the Canyon section because about 1.5 km inland from the coast Malibu Creek leaves its rock-controlled canyon and is influenced by base level and estuarine conditions as it nears the ocean.

The following discussion presents, first, an overview of the Late Cenozoic evolution of the region; then analyses of Late Pleistocene events during the last interglacial-glacial cycle, and of Holocene events as sea level rose to its present elevation; and concludes with a more detailed evaluation of the historical development of the lower basin and estuarine lagoon. Emphasis is accorded to those elements relevant to management issues in the lower Malibu basin.

1.1 Overview of Late Cenozoic Evolution

Malibu Creek drains portions of three morphotectonic units along the southern margins of the Western Transverse Ranges in southern California, namely the Santa Monica Mountains, Simi Hills, and Conejo Valley. The Western Transverse Ranges, namely that part of the Transverse Ranges that

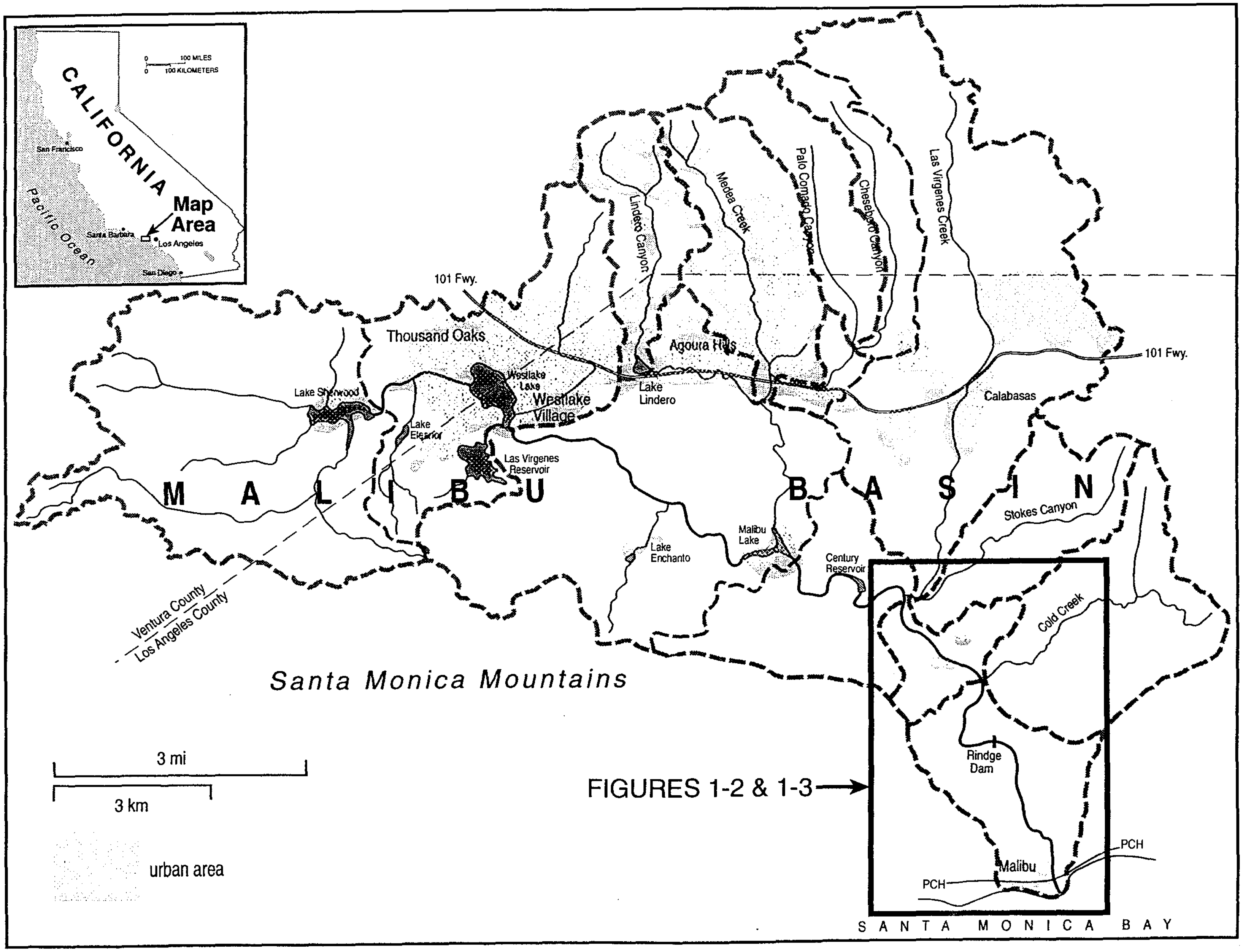

Figure 1-1. Malibu Creek drainage basin and principal sub-basins, southern California.

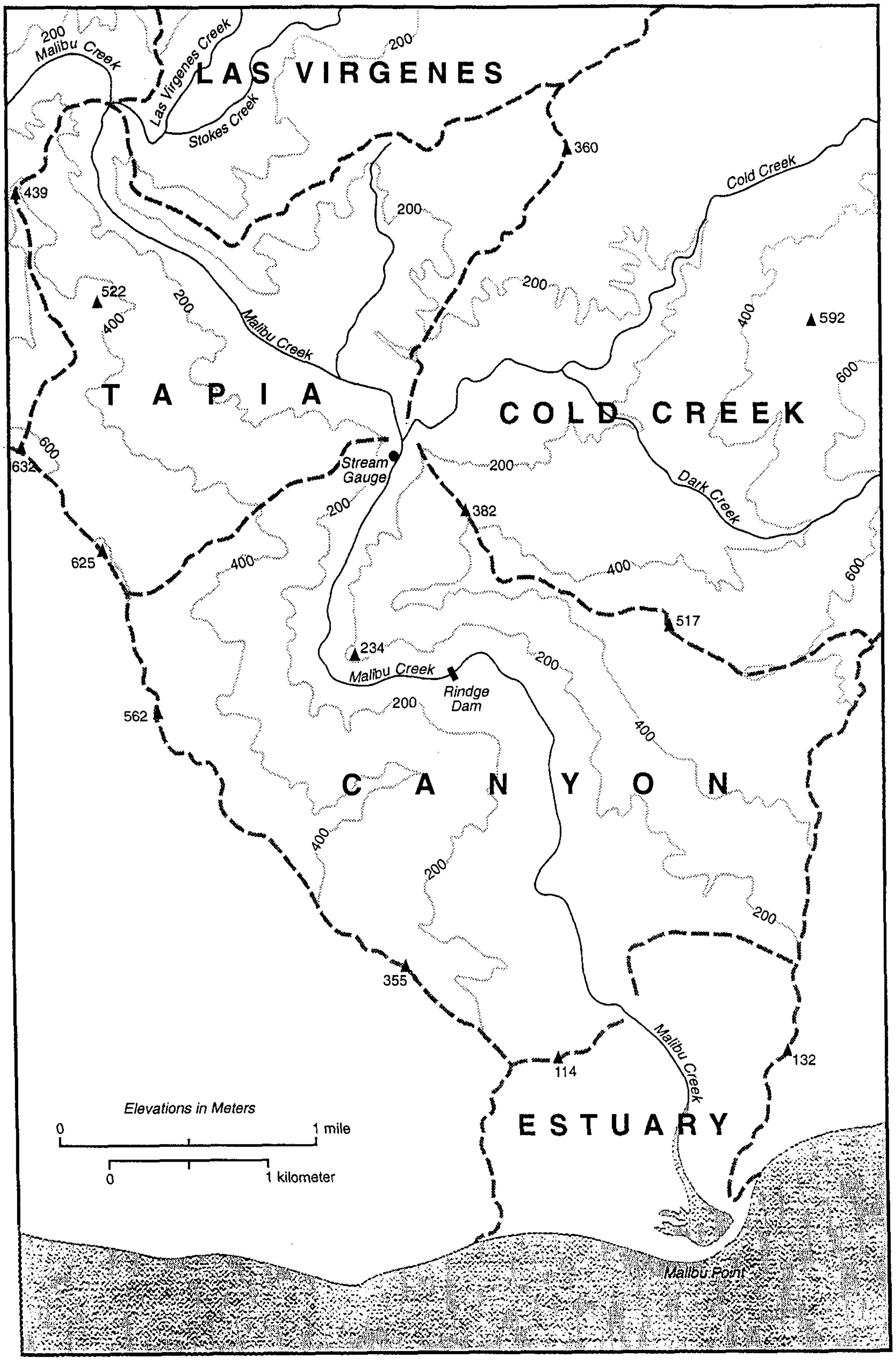

Figure 1-2. Lower Malibu Creek basin showing sections discussed in text

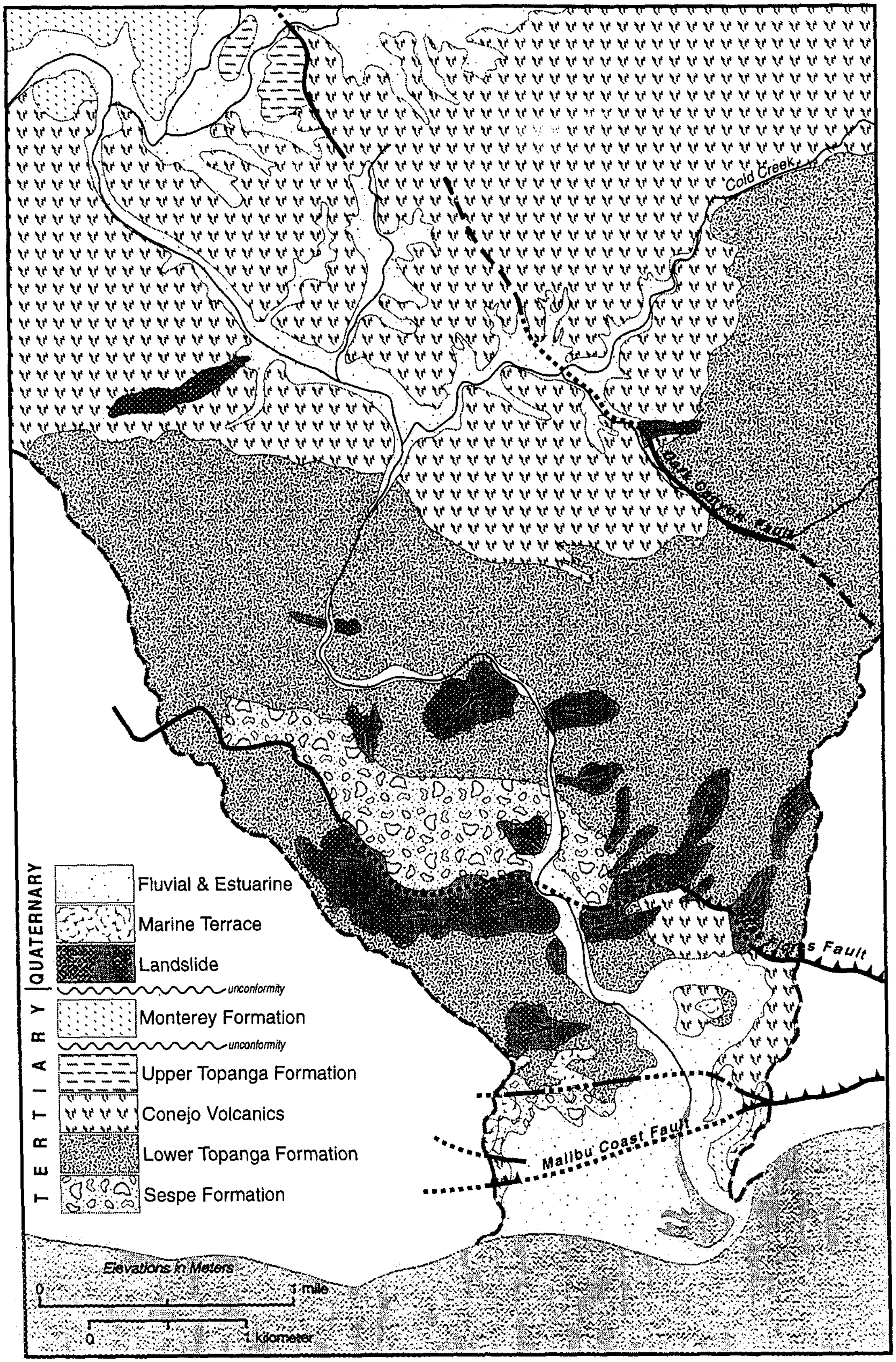

Figure 1-3. Geology of Lower Malibu Creek basin (based on Dibblee, 1993)

extend 200 km westward from the dormant San Gabriel Fault, are now characterized by active transpressional tectonics in contrast to the strike-slip tectonics of other parts of coastal California

The Santa Monica Mountains extend 75 km from the Los Angeles River Narrows west to Point Mugu, and range from 5 to 15 km in width Highest elevations occur along the southern margin of the upper Malibu basin, at Sandstone Peak (948 m) in the west, Castro Peak (861 m) in the center, and Saddle Peak (855 m) in the east The broadly anticlinal structure of the mountains is offset by several north-dipping thrust faults, among which the Malibu Coast Fault is most prominent Farther east, the mountains are cored by Mesozoic metasediments and granitic intrusions, locally overlain by late Cretaceous and Paleocene marine sediments but these rocks do not reach the surface in the lower Malibu basin (Yerkes and Campbell, 1980) The latter area is dominated by Oligocene and Miocene clastic sedimentary rocks, notably terrestrial conglomerates and sandstones of the Sespe Formation and marine and nearshore conglomerates, sandstones and mudstones of the Topanga and Monterey Formations, and by submarine and subaerial Miocene volcanic rocks, the Conejo Volcanics, which extruded during deposition of the Topanga Formation (Figure 1-3)

The Simi Hills are a broad anticlinal flexure, 5-10 km wide, extending for 25 km along the northern margin of the upper Malibu basin from the Santa Susana Mountains in the northeast to Conejo Creek in the west They are formed mainly from late Cretaceous, Paleocene and Eocene clastic sedimentary rocks of marine origin, specifically conglomerates, sandstones and mudstones of the Chatsworth (late Cretaceous), Santa Susana (Paleocene) and Llajas (Eocene) Formations (Dibblee, 1993) These hills reach 732 m above sea level in Simi Peak

The broad corridor intervening between the Santa Monica Mountains and the Simi Hills, herein called the Conejo Valley, is a broad synclinal structure dominated at the surface by fine-grained marine clastic sediments of middle and late Miocene age, notably the Monterey and Modelo Formations (Weber, 1984)

1 1 1 Tectonic and Geomorphic Evolution

The geomorphic character of the region has evolved since the Santa Monica Mountains, Conejo Valley and Simi Hills began to emerge from late Miocene seas There had been prior episodes of subaerial exposure, notably in the late Oligocene when coarse fluvial sediment of the Sespe Formation was deposited, and during the middle Miocene (17-13 Ma) when some breccias of the Conejo Volcanics were deposited as lahars, but only after the late Miocene emergence did the landscape begin to acquire its subaerial character The presence of marine Pliocene sediment in the Santa Clara and San Fernando valleys and the central Los Angeles Basin, and of nearshore marine sediment of middle Pleistocene age north of the Simi Valley, suggests that the Simi Hills-Santa Monica Mountains emerged initially as islands and later as peninsulas in the late Cenozoic sea, but not in their present location.

The anomalous east-west trend of the Western Transverse Ranges, lying across the predominant NW-SE trend of the Coast and Peninsular Ranges, is an enigma. Whereas the province, lacking a crustal root and underlain by an anomalously high seismic velocity ridge in the mantle, probably owes its present form to compression within a thin weak lithosphere, compression alone does not explain its orientation. The enigma may be resolved by invoking a 70-120^0 clockwise rotation of the region since early Miocene time from a former alignment parallel with the Coast Ranges (Kamerling and Luyendyk, 1979; Nicholson et al., 1994). This rotation, evidence for which occurs in the paleomagnetic record of the Conejo Volcanics, occurred around a pivot point at the eastern end of the province. Rotation, accompanied by a 10^0 northward latitudinal shift, was closely linked to the evolving Pacific-North American transform boundary, especially the capture of remnants of the subducting Farralon plate (the Monterey and Arguello microplates) by the Pacific plate around 20 Ma and development of successive strike-slip structures including the San Andreas fault system.

Around 5 Ma, as subduction of the Farralon plate remnants continued, the East Pacific Rise spreading center appeared beneath the Gulf of California. Thereafter, the peninsula of Baja California transferred to the Pacific plate and accelerated north and west away from western Mexico on the western limb of this spreading center, causing the Peninsular Ranges and neighboring borderland to push against the south front of the rotating Western Transverse Ranges. The latter subsequently suffered massive compression which expelled the sea and generated the elongate ridges and basins now seen in the Santa Monica Mountains, Conejo Valley and Simi Hills. Tectonic stress within the region is relieved intermittently by movement along mostly north-dipping reverse faults such as the Malibu Coast and Las Flores fault systems.

1.1.2 Geodynamic Significance

The significance of these events to Malibu Creek is that uplift occurred across a distributary drainage system that originated during the region's late Miocene emergence. Although mainstem drainage was constrained by the (now) east-west strike of the emergent Pleistocene peninsula, it maintained an outlet to the south through the emergent Santa Monica Mountains. The rapidity of uplift limited lateral erosion in Malibu Canyon. Rocks within the Lower Malibu Creek basin are characterized by moderate to steep dips, commonly 30-60^0 in the quadrant between NE and NW (Dibblee, 1993). These steep dips render the region prone to bedding-plane failures.

The oldest rocks reaching the surface within Lower Malibu Creek, the Sespe Formation, form relatively resistant outcrops, notably where massive terrigenous sandstones and conglomerates outcrop 2-3 km upstream from the coast (Figure 1-3) Mass movement occurs infrequently in these rocks, usually in the form of slab failures The overlying Lower Topanga Formation, comprising marine sandstones and conglomerates deposited as submarine fans, is similarly resistant and outcrops over much of the remainder of Malibu Canyon Slope failures in these rocks are commonly associated with oversteepened canyon walls, with interbedded shales and siltstones, and with the Las Flores fault zone The Conejo Volcanics, comprise mostly andesitic and basaltic breccias and basaltic flows deposited as submarine flows and subaerial lahars, interbedded with marine sandstones of the Middle Topanga Formation near Cold Creek These rocks outcrop across the Tapia section and reappear east of the Estuary between the Las Flores and Malibu Coast faults (Figure 1-3) Rock units are individually resistant to erosion and mass movement but yield rugged broken country by virtue of frequent lithological variations The overlying Upper Topanga and Monterey formations occur just outside the northern margins of the study area where, containing much siliceous shale and friable sandstone, they are prone to both landslides and debris flows that contribute significantly to the sediment load of Las Virgenes Creek At the coast, a small outcrop of the Monterey Formation is steeply overturned between strands of the Malibu Coast Fault

The Malibu Coast Fault is a high angle, north-dipping, reverse fault with a strong left-lateral strike-slip component that in general terms causes the Santa Monica Mountains to thrust upward and move westward relative to Santa Monica Bay (Treiman, 1994) Various splays of this fault presumably pass beneath the Estuary section as they offset late Cenozoic bedrock to both east and west The Las Flores Fault is a similar structure crossing Malibu Creek about 1 km farther north As will be shown in subsequent sections, the behavior of these faults, especially the Malibu Coast Fault, is a critical component of the structural dynamics of Malibu Lagoon

1.2 Late Pleistocene Events

Although shallow seas still persisted on Oak Ridge, north of Simi Valley, into mid-Pleistocene times, the Malibu basin was now fully emergent and subaerial erosion dominant For the most part, frequent climate fluctuations of the later Pleistocene ensured that climatic forcing of erosion and sedimentation became more significant than slower tectonic forcing Deprived by tectonism of other outlets, Malibu Creek now focused on incising its canyon outlet to the sea In doing so, it left a scattered legacy of former floodplains as fragmentary terraces, mostly in the Tapia section and farther upstream (Figure 1-4) Within the Canyon, only at the inside bend south of Rindge Dam is there a significant terrace fragment of uncertain age, mantled

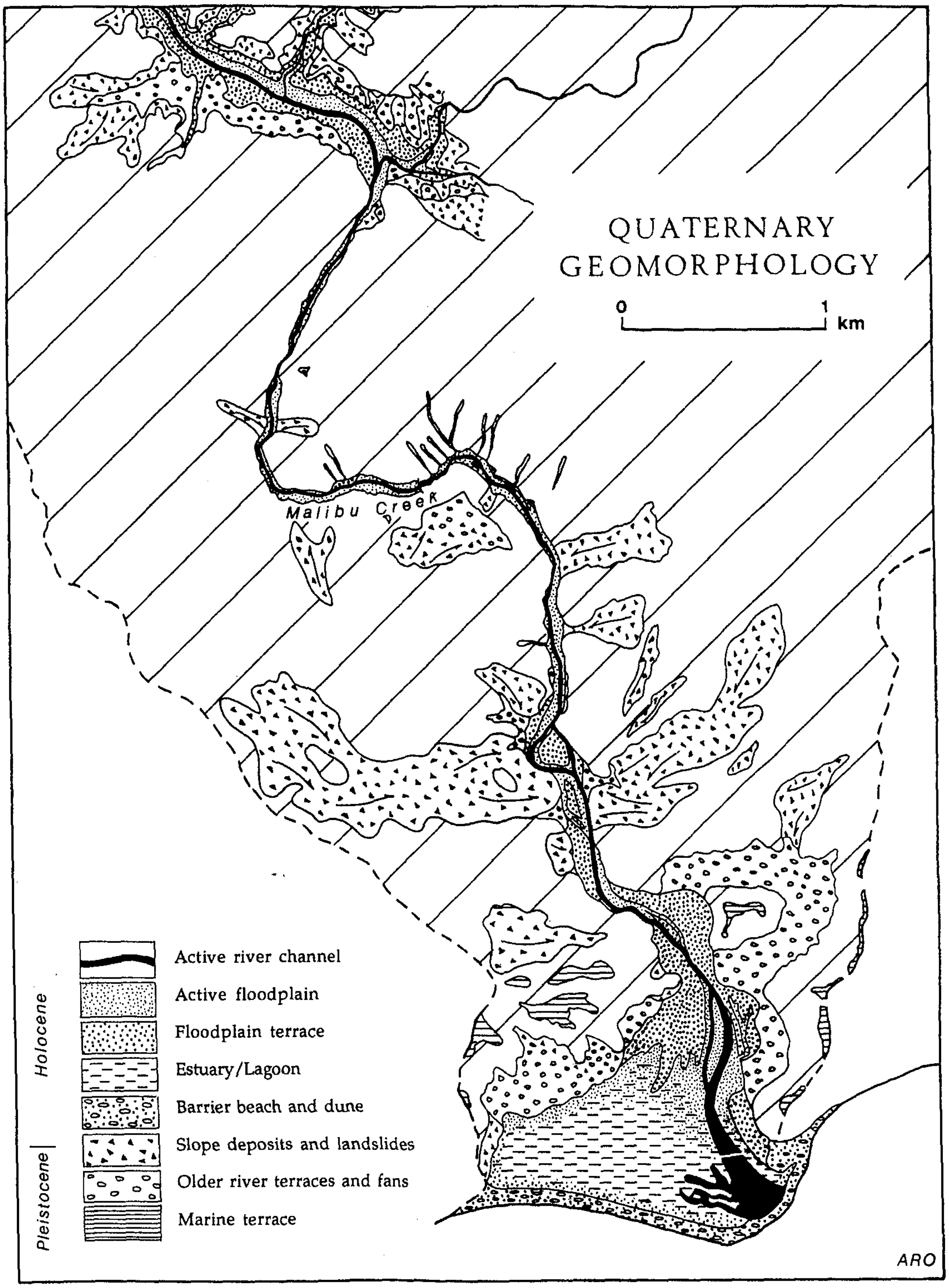

Figure 1-4 Quaternary geomorphology of Lower Malibu Creek and Malibu estuarine lagoon system. More detailed information on the evolution of the estuarine lagoon and its behavior during 1997-98 is presented in Chapter 2 (Figure 2-1 et seq.)

by landslide debris from farther upslope Certainly, the larger landslides within the Canyon probably moved repeatedly during Pleistocene wet intervals when soil moisture and pore pressures were greater than today

Only at the coast is there significant evidence for the interplay between tectonic and eustatic forcing of erosion during late Pleistocene times, although the fragments of earlier Pleistocene marine terraces that survive along the seaward flanks of the Santa Monica Mountains are insignificant compared with the remarkable records for net uplift provided by the terrace sequences in the Ventura Basin and Palos Verdes Peninsula (Orme, 1998) However, from Little Sycamore Canyon eastward to just beyond Malibu Creek, terraces dated by uranium-series methods to stillstands around 125 ka and 80 ka are well preserved (Birkeland, 1972, Szabo and Rosholt, 1969) There is also fragmentary evidence beneath colluvium for a further stillstand in the 50-ka range The 125 ka shoreline lies well above the +6-m eustatic sea level inferred from relatively stable coasts for the warm marine oxygen isotope stage 5e, the Last Interglacial The 80 ka shoreline, from the cooler stage 5a, similarly lies well above present sea level whereas on stable coasts it now occurs -5 m below sea level Tilted slightly westward, these shorelines give average uplift rates of about 0 30 m per 1000 years which, because they straddle or lie south of the Malibu Coast Fault, must represent a minimum uplift rate for the Santa Monica Mountains north of the fault Splays of this fault show signs of late Pleistocene and Holocene movement, notably beneath Winter Mesa (Rzonca et al , 1991, Treiman, 1994) The 125 ka shoreline reappears north of the Malibu Coast Fault near Topanga Canyon and on Castellemmare Mesa, Pacific Palisades, reaches 46 m above sea level for a minimum uplift rate of 0 32 m per 1000 years (Heron and Shaller, 1997)

These marine terraces are significant to Lower Malibu Creek and Malibu Lagoon because they demonstrate continuing tectonic instability of the past 125 ka, with net uplift of Santa Monica Mountains and net subsidence likely seaward of the fault Because displacement may also occur locally during more distant seismic events, as shown by coastal responses to the M6 4 Sylmar Earthquake of February 9, 1971, and the M6 8 Northridge Earthquake of January 17, 1994, sudden tectonic forcing is a real variable in seeking to explain the dimensions and behavior of Malibu Lagoon over the longer term

Uplift rates indicated by these terraces, around 0 3 m per 1000 years, are a magnitude less than the high rates defined for the Ventura area but a magnitude greater than those observed along the more stable outer coast of Baja California (Orme, 1998) Collectively, however, they imply a continuation of massive uplift related to convergence and crustal shortening in the Western Transverse Ranges These movements involve both sinistral strike-slip motion and high angle reverse faulting within the critical zone where Malibu Creek debouches into its estuarine lagoon The continuing rotation of the Western Transverse Ranges is probably responsible, at least in part, for the style and pattern of this deformation

1.3 Holocene Events

1.3.1 Regional Setting

Following the relatively high eustatic levels of +6 m, -5 m and -5 m during marine oxygen isotope stages 5e, 5c and 5a respectively, eustatic sea level fell well below the present during stage 4 (75-50 ka), rose to about -30 to -50 m during the interstadial stage 3 (50-30 ka), and then fell sharply to around -120 m during stage 2 (30-10 ka), the Last Glacial Maximum. During stages 4 through 2, net tectonic uplift of the Santa Monica Mountains continued at an average rate of 0.3 m per 1000 years but the ocean surface, though fluctuating always lay beyond and below present sea level, although its effects have been locally elevated by later tectonism. As a consequence, Malibu Creek continued to incise its canyon and over its lowermost 1.5 km was cutting its channel below present sea level. At some stage, it abandoned the incised meander that had taken the creek to the north and east of the present Serra Retreat and occupied its present course to the west (Figure 1-4). During this time, Malibu Creek also constructed a significant alluvial fan from the bedrock narrows towards what are now the inner margins of the lagoon. This fan was built by several distributaries, one of which later incised a deeper channel that stranded other parts of the fan as a floodplain terrace, occasionally flooded during historic times by high discharge events (Figure 1-4). Later, as sea level rose into this embayment, the distributary system acquired some of the characteristics of a fan delta, but fluvial processes remained dominant.

During the maximum eustatic drawdown of stage 2, the creek probably crossed the present coast in a bedrock channel at least 32 m below present sea level and extended some 5 km into the now submerged borderland. Water wells drilled in the vicinity of the present highway bridge across Malibu Creek reveal fluvial deposits to a depth of at least 32 m without reaching bedrock (Birkeland, 1972). In reaching the coast, the creek thus excavated a significant basin, probably on the site of former basins related to earlier low sea levels. This most recent basin was to become the site of the prehistoric Malibu estuarine lagoon.

The critical force in creating the present estuarine lagoon was the eustatic rise of sea level, the Flandrian transgression, that accompanied the decay of the world's last major ice sheets. This transgression began around 18 ka (^{14}C years before 1950), achieved maximum rates of 10-20 m per 1000 years between 15 ka and 8 ka, and then slowed as most ice sheets disappeared (Orme, 1991).

This sequence of events has been well illustrated by research along the central California coast. In San Francisco Bay, rising seas entered the Golden Gate about 10 ka and, rising at a rate of 20 mm per year, flooded laterally across San Francisco Bay as rapidly as 30 m per year until 8000 years ago (Atwater et al., 1977). The rate of sea-level rise declined rapidly between 8 and 6 ka as the last ice masses disappeared, and for the past 6000 years has

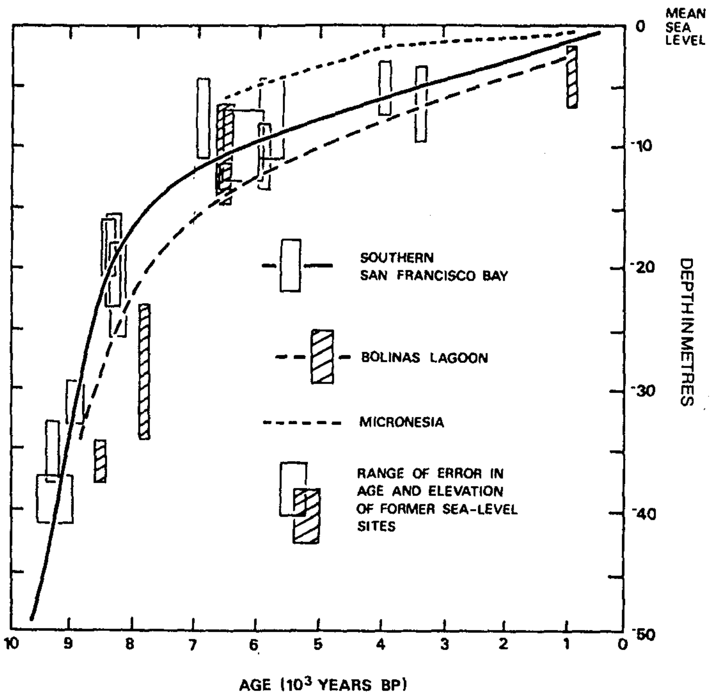

Figure 1-5 Holocene sea-level changes in southern San Francisco Bay and Bolinas Lagoon, California. Based on radiocarbon ages of submerged wetland deposits, the curves indicate tectonic and hydroisostatic subsidence relative to eustatic sea-level change in Micronesia (after Atwater et al., 1977, Berquist, 1978, in Orme, 1991)

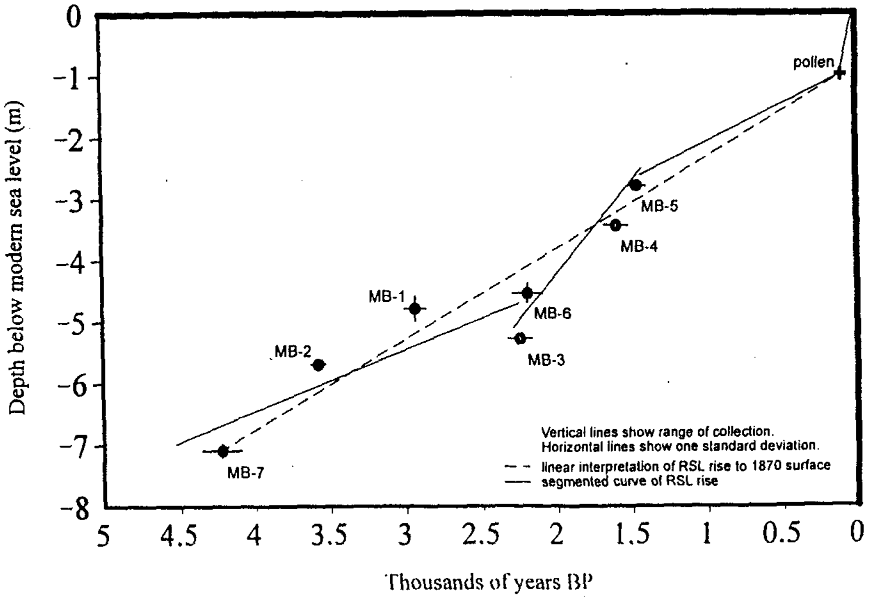

Figure 1.6 Late Holocene sea-level changes in Morro Bay, south-central California. Based on radiocarbon ages of shells and charcoal, and foraminiferal and pollen analysis of submerged wetland sediment, the data suggest an accelerated sea-level rise between 2500 and 1500 BP, possibly associated with co-seismic subsidence (after Gallagher, 1996, and Gallagher and Orme, in preparation)

averaged 1.0-2.0 mm per year (Figure 1-5). During this time, however, earlier Holocene salt marsh deposits in southern San Francisco Bay have subsided 5 m, owing to tectonism and isostatic loading. Data from Bolinas Lagoon, within splays of the San Andreas fault zone, reveal even more pronounced subsidence during later Holocene time (Figure 1-5) (Berquist, 1978).

The later part of the Flandrian transgression is also well revealed beneath Morro Bay on the south-central California coast (Orme and Gallagher, 1994; Gallagher, 1996; Gallagher and Orme, in preparation). Here, radiocarbon ages on shells and charcoal, combined with foraminiferal and pollen analyses of deposits beneath the Chorro delta, have revealed a late Holocene sea-level rise of 1.5 to 1.7 mm per year over the past 4200 years (Figure 1-6). Within this mean rate is a sharp increase to 3.0 mm per year between 2500 and 1500 BP, probably attributable to co-seismic subsidence along the Los Osos fault zone that passes seaward beneath Morro Bay. Nearer to Malibu, a radiocarbon age on shell fragments from the shelf off Santa Monica has suggested a sea-level rise of 2.6 mm per year over the past 3270 years (Nardin et al., 1981).

In summary, as sea level rose during the Flandrian transgression, so coastal systems migrated upslope across submerging land surfaces. Where beaches were forming across estuaries and lagoons, a barrier-estuary/lagoon-wetland sequence developed in a vertical plane that was identical to the horizontal sequence in the direction of the transgression (Figure 1-7).

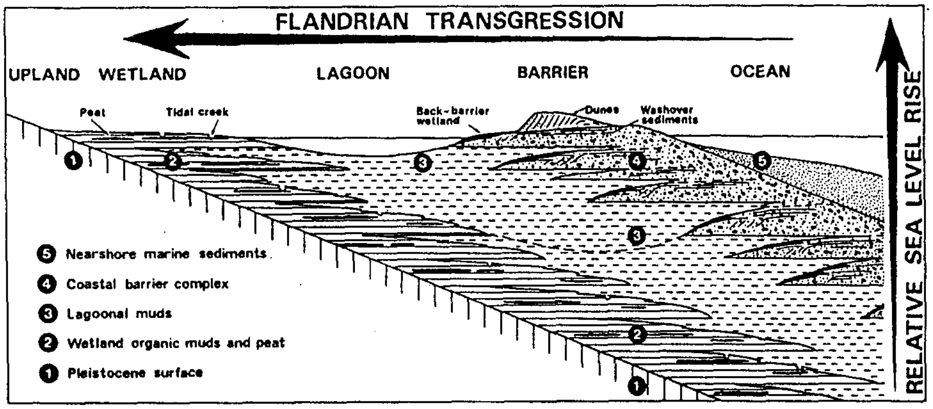

Figure 1-7 Schematic diagram showing how a relative rise of sea level against a sloping surface produces a barrier-lagoon-wetland sequence in a vertical plane that is identical to the horizontal sequence in the direction of the transgression (Orme, 1991)

The significance of the above considerations to the Malibu coast is threefold First, from a sea level some 120 m below present and 5 km offshore, the Flandrian transgression drowned the present nearshore area, rapidly between 15 ka and 8 ka when earlier freshwater marshes were presumably buried by marine sediment, and tidal marshes, if any, were confined to sheltered embayments along the immediate coast Second, the later part of this transgression, after 6 ka, is likely attributable not to glacioeustatic forcing but to hydroisostatic loading of the continental shelf or borderland interwoven with tectonic activity Whereas it is presently difficult to distinguish between hydroisostatic and tectonic effects, it is probable that the Malibu coast would have experienced a continuing modest rise of sea level over the past few thousand years, similar to that observed in Morro Bay and that relative movement within Malibu Lagoon would have been influenced by activity across the Malibu Coast fault zone (see section 1 4) Third, the patterns of sedimentation and wetland development within Malibu Lagoon would have been closely dependent on the rate of sea-level rise Rates of relative sea-level rise above 2 5 mm per year are probably too fast for wetland development because sedimentation rates do not keep pace with rising sea level (Orson et al , 1985) However, where sediment supply is abundant, as at Malibu, continued accretion may be possible with rates of relative sea-level rise as high as 3 0-4 0 mm per year Further, as relative sea-level rise slowed after 6 ka, conditions began favoring tidal-marsh accretion in sheltered locations (Orme, 1991)

In Malibu Lagoon, it is likely that sedimentation rates have significantly exceeded relative sea-level rise over the past few thousand years Therefore, the estuarine lagoon system created by the Flandrian transgression probably experienced erratic but cumulative sedimentation and wetland expansion, with concomitant reduction in water volume and area, until the system was restricted to a near-equilibrium condition just sufficient to transfer water seaward The near-equilibrium of that system would of course fluctuate between winter streamflow and summer drought conditions, and be prone to further disruption by storm waves and human activity

The above scenario implies that any reduction in the rate of relative sea-level rise would increase sedimentation within the estuarine lagoon, or put another way, less sediment would be needed to maintain existing conditions Conversely, any increase in the rate of relative sea-level rise would enlarge the open-water area, initially at the expense of wetland Assuming a stable rate of relative sea-level rise, any subsidence associated with the Malibu Coast fault zone would increase lagoon dimensions, any uplift would decrease those dimensions

In order to evaluate the precise nature of events leading to aggradation of the present system, a thorough investigation was made of the borehole test pit and trench records obtained in the Malibu lowland between 1960 and 1998, mainly from files maintained by the City of Malibu These data reveal spatial and temporal patterns of great complexity involving frequent lateral and vertical facies changes attributable to the conflict between fluvial, estuarine, lagoonal, beach, nearshore, and colluvial conditions Interpretation of these subsurface records is based on this investigator s familiarity with modern and ancient barrier-lagoon-estuarine systems, but even then the data reveal some curious anomalies To illustrate evolutionary patterns of sedimentation and related hydrodynamics, two sections were compiled from selected data and these are presented as Figures 1-8 and 1-9

The north-south section depicted in Figure 1-8 is based on this author's interpretation of data obtained from more than 100 sites within a broad 1-km long transect passing seaward through the Civic Center and the center of the Malibu Colony Geotechnical studies conducted by Leighton & Associates (1994) provided valuable data for interpreting the landward two-thirds of the section, though even here other borehole data reveal considerable variation in fluvial, estuarine and lagoonal environments to either side of their profile The seaward third of the profile was constructed from borehole records south of Pacific Coast Highway

To landward, the base of the north-south section, beneath 7-9 m below zero datum, comprises fluvial gravels representing a terrestrial environment when sea level was significantly lower and farther seaward These gravels were subsequently eroded or otherwise disrupted to provide a basin for estuarine and lagoonal deposition during the Flandrian transgression, presumably at times behind a transgressive barrier Eventually, in later Holocene time, the lower lagoonal complex was buried by a mix of fluvial gravel and coarse sand, estuarine fine sand and silt, and lagoonal silt and clay The coarser units reflect high energy conditions associated with flood discharges The estuarine units reflect modest stream discharges and tidal fluxes associated with an open river mouth, and are somewhat fossiliferous The lagoonal units, which range from fine grey sands to blue clays and often contain organic matter, reflect back-barrier and back-channel conditions associated mostly with a closed or restricted river mouth, wetland development, and anoxic conditions The historic lagoon, successor to a series of earlier lagoons, was a shallow feature, about 3 m deep between the latest barrier beach and the Pacific Coast Highway, but spilling northward at higher water stages across coarse fluvial sands towards the Civic Center Beneath recent lagoonal muds and sands and the underlying fluvial deposits, there existed a deeper, more extensive estuarine-lagoon, probably of late prehistoric age The timing of late prehistoric events is complicated by a paucity of datable materials and by rapid facies changes, but may be resolved by further investigation The section is blanketed by up to 2 5 m of artificial fill, notably between Malibu Road and Civic Center Way

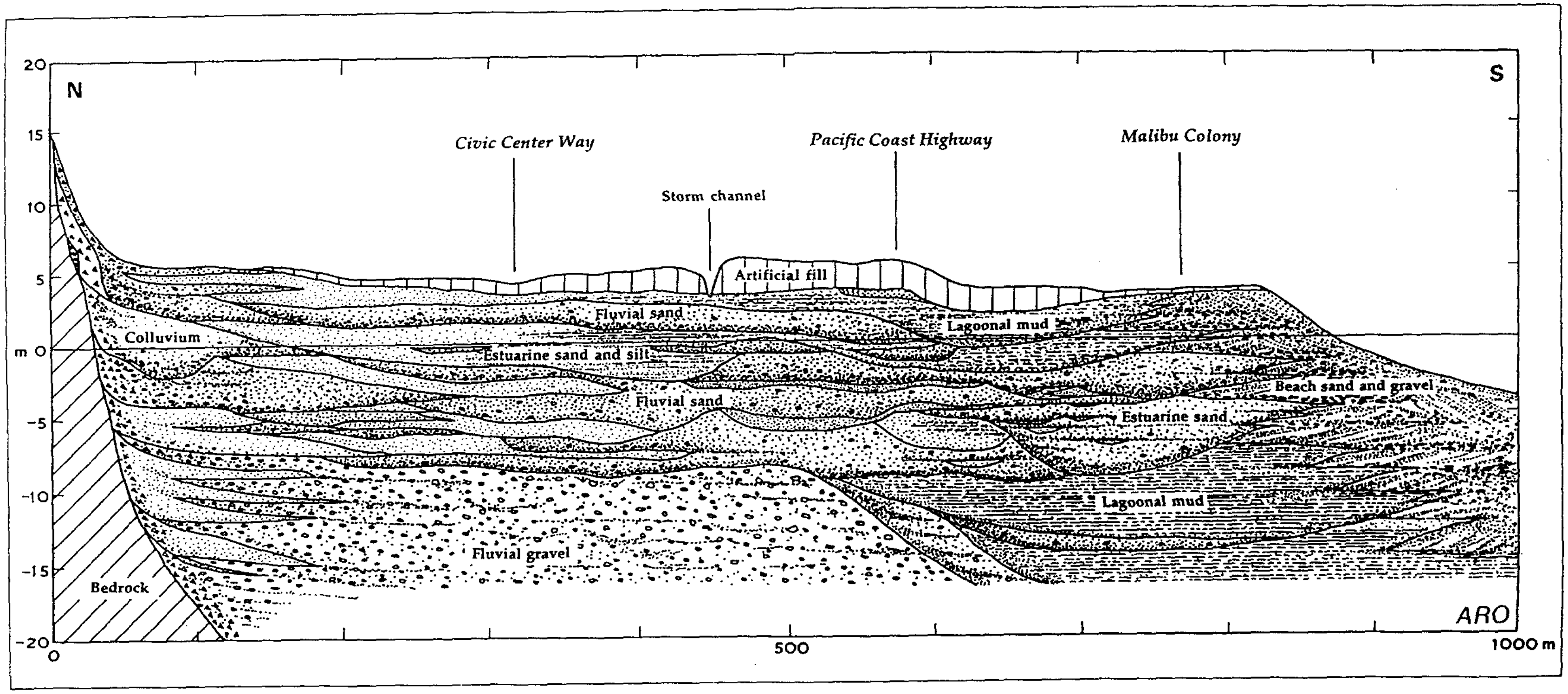

Figure 1-8 North-south section across the Malibu coastal lowland from behind the Civic Center to midway along the Malibu barrier beach. The section is based on the author's interpretation of borehole and other sub-surface data obtained at more than 100 sites between 1960 and 1998, including data provided by Leighton & Associates (1994). Zero elevation is the National Geodetic Vertical Datum of 1929 which is 0.80 m above Mean Lower Low Water. The vertical scale is exaggerated to 10 times the horizontal equivalent. Refer to text for further discussion.

The east-west section depicted in Figure 1-9 is based on the author's interpretation of 45 boreholes and numerous additional test pits and trenches, running the length of the barrier beach from the eastern end of Malibu Colony to Amarillo Beach The section is thinly veneered by artificial fill, exceeding 1-m thick towards the west where the barrier appears to have been historically lower Beneath the fill is a similarly thin veneer of aeolian sand, much disturbed by construction The main historic barrier is represented by a 3-5 m stratum of predominantly medium sand, with pebbles and cobbles increasing towards its base These beach deposits feather out landward and interfinger with muds from the historic lagoon Beneath this beach the barrier is founded on bedrock behind and below Amarillo Beach and on two bedrock knobs or 'islands' farther east, the more easterly of which is an onshore extension of the rock exposed in the intertidal zone offshore These bedrock foundations impart greater stability to the barrier than would be the case in their absence Prior to the formation of the present barrier, Malibu estuary sometimes reached the sea between these bedrock outcrops, while the course of Winter Canyon is also well defined immediately east of Amarillo Beach As the sedimentary record passes downward, so estuarine and lagoonal facies, mostly fine sands and muds, alternate with beach and nearshore facies, mostly medium to coarse sands, pebbles and cobbles This sequence is consistent with the model presented in Figure 1-7 wherein, during a transgressive phase, barrier beaches overlap earlier estuaries and lagoons and establish conditions favorable for estuaries and lagoons at higher elevations, the process continuing until sea level more or less stabilizes The sequences observed beneath Malibu colony in both Figures 1-8 and 1-9 are thus on intersecting planes The existence of an a lagoon at least 8-10 m deep below -10 m is a prominent feature of both sections, formed presumably when sea level was 7-10 m below present, approximately 4000 years ago

To evaluate further the nature of sea-level change and sedimentation relative to the evolving Malibu system, a further three cores were obtained during the present study The core locations were as follows Core A the corner of Civic Center Way and La Paz Lane, Core B the west end of Civic Center Way where it parallels Pacific Coast Highway, and Core C the south shoulder of Pacific Coast Highway immediately east of the confluence with Malibu Road This triangular array was designed to extract more information from three critical localities suggested by the existing data discussed above The new cores were examined for texture, mineralogy and organic content, and eight organic samples were submitted for radiometric dating based on Accelerator Mass Spectrometry (AMS) techniques with adjustments for $^{13}C/^{12}C$ ratios and local reservoir correction for the shell

Core A penetrated to a depth of 14 2 m from a surface elevation of +4 1 m MLLW, or to -10 1 m MLLW or -10 95 m MSL The core revealed a sequence of fine-grained, organic-rich, medium to fine sand, silt, and clay, alternating with coarse-grained, organic-poor pebbles and cobbles in a poorly sorted coarse sand matrix The fine-grained deposits were deposited under low-energy

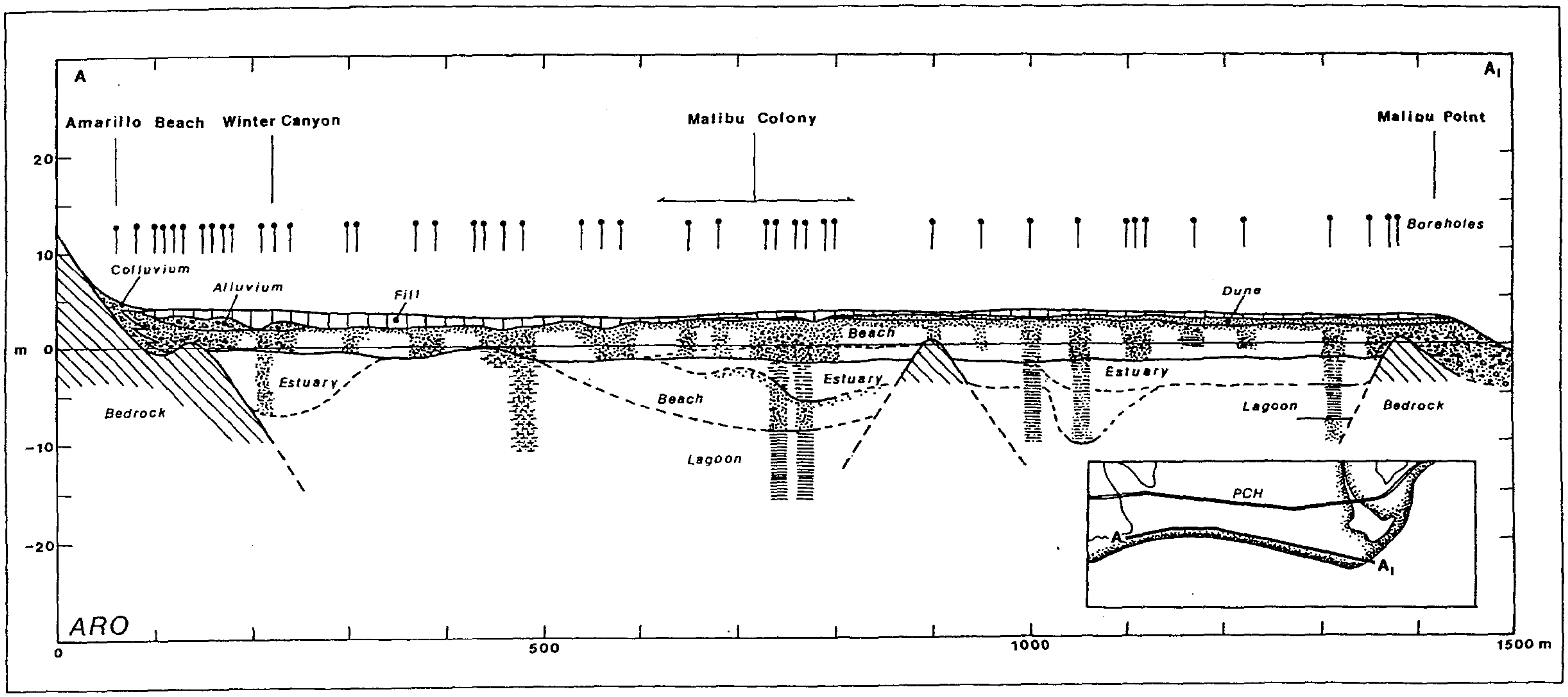

Figure 1-9 East-west section along the Malibu barrier beach from Malibu Point to Amarillo Beach. The section is based on the author's interpretation of data obtained from 45 boreholes and numerous additional test pits and trenches between 1960 and 1998. Zero elevation is the National Geodetic Vertical Datum of 1929 which is 0.80 m above Mean Lower Low Water. The vertical scale is exaggerated to 10 times the horizontal equivalent. Refer to text for further discussion.

conditions in fresh and brackish water just beyond the normal margins of Malibu Creek's main distributary channel, most likely in backswamps beyond low alluvial levées The coarse materials are fluvial and estuarine deposits laid down within the main channel as it shifted westward from time to time Of particular interest is a shell fragment (*Tegula* sp) recovered from a sandy gravel some -0 45 m MSL (3 7 m core depth) This yielded a conventional ^{14}C age of 780+/-40 BP which gives a calibrated calendrical age of AD 1660 to 1895 (2 sigma)(Beta-137799) The radiocarbon age intercepts the calibration curve at AD 1710 This implies that the site lay in a shallow estuary in early historic time and subsequently became a brackish to freshwater wetland, subject to inundation by Malibu Creek floodwaters, prior to development of the track that later became Civic Center Way A twig from loose estuarine, sand at -8 25 m MSL yielded a conventional ^{14}C age of 7090 +/-40 BP (Beta-137798)

Core B penetrated to a depth of 18 3 m from a surface elevation of +4 3 m MLLW, or to -14 0 m MLLW or -14 85 m MSL The upper part of this core revealed a complex of mostly fine-grained, organic-rich sand, silt and clay, including dense blue clay indicative of low-energy anaerobic conditions The deposits reveal many vertical textural changes but, where they contain plant material in growth position, presumably reflect wetland deposits subject to tranquil-water deposition from sediment in suspension At -10 2 m MSL these wetland deposits pass down into fluvial sands and gravels which continue to the base of the core These deposits correlate with the fluvial gravels depicted in Figure 1-8 Four organic samples recovered from between -11 05 and -3 95 m MSL yield ^{14}C ages from 7370 +/-40 BP to 6260 +/-40 BP (Beta-137800-3), a cluster over 7 1 m that indicates relatively rapid sedimentation, probably related to the closing stages of the main transgression Conversely, many facies changes in the overlying deposits suggest that frequent but shallow cut-and-fill episodes, associated with relatively small sea-level changes, have occurred since 6000 BP

Core C penetrated to a depth of 25 9 m from a surface elevation of +4 9 m MLLW, or to -21 0 m MLLW or -21 85 m MSL Compared to the other two cores, with their frequent low-energy facies changes, this core (beneath 4 m of fill associated with Pacific Coast Highway) contains a more or less continuous sequence of coarse fluvial sands and gravels to a depth of -13 6 m MSL, and again from -16 7 to -21 3 m These deposits represent a portion of the main distributary of Malibu Creek, flowing south along a path that lay up to 400 m west of its present constrained course and reaching the sea in the estuary depicted between the bedrock knobs in Figure 1-9 Such an alignment is also shown in Figure 2-1a Carbonized plant stems in growth position from a mud at -14 25 m MSL have yielded an age of 9470 +/-40 (Beta-137804), suggesting a freshwater wetland above the sea level of the time This is the oldest age revealed in these cores and supports the belief that Lower Malibu Creek and its environs have been the focus for episodic wetlands throughout the Holocene, even when sea level was more than 20 m below the present

The dated organic remains revealed in these cores suggest a Holocene sea-level curve similar in form to that from southern San Francisco Bay over the past 8000 years, including a similar reduction in the rate of sea-level rise between 8000 and 6000 BP However, the Malibu curve stands higher in elevation over the past 6000 years This may be explained by the relative subsidence of San Francisco Bay within the San Andreas fault zone, and/or by the relative uplift of the Malibu coast associated with long-term tectonic deformation and co-seismic movements along the Malibu Coast Fault

The information to be gleaned from these new cores and their dated materials are consistent with the interpretations provided in Figures 1-8 and 1-9 However these cores paint a clearer picture of the past 8000 years encompassing the waning stages of the Flandrian transgression and then, after 6000 BP, by a lengthy period of cut-and-fill within the topmost 5 m below MSL This is to be expected as the rate of sea-level rise diminished and Malibu Creek adjusted to higher sea levels by swinging laterally across its coastal lowland, transgressing across and then retreating from backswamps and wetlands along its margins

Wetland deposits exposed by floods in February 1998 along the east bank of the inner lagoon above the highway bridge, offer a further perspective on sedimentation-sea level scenarios Here, dark brown fossiliferous sand and sandy mud, 0 2 to 1 0 m thick, lie in a 30-m long hollow in underlying high-energy fluvial deposits and are overlain by approximately 1 0 m of historic low-energy overbank fluvial deposits The fossiliferous material contains two identifiable species, the cockle *Chione fluctifraga* and the black turban shell, *Tegula funebralis*, together with fragments of other pelecypod genera *Mytilus*, *Ostrea* and *Chione* Allowing for local reservoir effects and ^{13}C/^{12}C adjustment, the *Chione* fragments yielded a conventional ^{14}C age of 1710 +/- 60 BP, which in turn gave a calibrated calendar date of AD 930 (95% probability between AD 770 and AD 1050)(Beta-118587)

The nature of this deposit is consistent with deposition in the middle to lower intertidal zone of a sandy mudflat in an estuary or open lagoon, similar to that found in the present lagoon south of the bridge It does not appear to contain midden material or dredged spoil, although human disturbance cannot be discounted Assuming a natural origin, this deposit now rises to about 1 0 m above MHW Adopting a conservative 1000 year age for the deposit and a similarly conservative relative sea-level rise of 1 0 mm per year over this period implies that the deposit should now be at least 1 0 m below the present mid-intertidal zone, or marginally subtidal It is thus possible that the inner part of Malibu Lagoon has been raised significantly above its late prehistoric level, possibly by co-seismic activity along a branch of the Malibu Coast Fault Less likely, the deposit may have been emplaced at this elevation during tsunami activity These suggestions should be subject to further investigation Malibu Creek has continued to incise through this deposit during low flows while burying it during overbank floods

1.4 Historical Development

Evidence for the historical development of Lower Malibu Creek and Malibu Lagoon comes in part from field data but mostly from documentary sources, including tidal data, historical maps and aerial photographs which are the principal focus of this section. Tide-gauge data are discussed in this section because they complement the foregoing evaluation of late Holocene sea-level change. Other numerical data of an historical nature, dealing with precipitation and runoff, are deferred to Chapter 2.

1.4.1 Recent and Future Changes in Relative Sea Level

Whereas late Pleistocene and Holocene changes of sea level are of intrinsic interest and may provide a general indication of future trends, effective coastal management requires more precise data on likely sea-level scenarios, including the possible impacts of anthropogenic global warming. Such data are normally estimated from historical records of tide-gauge stations. Tide gauges, usually located on a pier or jetty, measure sea-level heights continuously and relate these to precisely positioned and stable bench marks. Yearly and monthly mean sea-level values are derived from the arithmetic means of a calendar year or calendar month of hourly heights. Hourly heights are either scaled directly from a marigram or obtained from the digital output of an analog tide gauge. The tide-gauge station maintained by the National Ocean Service on Santa Monica Pier, 16 km east of Malibu, is most relevant to this study.

The Santa Monica tide-gauge station was established in 1933 and, despite missing data from January 1966 to November 1973, and from January to July 1983, provides a good indication of recent sea-level trends. The data indicate a relative rise of 1.8 +/-0.3 mm per year for the period 1933-86, and 1.2 +/-0.5 mm per year for the period 1950-86 (Lyles et al., 1988). Values from the Port of Los Angeles (Berth 60) are 0.8 +/-0.3 mm per year for the period 1924-86 and 1.1 +/-0.5 mm per year for 1950-86. These trends appear to have continued since 1986. This rise is the *relative apparent secular trend*. The term 'secular' means nonperiodic, and 'apparent secular' is used because it is not known whether the trend is truly nonperiodic or merely part of a much longer oscillation. The term 'relative' means that the measurements of sea level are heights relative to land adjacent to the station and thus incorporate any net tectonic displacement. The large standard error to these trends is indicative of noise in the annual values and thus of the problems implicit in estimating future trends.

Nevertheless, the relative sea-level rise of 1.8 mm per year recorded at Santa Monica for the period of record is comparable to the late Holocene rates discussed above, namely the 1.5 to 1.7 mm per year rise observed in Morro Bay over the past 4200 years, and the 1.0 to 2.0 mm per year rise observed over the past 6000 years in San Francisco Bay. In other words, the recent instrumented trend seemingly represents a continuation of the late Holocene trend derived from submerged organics without any specific acceleration that could be attributable to such anthropogenic effects as global warming by greenhouse gases.

Whereas the above trends imply linearity, sea-level trends are rarely linear and, indeed, most California tide-gauge stations reveal an acceleration over the past three decades. Closer examination of the data, however, reveal that such acceleration is a statistical artifact attributable to the spike of significantly higher sea levels induced by occurrences of El Niño-Southern Oscillation, notably the 1982-83 event. Similar spikes occurred during January-April 1992 and August 1997-January 1998, again attributable to El Nino effects. As elsewhere, mean monthly sea level usually follows an annual cycle at Santa Monica, being lowest in March-April following winter cooling and rising about 150 mm higher with summer warming in August-September. Again, the data show the effects of El Niño events, with the seasonal range expanding to 262 mm in 1982, 487 mm in 1991-92, and 299 mm in 1997-98.

In general, then, relative sea level at Santa Monica has risen at a mean rate of 1.8 mm per year over the past 66 years. Because this value is comparable to the late Holocene change, this rise is probably due in large measure to the continuing effects of postglacial isostatic disequilibrium, the high viscosity of Earth's mantle implying that coasts are still adjusting to the shift of water mass from the ice sheets to the oceans that began around 18 ka. Assuming on present evidence that this rate will continue, the longer term management of the Malibu estuarine lagoon and barrier beach should incorporate a mean rise of sea level of 18 cm over the next 100 years. Additional thermal expansion of ocean water, leading to further sea-level rise, may also occur in response to anthropogenic global warming. The 18 cm rise per century is thus a modest minimum whose effects, though difficult to measure against noise implicit in the system, will determine the mean tidal range within which estuarine and lagoonal processes operate.

1.4.2 *Human Impacts*

Historical documents and maps should always be treated with caution, because of errors and misconceptions implicit in such documents and the subjective aspects of early field surveys and cartography. Nevertheless, carefully treated, such materials may offer useful glimpses of past landscapes against which to compare later observations and photographs.

The Spanish navigator, Juan Rodriguez Cabrillo, was the first European to record contact with the southern California coast and its peoples in 1542-43. His log, which has survived only as a contemporary summary by Juan Paez, offers no precise information on the Malibu coast although some historians identify Cabrillo's *Pueblo de las Canoas*, the Chumash settlement of *Xucu*, with Malibu (Rindge, 1985) *Xucu* was discovered when Cabrillo's ship "anchored before a large valley opening out on the coast"(Paez, translated Moriarty & Keistman, 1968) This uncertain record, together with subsequent observations by diarists Crespi and Font with the Portola and Anza expeditions of 1769 and 1776 respectively, offers nothing on which to recreate the physical system at Malibu Similarly, dietary information from the archaeological record excavated at the former Chumash village at Malibu tells us something about the ecology of the lagoon, its watershed and nearshore waters, but little about the physical system (Glassow, 1965)

1 4 2 1 1870-1920 The Early Map Record

The first useful document is provided by a survey and plat made by the United States Surveyor General's office in 1870 This work was done to confirm the title of Rancho Topanga Malibu Sequit to Matthew Keller who had purchased Malibu coastal land 1857 The Keller property in turn passed into the Rindge family in 1892, with ranching activities remaining reasonably intact into the 1920s

Although the 1870 survey stations appear to have been carefully located and defined, the remaining topographic detail was essentially sketched in The 1870 map shows the familiar double-meander course of Malibu Creek ("Cañada Malibu") below the bedrock narrows - the channel shifting first to the east and then to the west before entering an elongated lagoon ("lake") extending parallel with the shore The inferred length of this lagoon, 1 3 km, derived by comparing 1870 and modern survey points, is unusual because the modern embayment is only 1 5 km wide It was probably sketched in, although the more pronounced westward meander bend of 1870 suggests that the creek ran farther west than today From "Cañada Malibu", the 1870 lagoon extends eastward towards Keller's Shelter, an alignment consistent with recent winter-spring outlets diverted by shore-welding bars A small appendix runs about 150 m west from the mouth of the creek In the bedrock narrows, comparison of survey inflection points suggests that what is now a minor flood distributary of Malibu Creek was the main channel in 1870

The 1 62,500 Calabasas Quadrangle published by U S Geological Survey in 1903, was based on U S Coast and Geodetic Survey and on topographic survey controls of 1893 and 1900-01 It shows Malibu Lagoon extending for 750 m parallel with the shore behind a narrow barrier beach, mostly west of its present seasonal outlet A small lagoon is also shown behind the western end of the barrier Malibu Creek is more sinuous than today , the westward meander being prominent Serra Road and Cross Creek Road follow their present routes on or above the floodplain terrace, east and west of the creek respectively Their location implies that the floodplain terrace offered reasonably safe terrain above most flood levels Except for an east-west track and some structures east of the lagoon, the estuarine lagoon is undeveloped

Another track leads north along the floor of Malibu Canyon toward some structures 1 km above the bedrock narrows

These maps indicate that Malibu Creek was within its present floodplain during the later nineteenth century but that it meandered more freely towards its mouth and that its estuarine lagoon extended parallel with the shore for at least 0 75 km and perhaps as much as 1 3 km westward from its present constrained outlet The maps support the field evidence for a shallow elongate lagoon but are silent about related wetland dimensions

1 4 2 2 1920-1940 The First Aerial Photographs

The 1920s and 1930s witnessed several events which were to have a profound influence on the physical integrity of Lower Malibu Creek and its estuarine lagoon These events included dismemberment of Rancho Topanga Malibu Sequit, erection of the Rindge Dam in 1928, and construction of the coast highway, along the line of the shortlived railway, which provided ready access to the region and paved the way for establishment of the Malibu Colony and other developments Aerial photographs contained within the Spence and Fairchild collections in the Department of Geography at the University of California, Los Angeles, reveal something of the impact of these changes on the physical system

The first aerial photographs, from 1923-24 (Spence 5724, 8037, Figures 1-10, 1-11), show the impact of railway and dike construction on the lagoon The Hueneme, Malibu and Port Los Angeles Railway had been completed in 1908 and continued to be used into the 1920s for the shipment of grain and hides from the Rindge Ranch to a wharf at what is now Malibu Pier (Pfeifer, 1985) The 24-km, standard gauge, single track railway ran from near Las Flores Canyon in the east to Yerba Buena Canyon in the west It crossed Malibu Creek on a wooden bridge supported on pilings The bridge was of similar length to the present highway bridge However, it approached the creek on either side on an earthen embankment which by 1923-24 was clearly impeding drainage The photographs also show a probable bulkhead extending southeast from the western bridge abutment to the beach, a structure perhaps built to reclaim wetland for grazing

Despite these changes, however, much wetland remained in an arc from the present junction of Cross Creek Road and Civic Center Way to midway along the barrier, while the small lagoon shown farther west on the 1903 map survived as a marsh-fringed salt pan tenuously linked to the main estuarine lagoon That the small lagoon, when dry, best fits the image of a salt-encrusted pan flanked by the salt grass, *Distichlis spicata*, suggests that, even at this late stage, there may have been some direct connection to and from the ocean through the barrier Apart from subsurface seepage, the barrier may also have been lower here, some distance from the principal sources of sediment, thereby allowing storm overwash into the lagoon Sub-surface data support this interpretation (Figure 1-9) Despite later road construction, this

Figure 1-10. Malibu, looking north, 1924 (Spence 5724)

Figure 1-11. Malibu Lagoon, 1924 (Spence 8037)

lagoon/salt pan survived into the 1940s but was eliminated by sidecast from construction of the present Pacific Coast Highway in the late 1940s

Inland, a coastal road used the older river terrace and lower floodplain terrace to approach the creek, which it crossed on a short bridge 300 m above the railway bridge Farther upstream, evidence of recent flood activity extended west to Cross Creek Road while, farther west across the partially wooded floodplain terrace, a former creek distributary ran close to the hills, presumably used occasionally by floodwaters but normally blocked by deposition just below the bedrock narrows

In June 1929, a new state highway was opened for public use between Santa Monica and Oxnard, successor to earlier tracks and the county road of 1921 and predecessor to the modern Pacific Coast Highway (California Route 1) The county road and its bridge remained intact but little used The new highway had two impacts it directly affected the lagoon and it ended Malibu's relative isolation Aerial photographs from February 1932 (Spence E-3445-3449, Figures 1-12, 1-13) show how the new highway, departing from the inland route of the county road, crossed the creek on reinforced concrete pilings just downstream from the old railway bridge and, running a few degrees south of west, regained the shore at the lowland's southwest corner Its approach embankments, more massive than the railway embankment, severely constrained local drainage In the western back-barrier area, where the railway had crossed the small lagoon but had little impact on drainage, the new highway probably blocked that lagoon's occasional links with the larger lagoon to the east and with the ocean

From a collection of inexpensive beach cottages, the larger homes of the Malibu Colony began construction shortly after highway completion and by 1932 occupied most of the barrier, destroying the ribbon of low dunes and stopping only towards the approaches to the constricted distal exit of the lagoon Similarly, even as the Rindge Ranch was being dismembered, the family built a beach house, the Adamson house, in 1929 on the dune-mantled low hill east of the lagoon (Pfeifer, 1985) Immediately north of the Pacific Coast Highway bridge, a small levee was constructed along the east side of the creek around the time of bridge construction, behind which a few structures and a road connecting the Adamson house with the old county road were also built (Fig 1-9) This area reverted to scrub after the 1938 floods Thus, by the early 1930s, lowermost Malibu Creek and Lagoon were largely confined to their present location, constrained by the new bridge and levée to the east while links to wetlands farther west were maintained, if at all, by tenuous drains

The above changes were included in the 1 24,000 Las Flores Quadrangle map of the U S Geological Survey of 1932 Just below the bedrock narrows, this map also showed that Malibu Creek had now switched its main channel to the present course, abandoning the former channel of 1870 and 1903 to

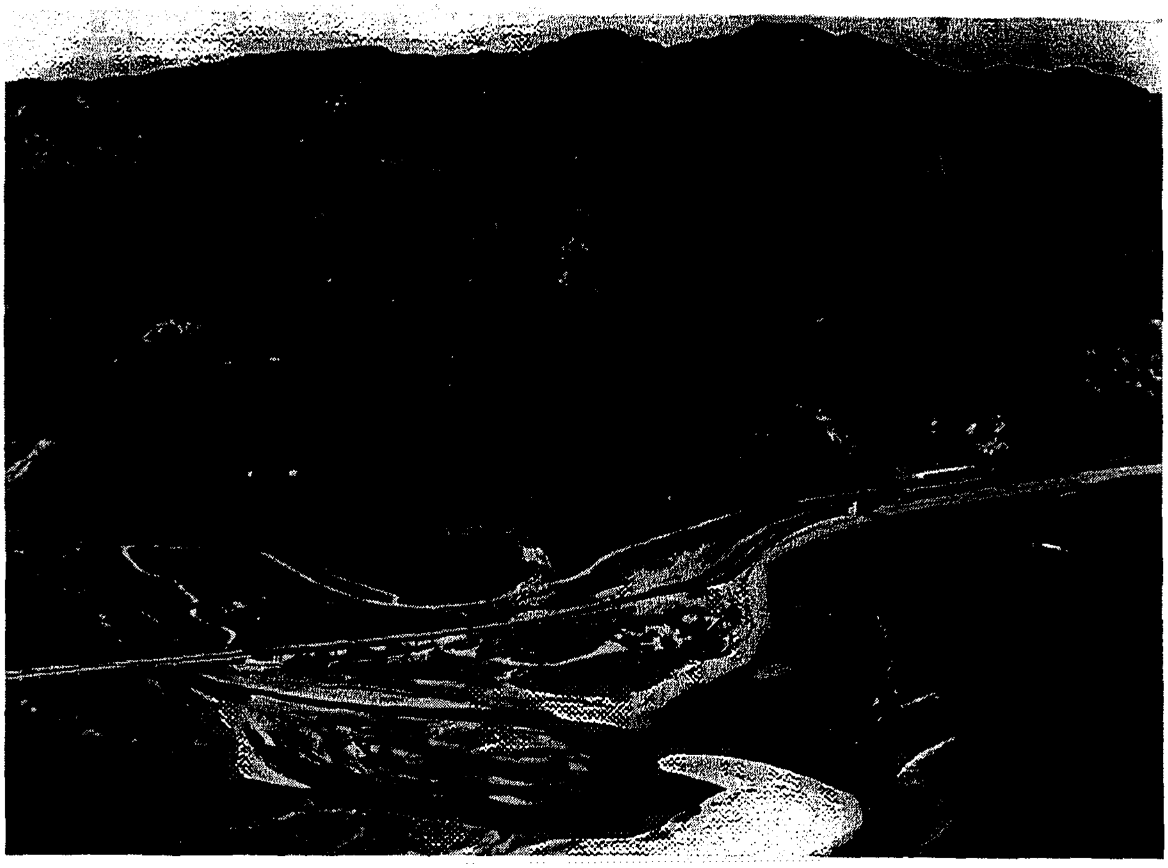

Figure 1-12. Malibu Lagoon and Adamson House, February 28, 1932 (Spence E-3449)

Figure 1-13. Malibu, looking northeast, February 28, 1932. Note small lagoon with old railway embankment north of coast highway in left foreground (Spence E-3445)

occasional flood use Just south of the Cross Creek Road crossing, the creek bifurcated as today, coming together again near the county road bridge

By February 28, 1936, the estuary seaward of the bridge was choked with recent flood sediment, raising most of the lagoon floor above mean sea level (Spence E-3449) This situation persisted into the summer when strong barrier construction, involving substantial overwash lobes, severely limited the raised water area, as shown by supercritical flow and standing waves in the narrow outlet on May 19, 1936 (Spence 0-3032)

The flood of early March 1938 revealed the extent to which the natural system had been changed by construction over the previous ten years (Spence 0-5620-5626, AA-681, H-1772, U S Army Map Service, 1944, Figures 1-14, 1 15) The flood destroyed both the now disused county road bridge and the abandoned railway bridge, and severely damaged five spans of the new highway bridge, reaching the sea along a broad front between the western bulkhead and the Adamson house Farther west, much water was impounded to the north of the main highway embankment and further constrained by field banks Saturated ground extended north of the old county road to the limit imposed by low gradient alluvial fans and colluvium, thereby outlining the approximate dimensions of the potential wetland on the site of the late Holocene estuarine lagoon (Figure 1-4) Much surface water was also ponded against the northern margins of Malibu Colony Road, individual ponds being connected at and beneath the surface Little surface water was apparent between these ponds and the main highway, although the ground was presumably saturated The photograph of March 5, 1938 (0-5626) provides as good an indication as any of the potential for wetland restoration in the estuary section, subject of course to constraints imposed by subsequent developments Although the 1938 flood was a major event, it occurred against a mean sea level for 1938 that was 190 mm lower than that of the 12 months ending July 1998 Thus a comparable flood today could theoretically have wider impact than the 1938 event, but this hazard has been largely offset by the addition of artificial fill over much of the basin

1 4 2 3 1940-1970

Aerial photographs of July 4, 1947 (Spence E-12998, E-12999, Figure 1-16), reveal widespread grading in progress for the present Pacific Coast Highway which departs from the previous main highway (now Malibu Road) just west of the bridge and extends just north of west up a broad constructed incline onto marine terrace terrain west of Malibu Portions of the terraces were excavated and the spur east of Winter Canyon flattened The wedge of land between the previous highway and the new route, together with a lengthy zone some 80-120 m wide north of the new route, were extensively regraded at this time, eliminating what remained of the former, quasi-natural surface Market gardens and numerous sheds cover most of the lowland north of the grading operation and the narrow wedge between the old main highway and Malibu Colony Road, a legacy perhaps of truck farming during World War II

Figure 1-14. Malibu during flood of early March, 1938, showing surface water ponded by coast highway and Malibu Colony Road (Spence 0-5626)

Figure 1-15. Malibu estuary on March 7, 1938, showing old county road bridge and railway bridge destroyed, and coast highway bridge damaged (Spence H-1772)

By the summer of 1949, the new Pacific Coast Highway was fully operational, although the land on either side remained much scarred and but sparsely vegetated (Fairchild 19151, May 22, 1949; Spence E-13561, August 28, 1949; Figure 1-17), The old county road had been diverted at its truncated western end into the new highway. Farther inland, Malibu Canyon Road had been completed as far north as the Rindge Dam by May 1949, construction involving much cut and fill, with rock debris sidecast downslope, thereby introducing large quantities of coarse clastic material to Malibu Creek. Subsequent completion of this road was to afford much easier access to the coast from the growing suburbs of Los Angeles in the San Fernando Valley. At this time, Rindge Dam still retained about 10-20% of its water-holding capacity, depending on stage.

Recognizing the problems that the massive inclined ramp of the Pacific Coast Highway would pose for local drainage, culverts were provided beneath the highway for the stream draining Winter Canyon and for local drainage immediately north of the ramp's eastern end. An open ditch was also deepened, running due east towards Cross Creek Road north of the highway. This ditch has since been flanked by 2-3 m of fill. These drainage systems have not worked well, and have led to the artificial development of a freshwater wetland at the northern foot of the highway ramp, across Civic Center Way from the inner margins of the former small lagoon/salt pan that had survived into the 1930s.

Both in July 1947 and August 1949, the lagoon is very shallow and completely closed by the barrier beach. In both years, there is a legacy of extensive grading in the estuarine lagoon south of the highway bridge. The purpose of this grading, limited eastward in 1947 by the former bulkhead but occupying most of the estuary in 1949, is uncertain but the photographic evidence suggests abortive reclamation efforts and attempted channelization of the creek, including levée construction and aggregate excavation, above and below the highway bridge. By this time, Cross Creek Road had been extended as a track south of the highway along the present western and southern boundary of Malibu Lagoon State Beach. The situation was similar in July 1951 but grading activities in the creek bed had been abandoned. The lagoon below the bridge was characterized by three ponds separated from the ocean by a broad barrier beach.

The above situation changed little during the 1950s (Spence E-16075-77, E-17216, Figure 1-18). In October 1957, west of Malibu Creek, market gardening continued to dominate the landscape north of Pacific Coast Highway, and the area occupied by the present golf course and state park south of the highway was a low poorly drained waste of marsh plants, grasses and low shrubs on abandoned, poorly graded wetland. Dunes on the closed barrier east of the lagoon had been partly colonized by low shrubs. Farther west, the wedge of land between the Pacific Coast Highway and Malibu Road began to see

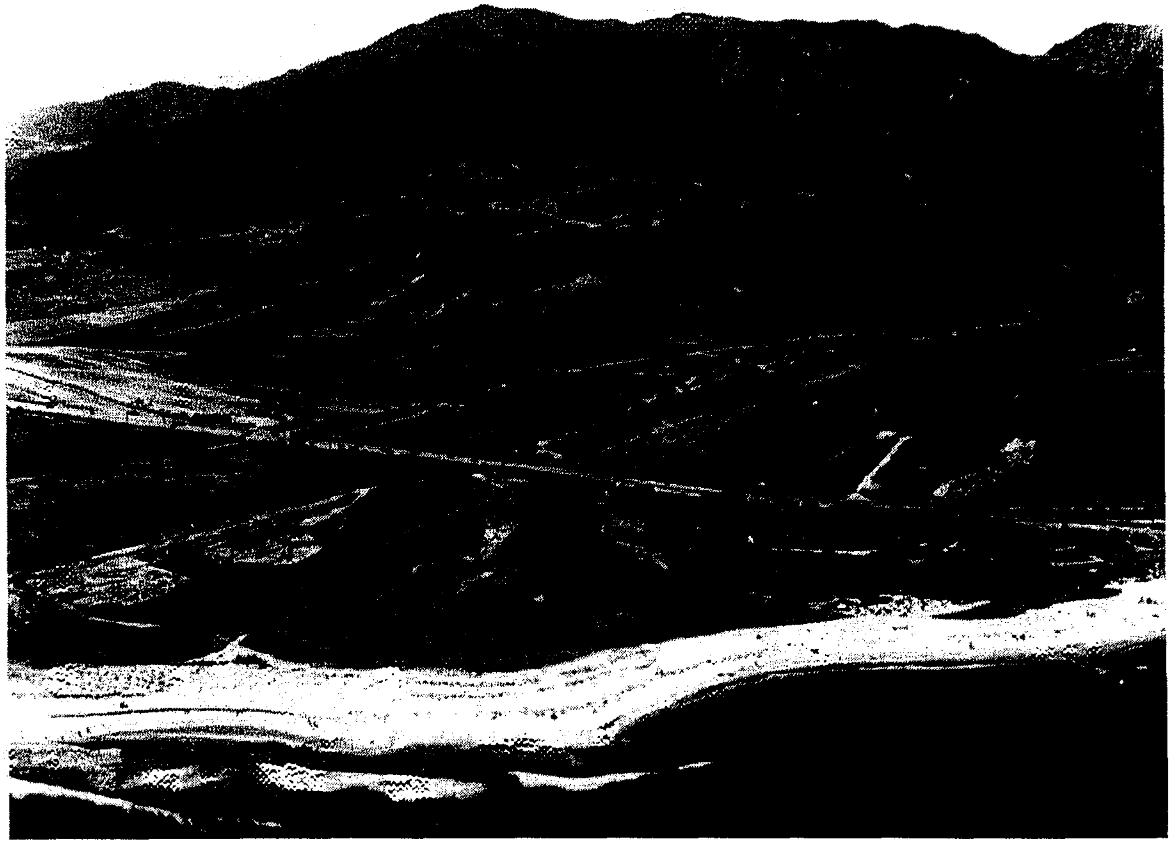

Figure 1-16. Malibu Lagoon on July 4, 1947, showing continuous barrier beach and lower end of ramp for new highway alignment (Spence E-12999)

Figure 1-17. Malibu on August 28, 1949, showing new Pacific Coast Highway and disturbed ground around the lagoon (Spence E-13561)

additional construction and, by March 1959, a shopping center with an extensive impermeable parking lot was in place on the approximate site of the small lagoon and salt pan noted in the 1920s and 1930s.

During the 1960s, the market-garden area north of Pacific Coast Highway and west of Malibu Creek began to change significantly as, first, the Cross Creek Shopping Center and, later, the Civic Center began construction, processes which continued well into the 1970s, at least until retarded by passage of California's Coastal Act in 1976 (Spence E-19863, Figure 1-19). The old county road of 1921 was resurrected as Civic Center Way and its western links with Pacific Coast Highway reorganized. The wet wasteland south of Pacific Coast Highway was subsequently transformed in part into a private golf course and in part into a restored wetland within Malibu Lagoon State Beach, the latter completed in 1983.

1.4.3 Retrospect and Prospect

The relatively natural system of Lower Malibu Creek and Lagoon during the late nineteenth century has been altered substantially by developments over the past 100 years. Initially, commercial cattle ranching and cultivation of feed grains and market crops undoubtedly had an impact on the region's ecology, replacing indigenous species with aggressive exotic plants and accelerating erosion and sediment delivery from grazed hillsides. Later, construction of the railway and county road had some impact on drainage within the lowland, but natural processes mostly prevailed. However, completion of the new highway in 1929 and its successor, the modern Pacific Coast Highway, in 1948-49, had a dramatic effect on the area - directly by disrupting and smothering the natural system, indirectly by providing access for a much larger population with consequent pressures for further development. During major storm events, Malibu Creek is still able to refashion its floodplain and flush large volumes of water and debris seaward, while storm wave activity can disrupt the barrier beach, including the Malibu Colony. Natural processes, however, are invited by human activity to function within an increasingly constrained and dysfunctional system. That nature does not always cooperate should not be a surprise.

In retrospect, it is easy to recognize when and where the system became dysfunctional. Assuming that some degree of development was inevitable in the post-ranching period, highway construction could have been more sensitive to the drainage needs of the natural system. Development of the Malibu Colony on what was an active barrier beach could have been modified. Provision of the commercial infrastructure could have been better located, away from an active outside meander bend of Malibu Creek. And when restoration of the rump wetland began, more attention could have been given to the physical functions and behavior of the estuarine lagoon and its associated wetlands.

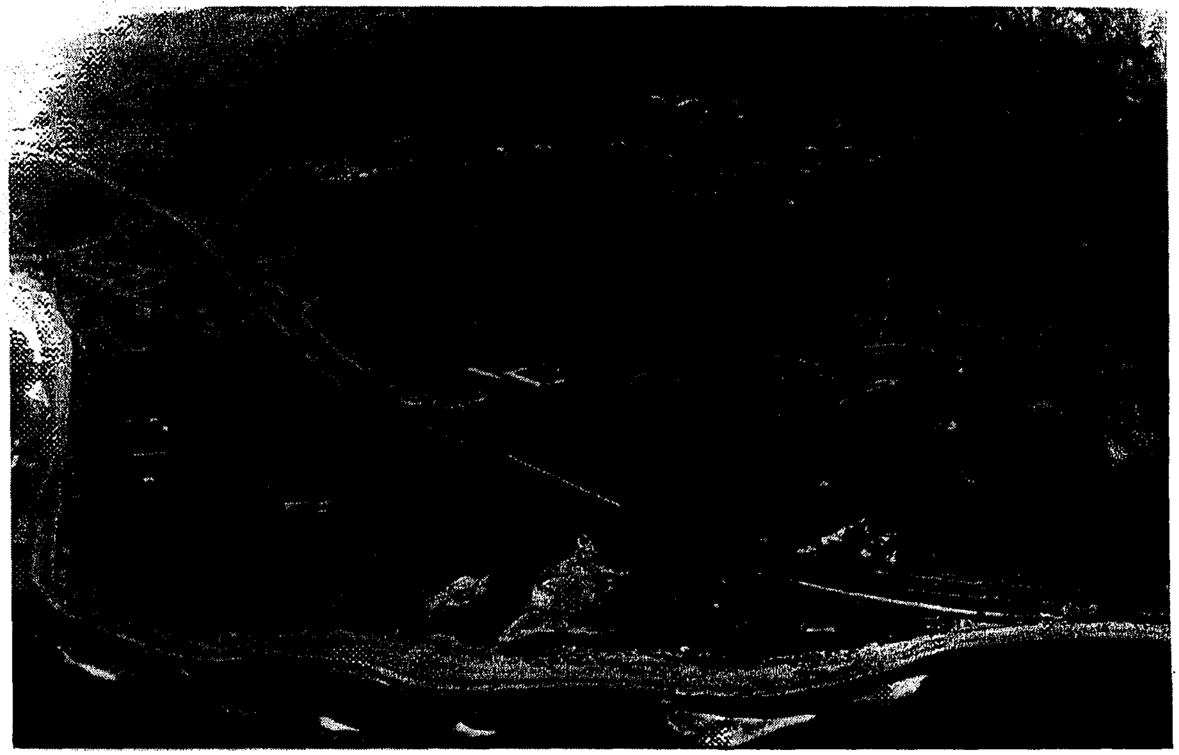

Figure 1-18. Malibu on October 2, 1957, showing still mostly farmland north of highway and wet wasteland to the south (Spence E-16075)

Figure 1-19. Malibu on April 4, 1969, showing recent construction of shopping centers and civic center (Spence E-19863).

With these developments in place, however, it is less easy to implement procedures for the effective restoration and management of the system. In the last analysis, more space and better drainage are necessary if the natural system is to function correctly, while posing minimal risk to local residents and visitors, and to their supporting structures. A reasonably effective quasi-natural estuarine lagoon system, with attractively landscaped buffer zones and recreational opportunities, could be recreated if the rectangular space from Malibu Creek west to lower Cross Creek Road and the triangular space between Pacific Coast Highway and Malibu Colony Road were available for restoration. Despite occasional buffeting by storm seas, the Malibu Colony barrier beach, anchored as it is to bedrock, would continue to form the necessary southern margin to such a restored system. The primary connection between the estuarine lagoon and the ocean would remain where it is today and has been throughout historic time.

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Chapter 2: Hydrology and Morphodynamics, 1997-98

Antony Orme, Kenneth Schwarz, Priya Finnemore,
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Contents

Chapter 2: Hydrology and Morphodynamics, 1997-98

**Antony Orme, Kenneth Schwarz, Priya Finnemore,
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2.1 Introduction

Lower Malibu Creek and its terminal estuarine lagoon are highly dynamic physical systems that respond swiftly to changes in their controlling variables, namely inputs of water and sediment from the larger watershed and from the neighboring ocean basin. Runoff and sediment discharge from the watershed are functions primarily of basin relief, precipitation, bedrock and soil properties, and mass movement, and these in turn are influenced by a broad range of climatic, biological and human factors. Ocean inputs of water and sediment are functions primarily of the semidiurnal tidal regime and climatic forcing of storm waves, swells and nearshore currents. Both inland and at the coast, these variables generate instantaneous positive and negative feedbacks within system geometries that are best defined by their changing morphodynamics.

The preceding chapter outlined how Malibu Creek originated during late Cenozoic times in response to tectonic and climate forcing, and how it then responded to changing Pleistocene base levels. The present estuarine lagoon came into existence towards the close of the Flandrian transgression, culminating in a reduced but continuing rise of relative sea level of about 1.8 mm per year during late Holocene and, as revealed by tide-gauge records since 1933, historic times. A reconstruction of the late Holocene estuarine lagoon some 2000 years ago, based on field investigations and comparable analogs, is presented in Figure 2-1a. At that time, Malibu Creek spilled from its bedrock narrows onto a fan delta, at times flooding the entire apex, at other times incising through its own deposits to leave a floodplain terrace which survives above the inner margins of the lowland, subject to inundation during unusually high magnitude floods. Farther downstream, the creek meandered through its estuarine lagoon but was pushed eastward by the onshore and downdrift construction of a low barrier beach. The greater part of the lagoon to the west was gradually, if erratically, filled with backwater sediment, occasional flood deposits, colluvium and alluvial fan deposits from the adjacent hillslopes, and flood-tidal deltas and overwash through and across the still incomplete barrier beach. With a larger tidal prism than today, channels through the barrier were maintained for a while by outflowing lagoon waters and the consequent formation of ebb-tidal deltas.

By early historic time, around 1800 AD, the lagoon would have been much reduced in size as alluvial sediment from the creek and nearby hillslopes, including sediment reworked by tidal processes, caused intertidal flats to build southward, restricting open water to the immediate back-barrier area (Figure

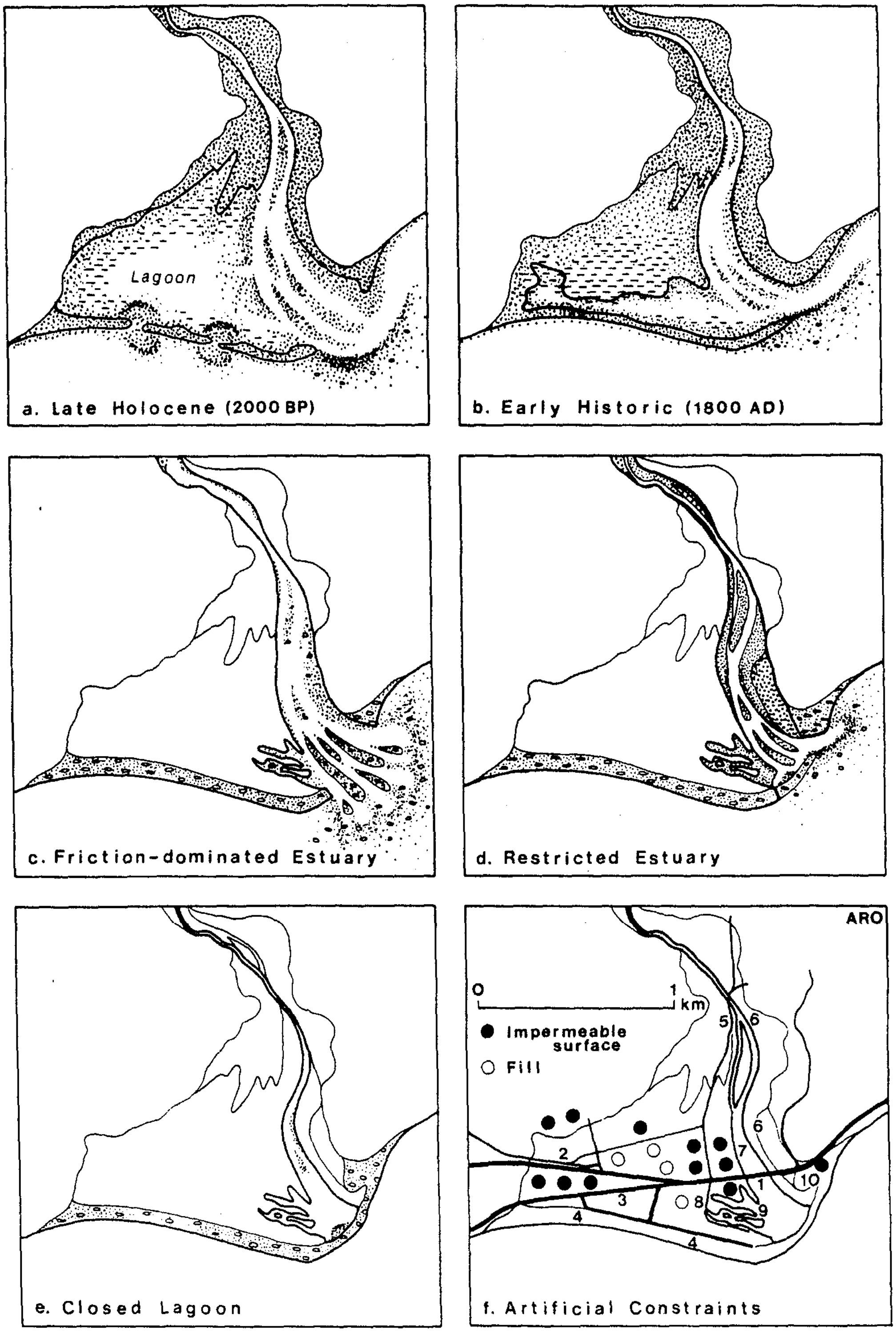


Figure 2-1 Malibu estuarine lagoon system: late Holocene and early historic stages, present morphodynamic options, and artificial constraints

2-1b). Such a scenario is reinforced by the imperfect map evidence from 1870 and 1903 (see Chapter 1.4.2). As bottom deposits rose into the intertidal zone, lagoonal sedimentation accelerated in association with salt-marsh vegetation and increased friction, leaving perhaps a few tidal creeks to serve wetland drainage. By this time, the barrier beach, though relatively low and subject to wave overwash, was more or less continuous and low dunes began accumulating, notably east of the estuary. The estuary was largely confirmed within its present corridor by this barrier, but floodwaters could still inundate the emergent wetlands to the west. During drought periods, the barrier closed the estuary and lagoonal evaporation probably generated desiccating salt flats behind the barrier. Vegetal colonization of the intertidal wetlands was probably initiated by *Spartina foliosa,* followed later by *Salicornia virginica, Suaeda esteroa* and *Batis maritima* and, as salt flats replaced open water, by *Distichlis spicata.* A greater variety of aquatic and terrestrial plants, including *Scirpus* and *Atriplex,* probably invaded the brackish and freshwater margins of the former lagoon and nearby estuary.

There is a considerable body of scientific literature dealing with river-mouth dynamics and related wetlands (see Orme, 1991). The following overview is a prelude to details presented later in this chapter. In the absence of artificial constraints, estuarine lagoonal systems such as that at Malibu respond to terrestrial and marine forcing by adapting within a spectrum of morphodynamic conditions, the end members of which are a river-dominated estuary characterized by fully turbulent jetflow and a wave-dominated barrier-lagoon system. In reality, such is the delivery of sediment to Malibu during flood events that fully turbulent jetflows rarely occur and, under these conditions, a friction-dominated estuary usually results (Figure 2-1c). Such an estuary is characterized by one or more middle-ground bars composed of seaward-fining sand and gravel, with numerous boulders and organic debris, which constrain discharge and barrier emplacement during flood recession. During flood peaks these bars and their accompanying river-mouth geometry may push far seaward. During flood recession, and particularly in the weeks following a major flood, these middle-ground bars are reworked at their distal ends, providing material for the onshore migration of longshore and oblique submarine bars in response to nearshore wave and current processes. In this way, the friction-dominated estuary becomes progressively restricted (Figure 2-1d). Gradually, migrating bars weld together in moving onshore and, as reduced river discharge becomes unable to maintain an outlet in the face of constructive wave action, an emergent barrier forms across the estuary, enclosing a lagoon (Figure 2-1e). Observations at Malibu during the 1997-98 water year have revealed a range of scenarios - from a closed lagoon in autumn 1997, to a friction-dominated estuary in February and March 1998, to a closed lagoon again in August 1998.

But the Malibu estuarine lagoon is no longer a natural system because, although stream floods and storm waves may sometimes reassert dominance, there are now many constraints imposed by human activity. Changed hydrologic inputs attributable to urban growth in the upper basin and to altered fire frequencies clearly impact the lower basin by changing the magnitude and frequency of runoff and sediment delivery. For the estuarine lagoon, a significant number of artificial constraints on the physical system may be enumerated, the more important of which are shown in Figure 2-1f. The first group relates to road construction. The Pacific Coast Highway (PCH) bridge and its approach ramps (1), the PCH incline farther west (2), the older Malibu Road (3), the Malibu Colony Road (4), and to some extent Cross Creek Road and its upstream crossing (5) all impact drainage - constraining, diverting or ponding surface water and impeding exchange of subsurface water. The second group relates to other changes in or near Malibu Creek. Variable upstream channelization and levée construction (6), ill-conceived riprap emplacement alongside the shopping center near the bridge (7), separation of wetland from golf course (8), poorly executed wetland restoration in Malibu Lagoon State Beach (9), and various structures around the Adamson property (10) further disrupt natural functions of the physical system. Additionally, extensive areas of impermeable surface affect local hydrology, inhibiting infiltration and causing ponding or diversion of drainage into ditches and culverts. Such surfaces are associated particularly with shopping centers, other large buildings, parking lots, and tennis courts (Figure 2-1f). Much of the Malibu Colony is now impermeable to direct precipitation and its impact on direct ocean-back barrier water exchange is less predictable. Lastly, apart from fill associated with the above features, fill emplaced between Pacific Coast Highway and Civic Center Way now confines the former wetland functions of this area to a narrow 2-3-m deep drain which reaches the creek through sharply angled culverts. The private golf course south of PCH and west of the restored wetland has also subsumed former wetland. These and other constraints on the natural system will be revisited in this and later chapters.

This chapter now examines the hydraulic geometry of Lower Malibu Creek and its estuarine lagoon, then discusses the hydrology of the 1997-98 water year which was associated with a strong El Niño-Southern Oscillation event, then examines the changing morphodynamics of the barrier beach in preparation for a thorough evaluation of estuarine and barrier lagoon morphodynamics, and concludes with a perspective on future hydrology.

2.2 Hydraulic Geometry

2.2.1. Channel Changes

Fifteen cross-sectional profiles were surveyed at the beginning of the 1997-98 water year in September and October 1997. These initial surveys offered a baseline against which to compare changes in channel geometry throughout the water year. Beginning just upstream of the barrier beach, five transects (L1-L5) were surveyed across the main body of the lagoon between the coast and the Pacific Coast Highway (PCH) Bridge (Figure 2-2). Upstream of the PCH Bridge, 10 additional profiles were measured across a transitional fluvial landscape leading to the mouth of Malibu Canyon.

Figures 2-3 and 2-4 illustrate comparative profiles from September 1997 and June 1998 for the main body of the lagoon. Profiles L5-L1 are graphed at comparable vertical and horizontal scales, where vertical exaggeration is high (37x). The general interpretation from these five transects is that, over the 8-month period, bed elevation was lowered 0.5 to 1.0 m across much of the lagoon, and as much as 1.5 m in places. Considering that the original depth of the lagoon, measured from bank to bed, was 1.5 to 2.0 m along Profiles L2-L5, and about 3.0 m along Profile L1, the observed changes represent a 25-50% net increase in channel depth. Besides changes in depth, the overall bed configuration was altered because the channel thalweg migrated westward. This is most apparent along the broader L5 and L4 profiles, but is also true for the narrower transects towards the bridge. The degree of relief across the profiles also increased during the period. The smoother September 1997 profiles represent a less undulating surface, whereas the June 1998 profiles indicate a surface marked with bars and channels.

In Figure 2-5 profiles from the summer months of 1998 are shown. Between June 1 and July 29 changes measured along the L5 and L3 profiles were slight. In general, less than 0.1 m of material was deposited across the lagoon floor as finer sediments fell out of suspension in the low energy lagoonal environment upstream of the emerging barrier. Between July 29 and October 21 significant deposition occurred in the southwestern portion of the lagoon. Following the opening of a new tidal channel at the western margin of the barrier on August 13, 1998, wave and tidal forces created a flood tidal delta comprising nearshore sands across the western portion of Profile L5 (Figure 2-46). This delta extended as a lobe of sand upstream beyond Profile L4 but did not reach Profile L3.

Profiles AB1-AB10 upstream of the PCH Bridge are shown in Figures 2-6 to 2-10. In these diagrams, the vertical scale was maintained similar to the

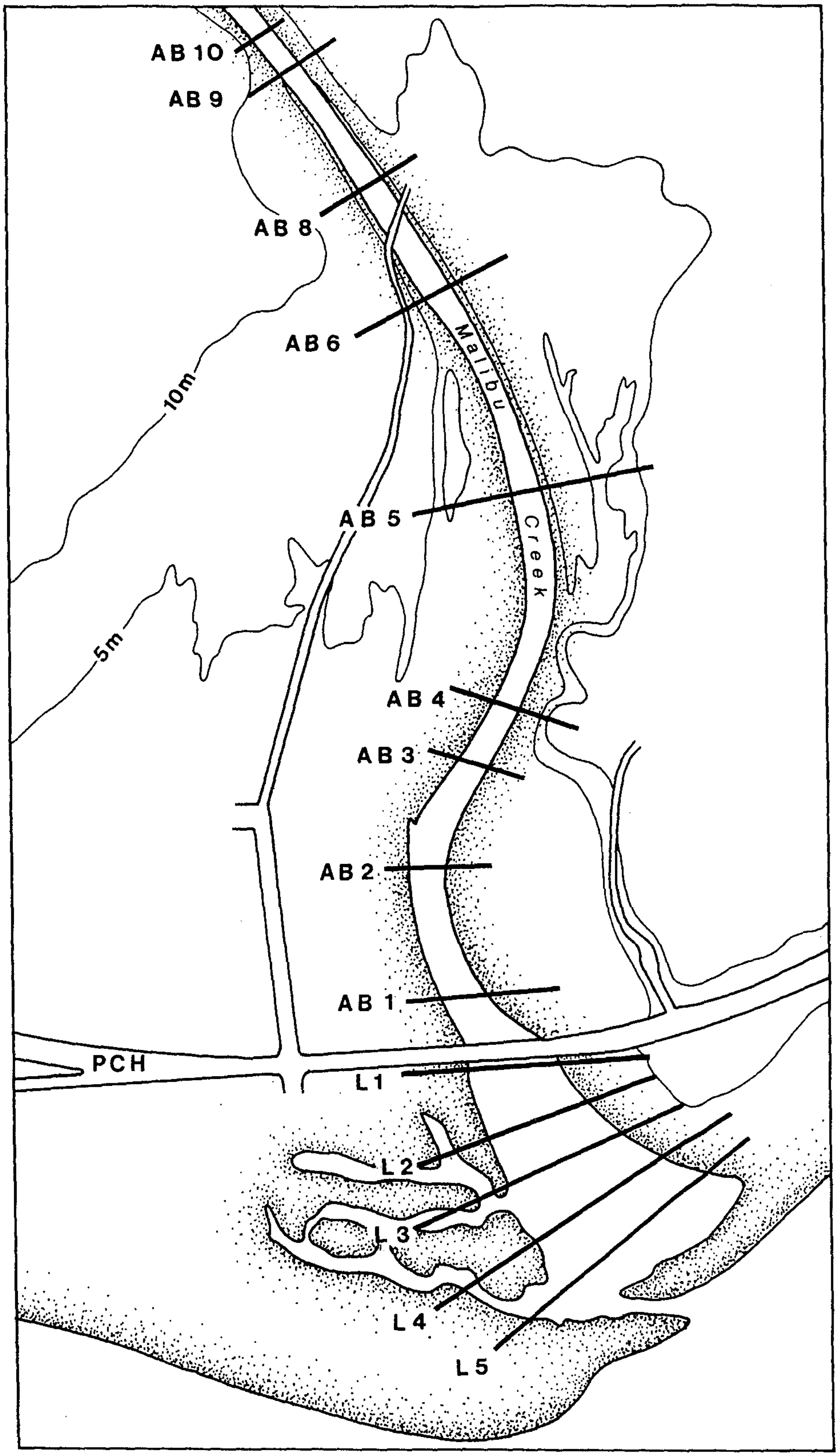


Figure 2-2 Malibu estuarine lagoon system: profiles discussed in text

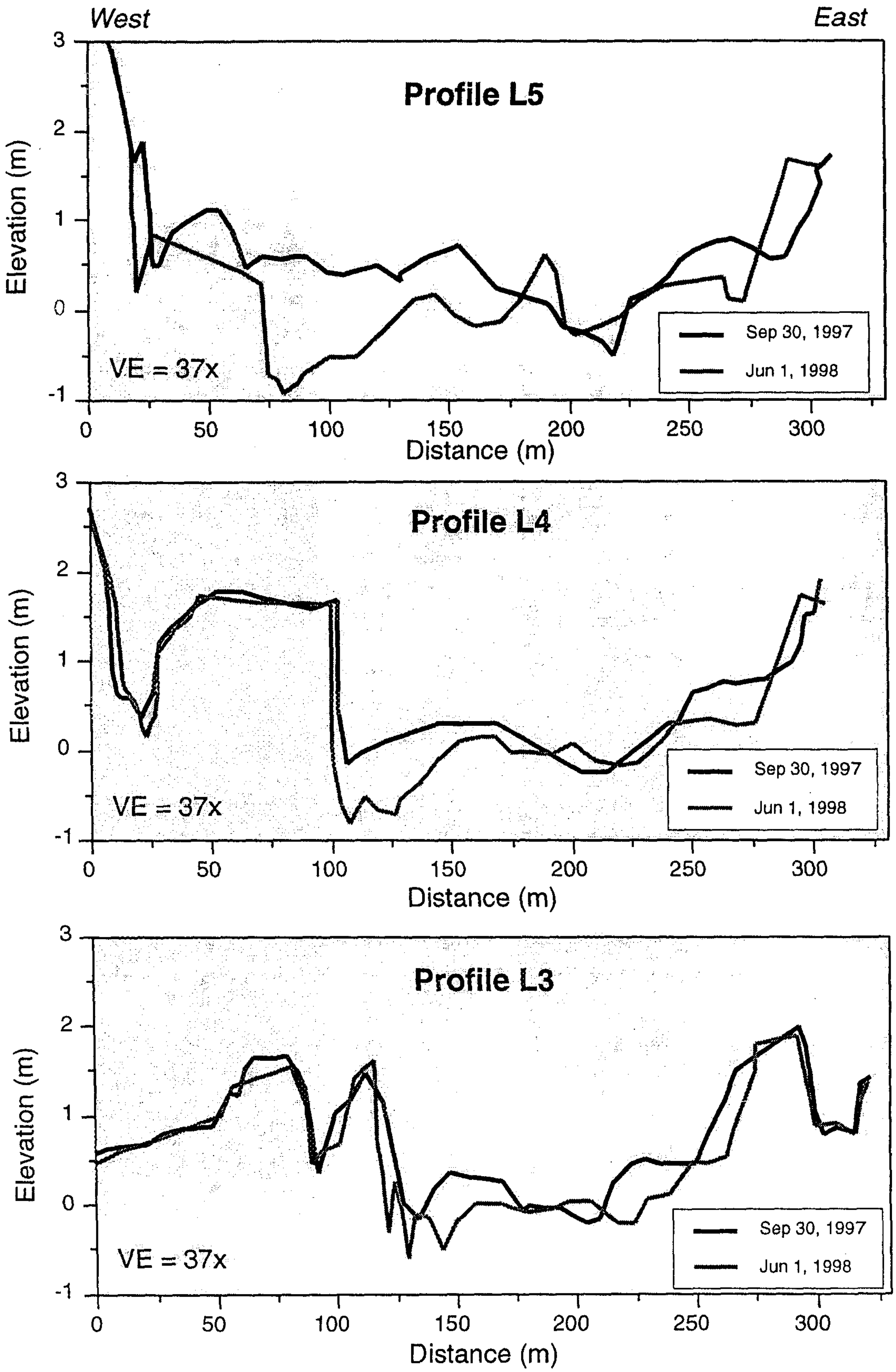
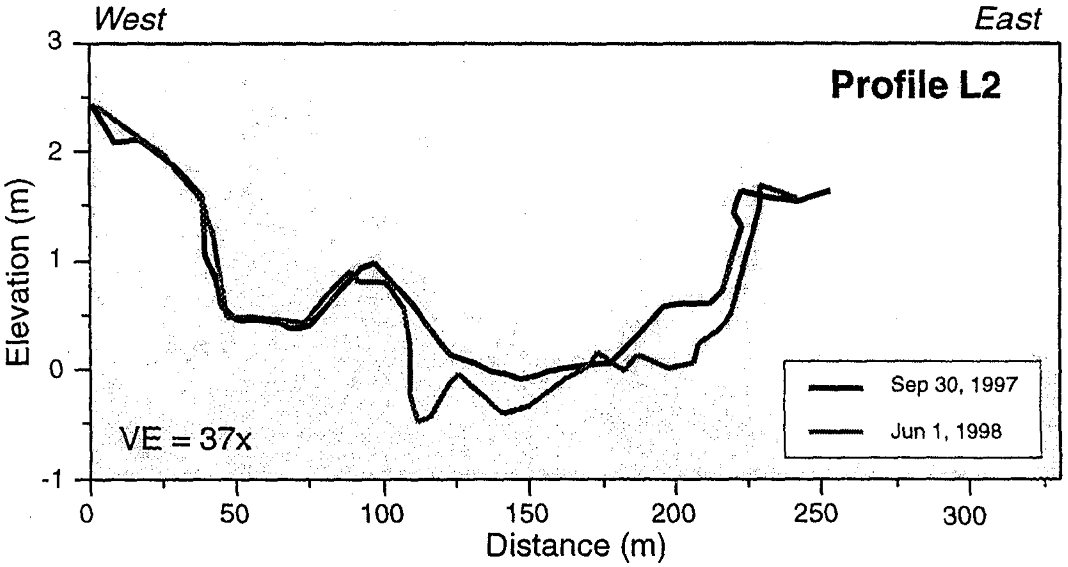


Figure 2-3 Malibu estuarine lagoon - Profiles L3-L5



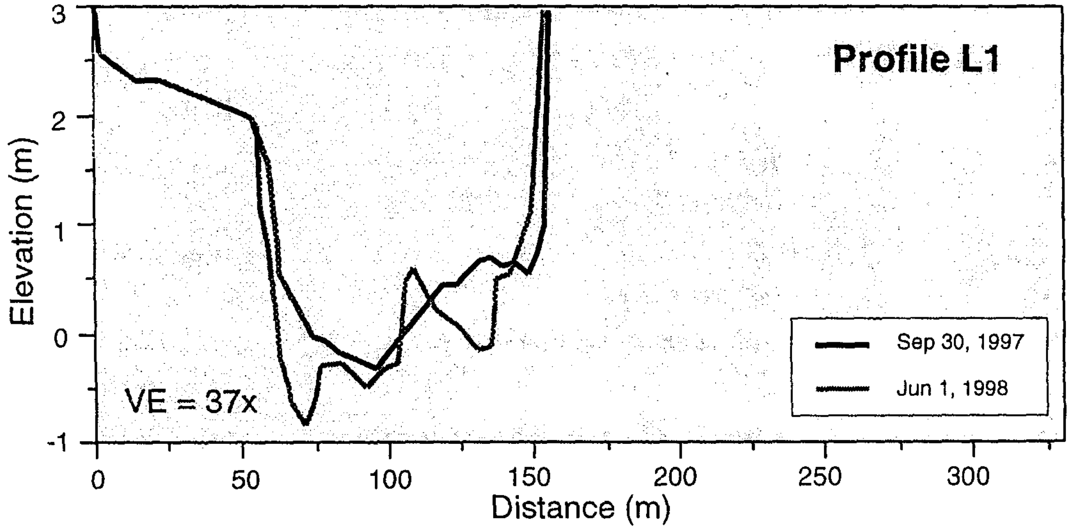


Figure 2-4 Malibu estuarine lagoon - Profiles L1,L2

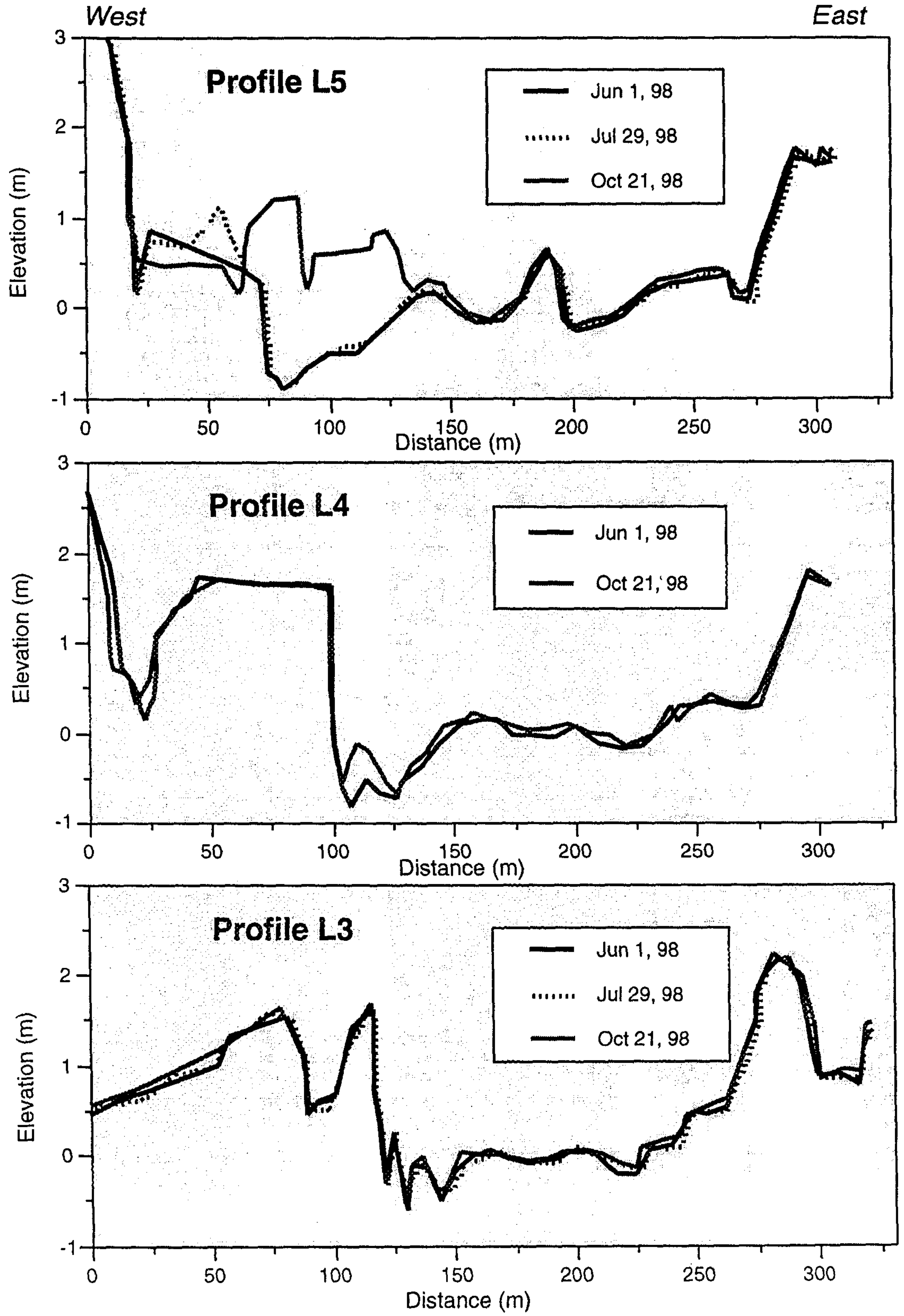


Figure 2-5 Malibu estuarine lagoon - Profiles L3-L5, Summer 1998

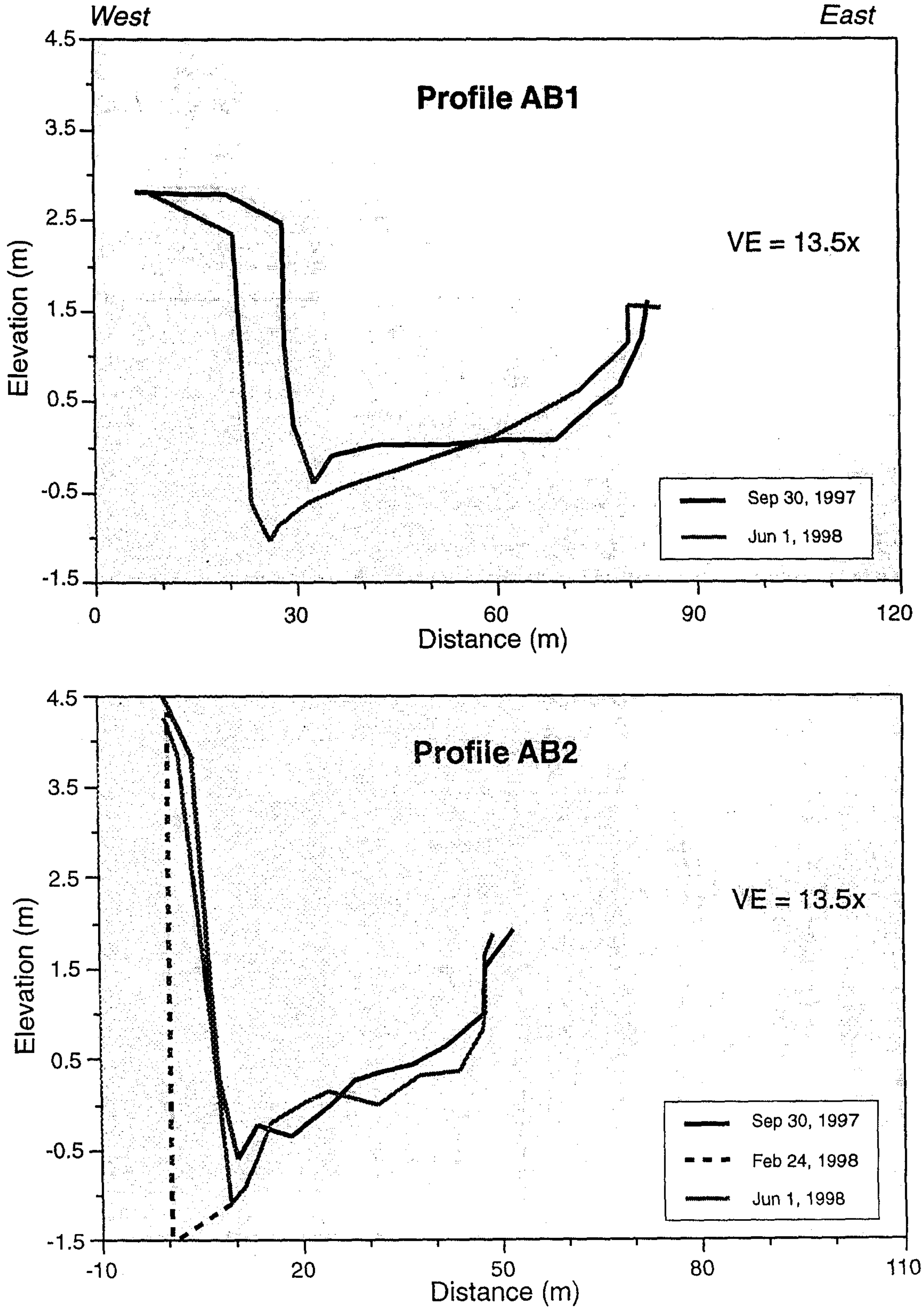


Figure 2-6 Malibu estuarine lagoon - Profiles AB1,AB2

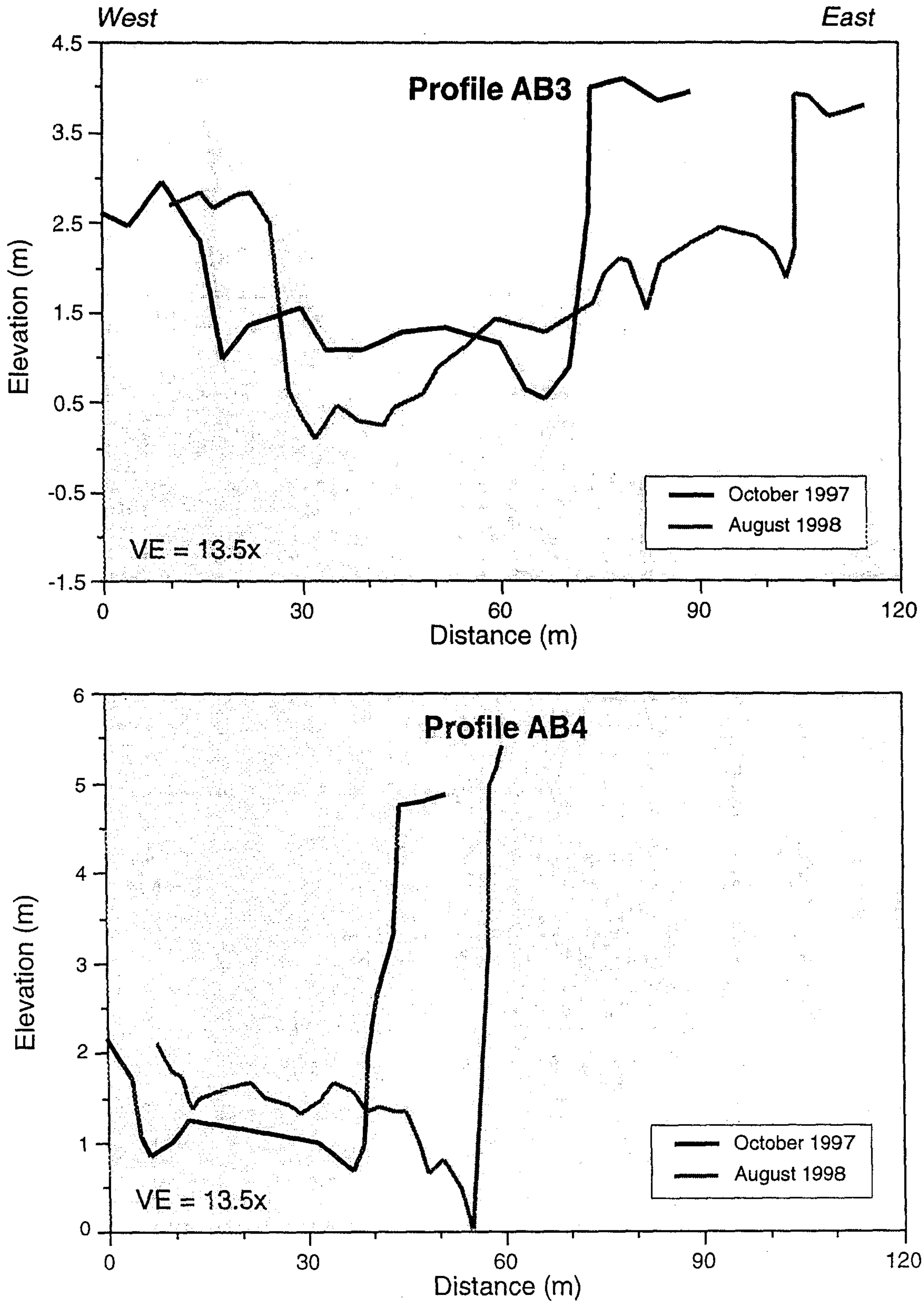


Figure 2-7 Malibu estuarine lagoon - Profiles AB3,AB4

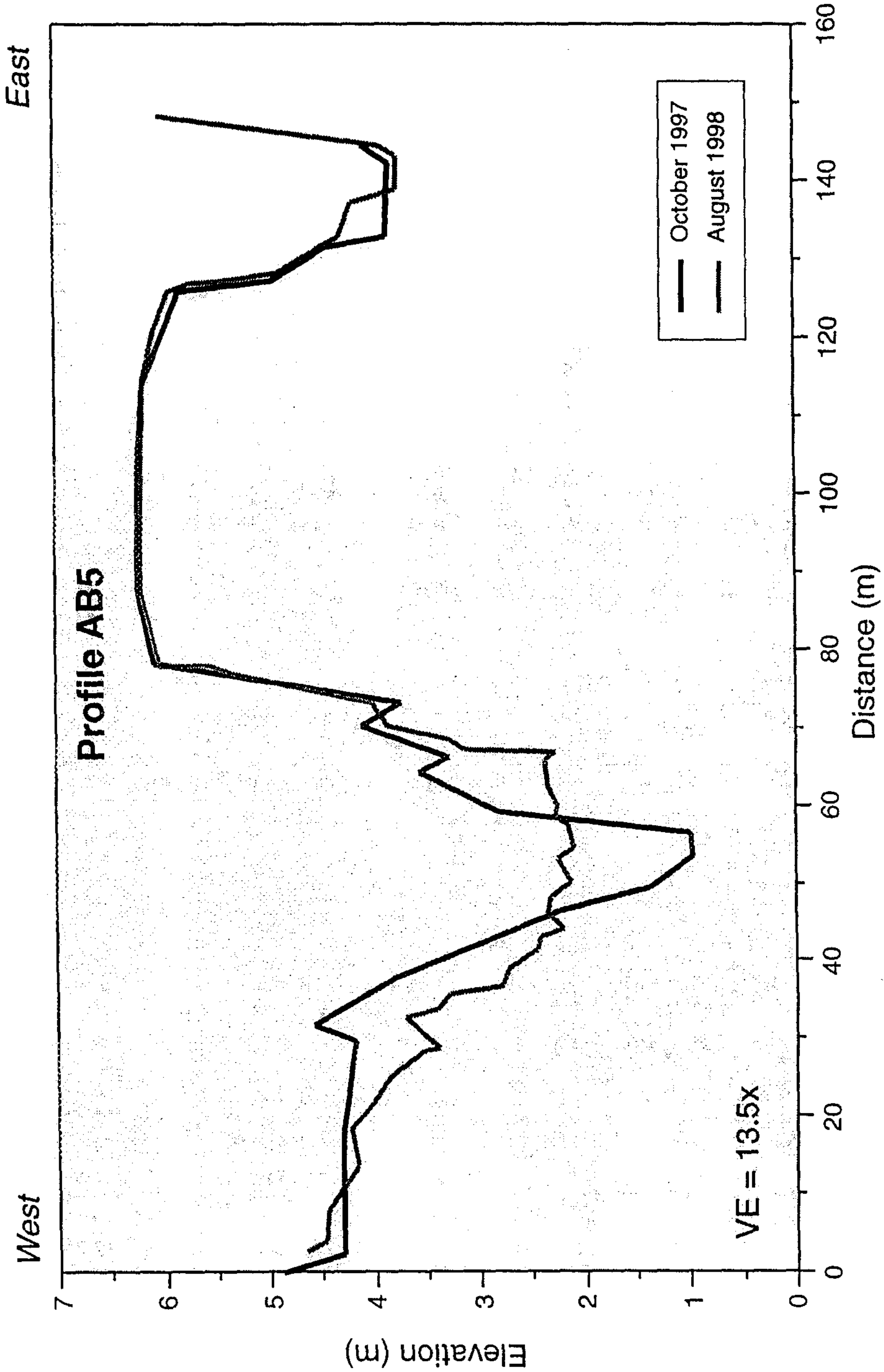


Figure 2-8 Malibu estuarine lagoon - Profile AB5

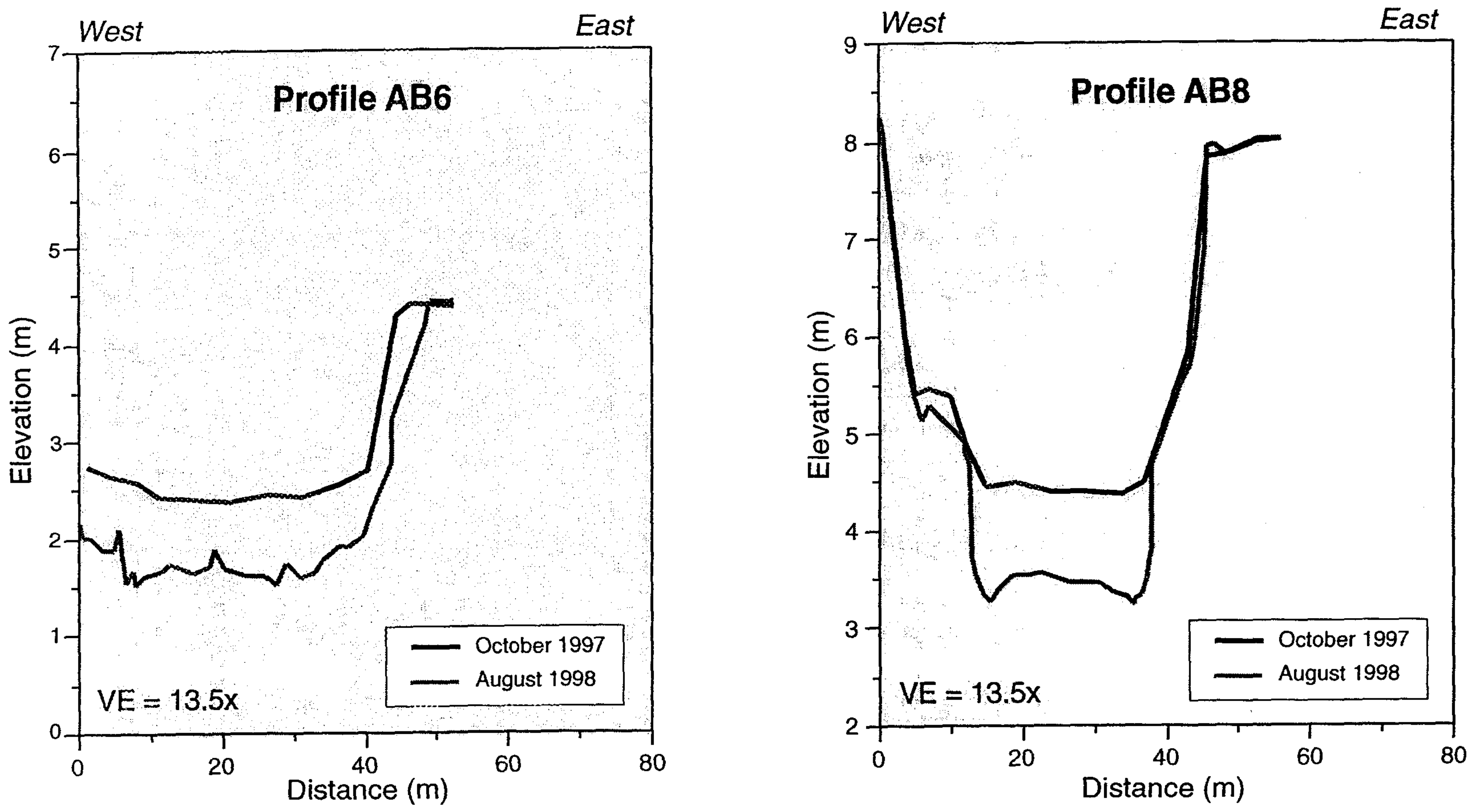


Figure 2-9 Malibu estuarine lagoon - Profiles AB6, AB8

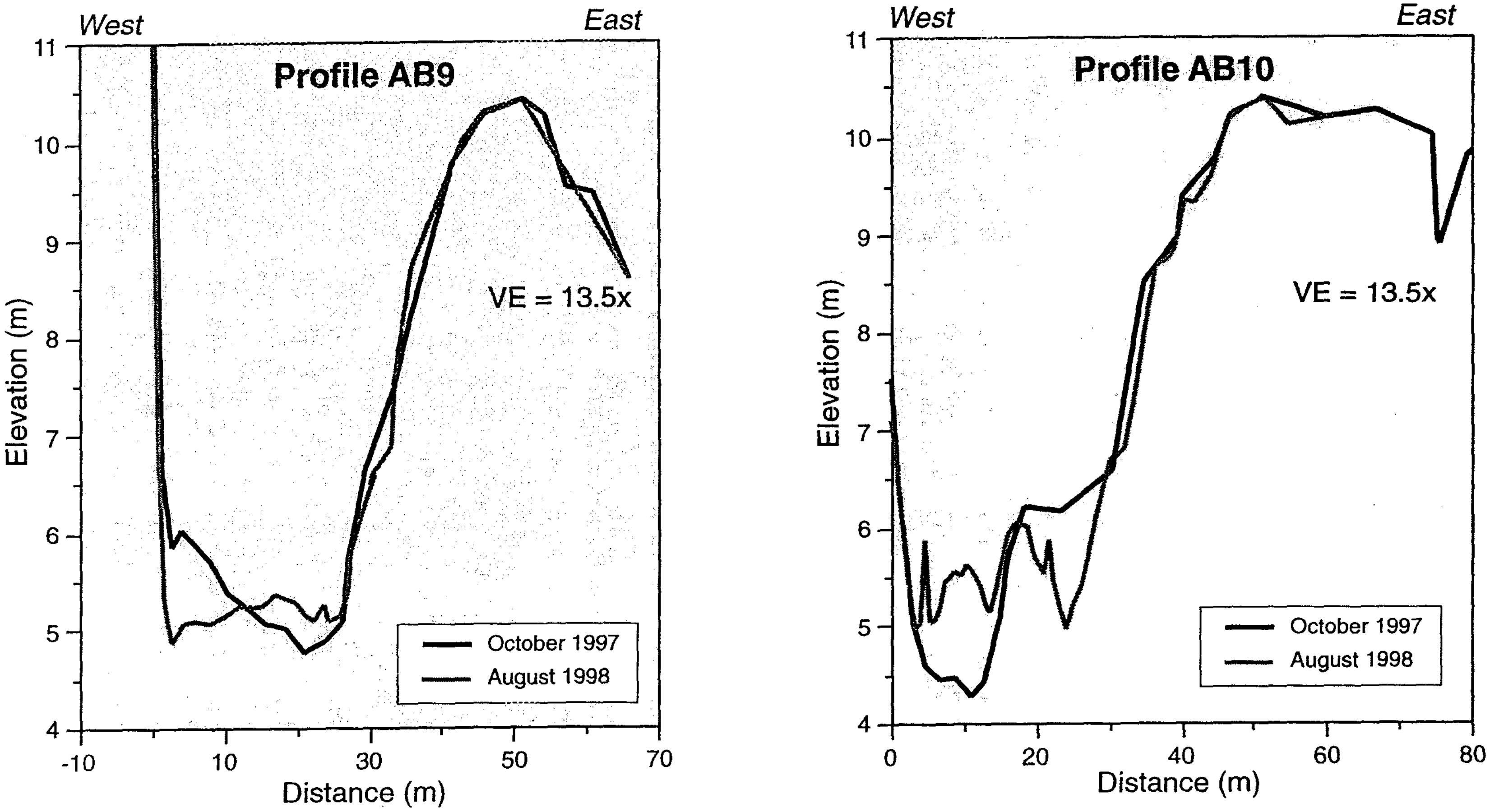


Figure 2-10 Malibu estuarine lagoon - Profiles AB9, AB10

lagoon profiles (L1-L5) but, because of reduced channel width upstream, the horizontal scale was enlarged resulting in a reduced vertical exaggeration (13.5x).

Profiles AB1 and AB2 represent a transitional area between the broader, shallower estuarine lagoon downstream of the bridge and the deeper, narrower fluvial channel upstream. Located along a westward meander opposite a large arcuate point bar (Figure 2-2), the channel in the vicinity of profiles AB1 and AB2 begins to show geomorphic evidence of more channelized flow. However, other hydrologic qualities like the degree of tidal exchange and water salinity are more typically lagoonal or estuarine here than conditions farther upstream. In Figure 2-6 repeat surveys of profiles AB1 and AB2 indicate that 8-10 m of bank erosion occurred along the western bank of the meander during the 1998 winter storm season. For Profile AB1 this lateral migration of the channel was complemented by deposition along the inner bank adjacent to the point bar. Although wider and deeper, the resulting channel form was fairly similar to the original AB1 channel shape.

In the case of Profile AB2, the 10 m of bank erosion indicated by the February 8 profile was mitigated by the mechanical deposition of artificial fill and the placement of several tonnes of granitic boulder riprap during mid-February. By June 1998 the newly constructed western bank had a profile similar to the original 1997 bank. Unlike AB1, erosion rather than deposition occurred at the eastern portion of AB2 along the inner bend of the meander. Point-bar deposition was curtailed naturally at AB2 because of the bank stabilization program on the outer bend of the meander which arrested the processes of lateral channel migration with point-bar replacement.

Upstream of AB2 the channel bends eastward around an even larger point bar which extends northwards to the vicinity of Profile AB6 (Figure 2-2). Similar to the smaller bar downstream on the eastern bank, this large point bar on the western bank is not a uniform surface but comprises several slivers of alternating longitudinal bars and swales. The elevations of these bars increase away from the channel. Profiles AB3 and AB4 both captured extremely dramatic erosional events that occurred in the central reach of the study area during the 1998 winter (Figure 2-7). At AB3 the eastern bank punched over 30 m eastwards while the western bank also migrated about 10 m eastwards, resulting in a net increase in channel width of over 20 m. Whereas the thalweg was previously adjacent to the eastern bank at AB3, by August 1998 a sloping ramp of boulders kept the thalweg towards the western bank. Owing to its composition, structure and placement, this collection of boulders, seen as a ramp in Profile AB3, probably represents the terminal deposition of some type of fluidized debris flow. Beyond the eastern bank of

AB3 exists a floodplain which has a lower elevation than the levée on the eastern boundary of the point bar east of AB1 and AB2. This zone was inundated following the larger runoff events of the 1998 season when discharge overtopped the east bank in the vicinity of AB3, flowed in a few swales southward and rejoined the main channel just upstream of the PCH Bridge. The combined hydrologic and geomorphic evidence suggests that the events of February 1998 were working towards a major channel avulsion, whereby the active channel would have circumvented the lower point bar. This result did not occur, yet it remains a possibility for the future. Profile AB4 also shows a great amount of erosion on its eastern bank where over 15 m of unconsolidated alluvium was removed. The August 1998 AB4 line indicates a bank surface that at its base has been eroded completely to bedrock.

Upstream of AB4, an additional 150 m length of the eastern bank was eroded back between 15-35 m. Much of this loss was initiated by turbulent flood scour, but a large proportion of this area's erosion fell as rotational slumps when saturated banks and hillslopes were undermined during receding flows. In October 1997, Profile AB5 revealed an incised portion of the stream nestled between the higher floodplain terrace to the east and the large point bar to the west (Figure 2-8). During the 1998 storm season this narrow channel was widened and elevated, the removal of material from the banks exceeding deposition in the bed. The differences seen in Profile AB5 are representative of channel changes in the 150 m reach upstream of AB5 towards the northern limit of the large point bar.

Farther upstream beyond the point bar, Malibu Creek occupies a very straight corridor for roughly 500 m until reaching the canyon outlet. At the lower end of this corridor, profiles AB6 and AB8 depict a stream that scoured its bed over 1 m deep uniformly across its width (Figure 2-9). At the upper limits of this corridor, where the steep bedrock canyon meets the alluvial apron of the coastal zone, profiles AB9 and AB10 show the replacement of an incised channel by a widened channel bed (Figure 2-10). In the case of Profile AB9 the amount of material cut from the western bank is not much greater than the amount of material which filled the eastern channel bed. The later bed surface of Profile AB10 is irregular and contains several new bars and channels formed by the downstream pulsing of boulder snouts which now emerge from the canyon mouth.

2.2.2. *Lagoon Volume*

In Figure 2-11 the volume of water in Malibu Lagoon is plotted as a function of water level in the lagoon for September 1997, June 1998, and October 1998 conditions. These volumetric relationships were calculated using *ARC/INFO®* software, where a triangulated irregular network (tin) was generated to analyze a complex surface based upon a very detailed survey of the lagoon. For example, the June 1998 lagoon survey included 915 points (Figure 2-12). The volumes are based on a lagoon whose upstream boundary is the storm drain culvert roughly 75 m upstream of Profile AB2 (Figure 2-2). The reconstructed channels of the western portion of the lagoon are included in the measurements.

The shapes of the curves in Figure 2-11 are quite uniform and similar. At lower water elevations, increases in water level do not account for rapid increases in volume because much of the lagoon basin is dry and new water is first distributed horizontally with large increases in water-surface area. In the middle portion of the curves, at water depths of 0.6 m to 1.4 m, the relationships steepen. Here the lagoon begins to rise against its wider banks (Figures 2-3 to 2-10), whereby increases in water level reflect larger increases in water volume. This relationship accelerates at even higher lagoon levels. Beyond water levels of 2 m the relationship most likely becomes increasingly exponential. At a certain upper water level, once the peripheral banks of the lagoon basin are overtopped, the model is no longer applicable, but this situation did not occur during 1997-98.

The shift between the September 1997 and June 1998 functions reveals a new lagoon with a greatly expanded storage capacity following the 1998 winter season. The high degree of bed scour illustrated above in the cross-channel profiles readily explains the increases in lagoon volume. At a water level of 0.5 m, the June 1998 lagoon (33,790 m^3) had increased its capacity by 100% compared to its earlier September 1997 form (16,900 m^3). With higher water levels the proportional growth declines. For example, with a water elevation of 1.25 m, the September 1997 lagoon of 72,670 m^3 increased 28.4% to 93,300 m^3 by June 1998 (Table 2-1). The deposition of new sediment during the summer of 1998 (Figure 2-5) reduced lagoon volume measurably and explains the downward shift of the October 1998 curve below the June 1998 curve. For water levels of 1.25 m, a 5.7% reduction in lagoon volume occurred between June 1 and October 21. These curves help illustrate not only the impact of high magnitude events, but also the more subtle nature of geomorphic recovery following such an event. The position of upper and lower boundary curves for the relationship in Figure 2-11 is uncertain. The range of values between the September 1997 and June 1998 curves suggests an initial envelope with which to assess future seasonal changes in lagoon volume. Figure 2-11 will be further addressed below in the discussion of lagoon circulation and tidal exchange.

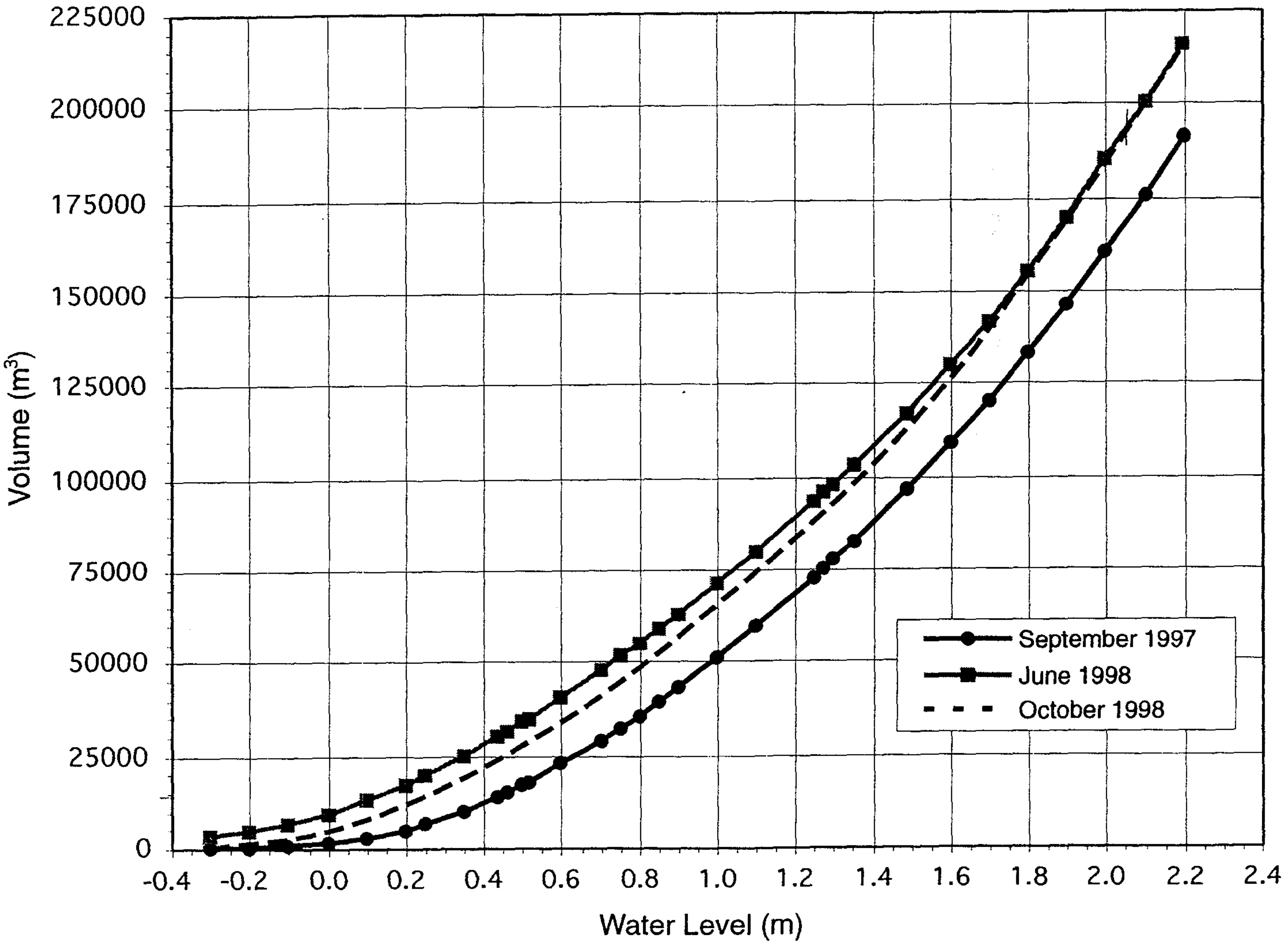


Figure 2-11 Lagoon volume as a function of water level

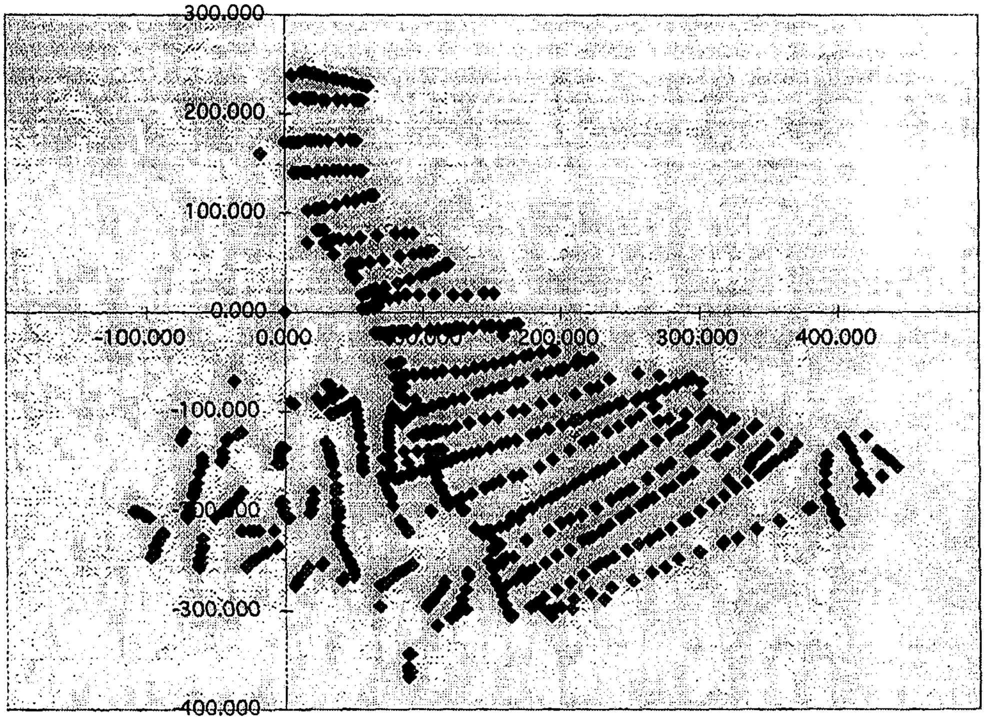


Figure 2-12 Survey points used to construct lagoon volume model

Table 2.1
Lagoon volume summary statistics

	Volume (m^3)					
Lagoon Level (m)	September 1997	June 1998	October 1998	% Growth Sept 97 to June 98	% Growth June 98 to October 98	% Growth Sept 97 to October 98
0.50	16902	33789	27523	99.9	-18.5	62.8
0.52	17790	34879	28563	96.1	-18.1	60.6
0.60	22510	40527	34010	80.0	-16.1	51.1
0.70	28656	47584	40981	66.1	-13.9	43.0
0.75	31979	51271	44692	60.3	-12.8	39.8
0.80	35478	55063	48539	55.2	-11.8	36.8
0.85	39128	58945	52514	50.6	-10.9	34.2
0.90	42905	62911	56596	46.6	-10.0	31.9
1.00	50800	71101	65044	40.0	-8.5	28.0
1.10	59185	79688	73906	34.6	-7.3	24.9
1.25	72671	93303	87945	28.4	-5.7	21.0
1.28	75035	95662	90386	27.5	-5.5	20.5
1.30	77433	98048	92861	26.6	-5.3	19.9
1.35	82332	102899	97904	25.0	-4.9	18.9
1.49	96676	117060	112797	21.1	-3.6	16.7
1.60	108752	129465	126451	19.0	-2.3	16.3
1.70	120242	141798	139651	17.9	-1.5	16.1
1.80	132788	155335	153717	17.0	-1.0	15.8
1.90	146369	169885	168649	16.1	-0.7	15.2
2.00	160652	184952	184101	15.1	-0.5	14.6
2.10	175494	200410	199994	14.2	-0.2	14.0
2.20	190789	216183	216222	13.3	0.0	13.3

2.3 Hydrology for the 1997-98 Water Year

2.3.1. Precipitation

Various public agencies operate several precipitation gauges in the Malibu Creek watershed. The Agoura station, maintained by the Los Angeles County Department of Public Works (LACDWP), is a particularly valuable reference because of its historical record. At 243 m elevation, the Agoura station offers good altitudinal representation of much of the watershed and is also centrally positioned in the upper basin. In Figure 2-13 annual precipitation totals are plotted for the last 59 years. Typical to the Mediterranean climate of coastal southern California, the range of annual values and the yearly fluctuations are very high. The maximum rainfall year occurred in 1940-41 when 107.6 cm of precipitation fell. Other notable wet years include 1968-69, 1977-78, 1982-83, 1994-95, and 1997-98. In fact, the recent 1997-98 season (100.7 cm) is the third wettest year on record. Clusters of dry years are also visible during the periods 1948-51, 1959-64, and 1984-89. In general, the 1990s have been a moist period but, based on the 59-year record, a return to drier conditions may be predicted, starting perhaps as early as 1998-99.

Shifting focus to the distribution of rainfall within a year, Figure 2-14 compares mean monthly precipitation from the long-term record to monthly totals from the 1997-98 season. The smooth and sinuous long-term average curve exemplifies a true two season wet-dry Mediterranean climate where the bulk of rainfall arrives in the five month period November to April. In 1997-98, the month of February was exceptional. During this remarkable month 48.1 cm of rain fell representing a 485% increase from the norm. At Agoura, the February 1998 monthly rainfall total has an expected return frequency of 36 years (Figure 2-18). Not only was this the wettest February on record for Agoura, but a similar series of deluges occurred throughout much of California. At Agoura, February 1998 is the third wettest month for all months on record trailing January 1969 (52.7 cm) and, more recently, January 1995 (53.6 cm). December 1997 and May 1998 were also much wetter than normal during the 1997-98 water year. Interestingly, January, which is typically the wettest month of the year, was drier than average during 1998.

Before concentrating on the daily rainfall amounts from 1997-98, Figure 2-15 offers annual totals from another important precipitation station in the Malibu Creek watershed. The Monte Nido gauge is located near the entrance to Malibu Canyon, 1.3 km upstream of the Malibu Creek-Cold Creek confluence. At an elevation of 183 m, the Monte Nido gauge is 60 m below the Agoura station. However, the lower elevation of Monte Nido does not result in decreased precipitation. Rather, the opposite occurs, where, Monte

Nido receives, on average, 25% more annual precipitation than Agoura. Several aspects of Monte Nido's topography and microclimate may explain why it receives the larger share of rainfall, being situated in a more mountainous and rugged setting, as well as being closer to the ocean when storms arrive from the south and southwest. Whereas the Agoura station fairly represents the broad hills and valleys of the upper basin, the Monte Nido record offers a better idea of rainfall falling along the central axis of the Santa Monica Mountains.

Combined and averaged daily precipitation amounts for the 1997-98 water year from Agoura and Monte Nido are graphed in Figure 2-16. Daily totals were recorded each midnight, therefore the listed values represent the entire undivided calendar date. When rainfall events straddled the midnight time boundary they were recorded as portions on two consecutive days. Far more often, discreet storm events occurred within a given calendar day; therefore daily rainfall is a good indicator of storm events. On occasion the daily total may reflect more than one storm event. Sixty eight rain days were recorded during the water year. As mentioned above, February was the most active period having 17 days with some precipitation.

Geomorphically, the most important events occurred on February 3, 6, 7, and 23. These were the events that were largely responsible for the erosion illustrated earlier by the channel profiles. The rainfall and resulting storm runoff of February 6 and 7 were responsible for the floods which removed much of the barrier beach. As individual rainfall events, none of the storms of February 1998 was truly exceptional. Even the season's largest rainfall which occurred on February 23, when a powerful cyclone stalled off the central California coast and sent successive waves of moisture onshore northward across the Transverse Ranges (Figure 2-17), only had a moderate expected frequency. On this day, Agoura and Monte Nido collected 12.4 cm and 8.9 cm of rain respectively. These magnitudes equate to expected return frequencies of just over 6 years at Agoura and less than 2 years for Monte Nido (Figures 2-18, 2-19). In contrast, the return frequencies for the entire month of February were 26 and 19 years at Agoura and Monte Nido respectively. So, while the individual events were in themselves generally modest, the clustering of so many of these events within a brief four week span from January 29 to February 24 was extraordinary.

2.3.2. *Discharge*

Although discharge is largely a function of precipitation amounts, several other variables are important in explaining streamflow, including basin geometry and geology, rainfall intensity, antecedent soil moisture, degree of vegetative cover due to season or fire, storm type, direction and timing, and evapotranspiration. Additionally, several anthropogenic factors like the amount of released imported water and changing land uses in the watershed also influence stream discharge.

Mean daily discharge rates for the 1997-98 water year are plotted in Figures 2-20 and 2-21. Malibu Creek discharge data are based on a gauging station operated by the Los Angeles County Department of Public Works located just below the confluence of Malibu Creek and Cold Creek. This gauge receives streamflow from a 272 km^2 drainage area which represents over 96% of the entire 284 km^2 Malibu Creek watershed. The county gauge records river stage at 5 minute intervals. Water released from the Las Virgenes Municipal Water District's Tapia Reclamation Facility just upstream of the county operated gauge is also indicated in these figures.

In general, average daily runoff values for Malibu Creek show agreement with trends in daily rainfall amounts seen in Figure 2-16. Prior to the season's first rains in mid-November, discharge rates were meager, averaging around 0.1 m^3s^{-1}. The season's early rains largely went towards recharging soil moisture, yet by December 8 stream baseflow had elevated to roughly 1 m^3 s^{-1}. The storm of December 18 generated a mild stream peak lifting mean daily discharge to 8.6 m^3s^{-1}. The remainder of December was dry and the hydrograph again fell below the 1 m^3 s^{-1} mark. January included a series of light rains which maintained some degree of antecedent soil moisture and kept baseflow hovering around the 1 m^3 s^{-1} level much of the month.

The series of storms which brought abundant rainfall between January 29 and February 24 produced a hydrograph with several peaks, and a February monthly average of 24 m^3 s^{-1}. The highest of the mean daily peaks occurred on February 24 when an average runoff value of 114 m^3 s^{--1} was recorded for the day (Figure 2-20). Other noteworthy flood events happened on February 3, 6, and 7. Flow diminished throughout the first three weeks of March which, surprisingly, was a very dry period compared to February (Figure 2-16). The March 25 storm created a flood comparable to the flows of February 14. The remaining spring rains generated mean daily flows which peaked around 10 m^3 s^{-1}, but by June average daily discharge had returned to a level last observed in January (Figure 2-21). Discharge gradually diminished throughout the dry summer months of July, August, and the first half of September. A seven week hiatus in discharge from the Tapia facility occurred between July 29 and September 18.

In Figure 2-22, higher resolution hydrographs based on hourly and maximum storm values, as well as hyetographs, are given for the February storms. In Figure 2-22 discharge values are plotted arithmetically rather than logarithmically as in Figures 2-20 and 2-21. The three sharp hydrographs from February 3-9 and the broader hydrograph from the February 23 storm are plotted in even greater detail in Figures 2-23, 2-24, and 2-25.

The rains of February 2 helped elevate baseflow and also likely decreased the infiltration capacity on the slopes and valleys of the watershed prior to the 8.41 cm of precipitation which fell on February 3 (Figure 2-23). The fast moving cold front which generated the storm of February 3 can be described as advanced in character in that rainfall was greatest during the early portion of the storm and then tapered off. Interestingly, at the Monte Nido station, the highest short-term rainfall intensities of the storm and the entire year, based on 10 to 60 minute durations, occurred in the late afternoon of February 3 and are most likely attributed to a high degree of atmospheric instability in the wake of the morning's passing front. Most of the stormflow of February 3 passed within a brief 10-hour period. The flood peaked at 8:15 am with a flow rate of 436 $m^3 s^{-1}$. The sharp hydrograph indicates a very flashy hydrologic response where the lag time between the centroid of mass of rainfall and peak streamflow was only 2.25 hr. The separation of stormflow from baseflow indicated that the average runoff depth across the basin from this storm was equivalent to 2.12 cm while the average precipitation depth across the basin equaled 8.41 cm. Stream response, a measure of the proportion of storm precipitation arriving as runoff to the stream channel was therefore 25.2%. The remaining 6.29 cm of rainfall remained in the subsurface as soil moisture recharge.

On February 6 another swift moving cold front dropped 6.16 cm of rain across the Malibu Creek Watershed during the mid-morning hours (Figure 2-24). In amount and short-term intensity the rain of February 6 was not as great as the earlier February 3 storm. Although, at the Agoura station, the slightly longer 1 and 2 hour duration intensities were greater on February 6 than on February 3. The resulting flood of February 6 had a lag time of 3.25 hours and peaked at 12:55 pm with a flow rate of 359 $m^3 s^{-1}$. On this day average runoff depth in the basin was 2.45 cm and soil moisture recharge equaled 3.71 cm. Hydrograph comparison between February 3 and 6 indicates that although the flood of February 6 had a lower peak discharge it generated a larger volume of stormflow and a greater proportional stream response (39.7%). The stronger hydrologic response to a weaker rainfall event is directly attributable to the higher level of antecedent soil moisture prior to the February 6 event. Additionally, much of the stormflow of February 6 occurred during the period of flow recession following peak discharge. In contrast, on February 3 runoff diminished more immediately following peak flow. The shorter lag time of the February 3 event was likely due to the greater rainfall intensities of this storm which probably caused more runoff to travel quickly as overland flow.

When the evening storm of February 7 struck baseflow in the creek was still elevated and hillslopes were still moist from the previous day's rain. Of the 7.56 cm of precipitation which fell mostly over a 5 hr period, 3.54 cm contributed directly to stormflow runoff. This 46.8% stream response dramatically illustrates the important role of antecedent soil moisture and the cumulative effect of the previous week's rains. Like the February 6 storm, the rains of February 7 were less than the February 3 event but they generated a larger stormflow volume. Furthermore, in the case of February 7 a lighter rainfall amount with smaller short-term intensities, compared to February 3, created even a greater magnitude flood peak (541 m^3 s^{-1}). The intermediate duration precipitation intensities (4-6 hr) were greater for the February 7 rainfall than either of the February 3 or 6 events. The basin lag time of 3.25 hr for the February 7 storm was identical to the lag time on February 6.

When plotted arithmetically, the events occurring in mid-February look inconsequential compared to the floods of the first week of the month (Figure 2-22). Yet, these smaller flows and their associated rains were important in maintaining runoff in the creek (Figure 2-20). The largest daily precipitation event of the year, which occurred on February 23 (Figures 2-16, 2-17), produced a hydrograph with a much different shape than the earlier February storms (Figure 2-25). In contrast to the relatively short and intense rains of the previous storms with their needle-like hydrographs, the stalled front of February 23 caused precipitation to fall through much of the day. This is reflected in a broader storm hydrograph where the instantaneous peak never attained the levels of the earlier February storms. More importantly though, discharge rates greater than 50 m^3 s^{-1} were maintained for a 24 hour period and flows above 100 m^3 s^{-1} lasted for roughly 12 hours. The precipitation of February 22 was important in recharging soil moisture and elevating baseflow prior to February 23. Without the rains of February 22 the 36.6% stream response of February 23, which was less than that of February 6 and 7, would have been undoubtedly lower.

To illustrate how some of the flow conditions described above filled Malibu Creek, wetted perimeters across profiles AB-7 and AB-10 of the lower creek are graphed for various flood stage conditions in Figure 2-26. During the February 6 storm at the Arizona crossing of Cross Creek Rd. (Profile AB-7) the stream surface rose 2.4 m in just 4.6 hours. By 4:35 pm, 3.5 hours after peak discharge, the stream surface had dropped 1.18 m. Upstream at Profile AB-10, located at the outlet of the rugged Malibu Canyon, a more incised channel profile indicates relationships between flood stage and channel morphology Benches along the northern bank of the channel are associated with discharges of various magnitudes For example, peak discharge during the February 6 storm required the stream level to rise 3 4 m to an elevation of 9 4 m which corresponded to the top of one of the cut-bank notches along the northern bank During the following night's event on February 7, the flood's peak flow, which was also the maximum instantaneous discharge of the entire year just overtopped the crest of the northern bank indicating that bankfull discharge was attained River stage shown on February 20 is representative of lower magnitude conditions maintained during the dry periods between winter storms These baseflow conditions also correspond to channel morphology by occupying the entire portion of the incised lower channel

The significance of the events monitored during the winter of 1998 is evaluated by comparison to other seasons and storms In Table 2-2 and Figure 2-27 volumes of total annual discharge for the 67 years of record are shown in both hectare-meters and acre-feet In terms of total annual discharge, the 1997-98 season ranked third behind 1968-69 and 1982-83 and was very similar in total volume to the 1977-78 year Several interesting questions arise when one compares these values of annual discharge to corresponding measures of total annual precipitation from the Agoura station (Figure 2-13) During the 1940s and 1950s there were several notable wet years including the top ranking 1940-41 and seventh ranking 1951-52 seasons However, the causal relationship between precipitation values and annual discharge during the earlier years of record is suppressed compared to the more recent years following the 1970s This phenomena is perhaps even more striking during dry periods For example, the dry years during the late 1940s are comparable, if not wetter, in terms of annual precipitation to some of the dry years of the late 1980s Yet the annual discharge values for the later period are far greater The cause of this increased stream response in both wet and dry years is undoubtedly the role of changing land use in the Malibu Creek watershed The increasing proportion of impervious surfaces has led to increased surface runoff

Table 2-2 also includes annual values of maximum instantaneous discharge, which are graphed in Figure 2-28, and discharge data from each year's wettest month The peak instantaneous flow during 1997-98 (540 5 m^{3}s^1) was comparable in magnitude to the flood peak of March 4, 1978 (549 3 m^3 s^1) Six years on record had maximum peak flows greater than the 1997-98 instantaneous maximum, although the floods from January 1969 and January 1980 were considerably higher than any of the other values on record Similar to the trend observed for total annual discharge, annual peak flows also increase in magnitude towards the present time The relevant stature of

1997-98 as a high flow year improves in considering monthly discharge. Only January 1969 had a mean monthly discharge greater than February 1998 (Table 2-2). Frequency-magnitude relationships for daily, annual, and selected monthly discharge were calculated according to a log-Pearson type 3 distribution and are plotted in Figure 2-29. The 1997-98 annual discharge total had an expected return frequency of just over 18 years while the year's maximum daily discharge had an expected return frequency of just greater than 7 years. However, the mean monthly discharge for February 1998 had a return period over 62 years. Thus, the conclusion drawn above regarding precipitation during the 1997-98 season also holds true for discharge. In view of the historical record, the flood events of 1997-98 are not exceptional individually, but collectively within the time span of one month, the discharge of February 1998 was remarkable.

2.3.3. Suspended Sediment

Measures of suspended sediment in the creek were collected using a USGS DH-48 sampler followed by vacuum extraction and density calculation. Samples were taken under various flow conditions where sampling during storm events was dictated by conditions of safe access to the channel. Results from samples collected between December 1, 1997, and April 6, 1998, are shown in Table 2-3. During the first collection days in December samples were taken from the channel at both the L.A. County gauge station and the Arizona crossing of Cross Creek Rd. Assessment as to whether the stream gains or loses suspended sediment through Malibu Canyon is inconclusive due timing differences in the samples as well as expected sampling error. During March and April 1998 samples from the Arizona crossing were compared to samples collected from the tidal channel at the barrier beach during outflow conditions. These samples suggest that sediment concentration exiting the lagoon is greater than entering the lagoon during outflow conditions. It is believed that this loss of material is compensated during ocean inflow conditions when the lagoon gains sediments from both fluvial and marine sources.

The association between suspended sediment concentration and the determinant variable stream discharge is examined in Figure 2-30. Although plotted with log-log axes, a strong positive linear relationship ($y=14.5x + 262$, $r^2=.88$) is observed between the two variables. In Figure 2-31 the relationship between discharge and sediment concentration is separated for samples taken prior to or following peak discharge. This approach indicates that pre-flood samples have a higher sediment content.

During the 1997-98 water year, suspended sediment samples were also collected monthly by the Las Virgenes Municipal Water District (Table 2-4). These samples were taken primarily to study water quality and not timed for specific hydrologic events. These samples do support the claim made above that the lagoon has higher sediment concentrations than stations farther upstream. Measurements made by the Los Angeles County Environmental Programs Division (LACEPD) during storm events are more relevant regarding geomorphic processes (Table 2-5). The sample taken by LACEPD on December 5 agrees very closely to the other samples taken for the present study on this day (Table 2-3).

The most valuable measurement from the LACEPD data was taken during the flood of February 6 when Malibu Creek carried 2321 mg/L of suspended sediment. This sediment concentration was not based on one instantaneous sample, but rather was taken as a composite sample at 15 minute intervals between 9:50 am and 2:37 pm. The composite sample taken during peak flow hours of February 6 used in combination with additional samples taken with the DH-48 before and after peak flows (Table 2.2) offers a very good basis for calculating total suspended sediment yield (12.66 X 10^6 kg) during stormflow (Figure 2-24). This analysis between total stormflow volume and total suspended sediment for February 6 was then used as a model to estimate sediment yields for the other large February storms (Figures 2-23 to 2-25).

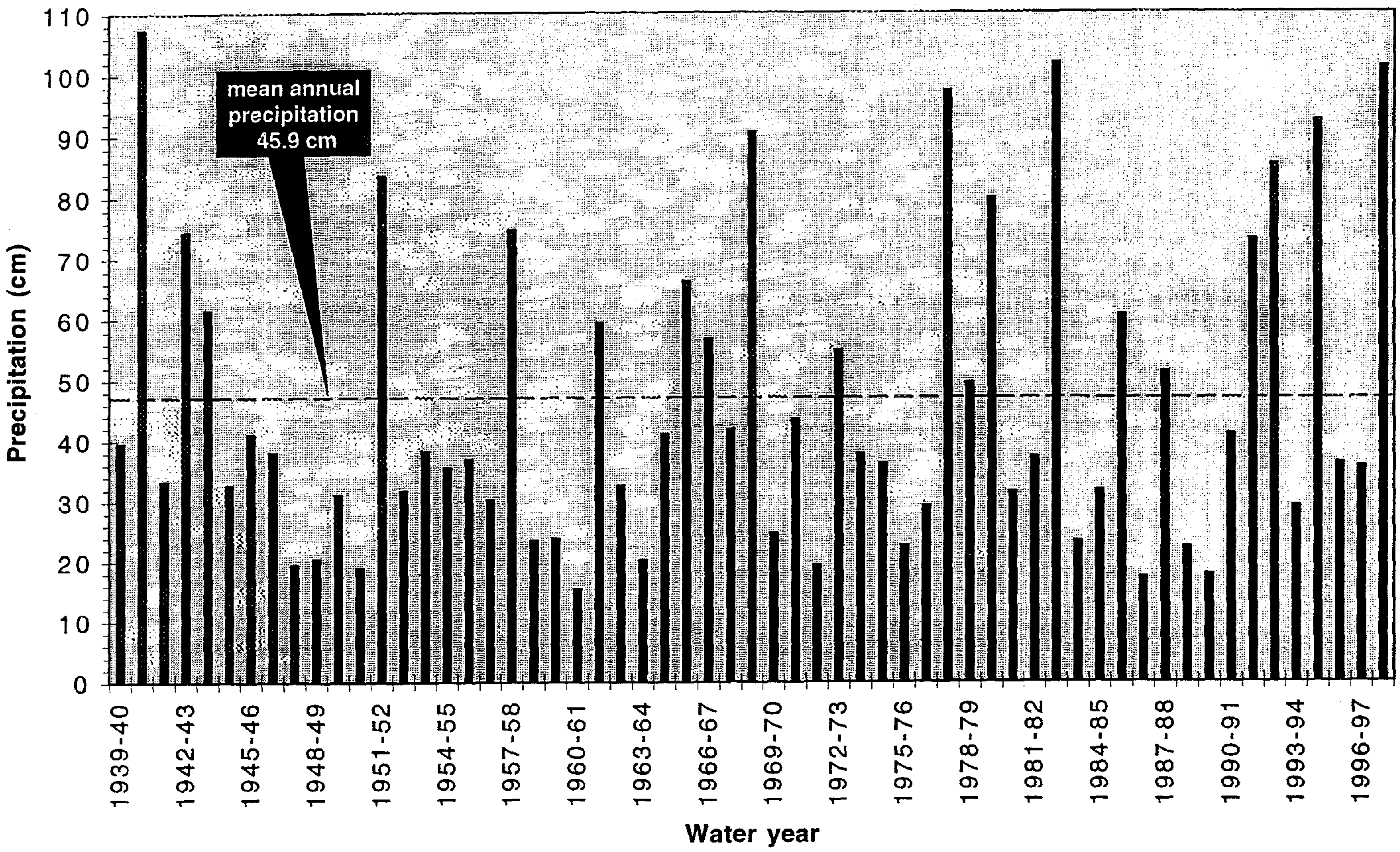


Figure 2-13 Total annual precipitation at Agoura, Ca (el. 243 m)

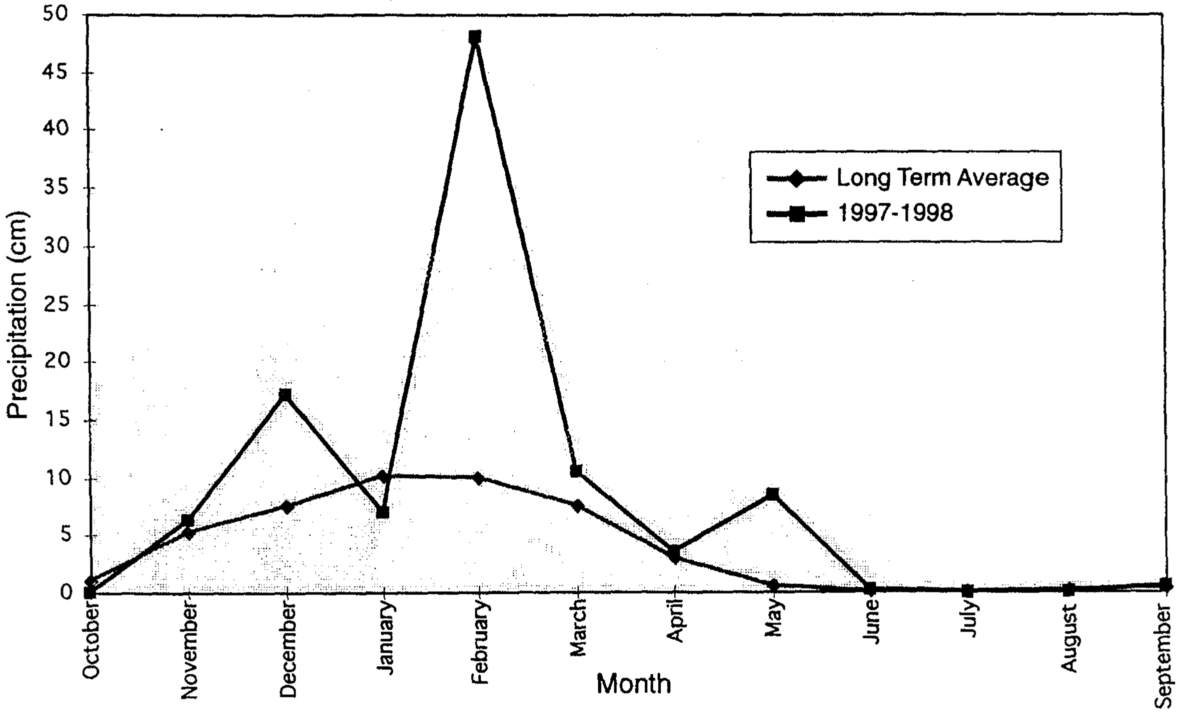


Figure 2-14 Mean monthly precipitation at Agoura, Ca (el. 243 m)

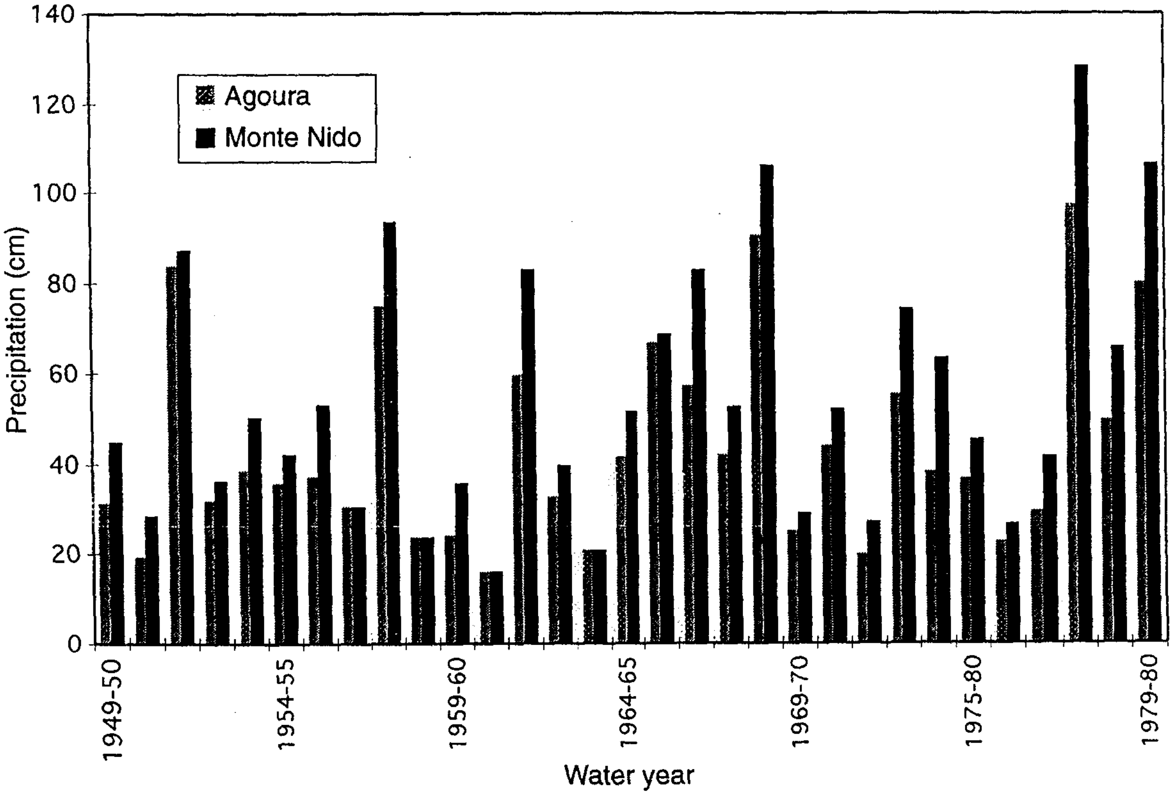


Figure 2-15 Annual precipitation, Agoura vs. Monte Nido

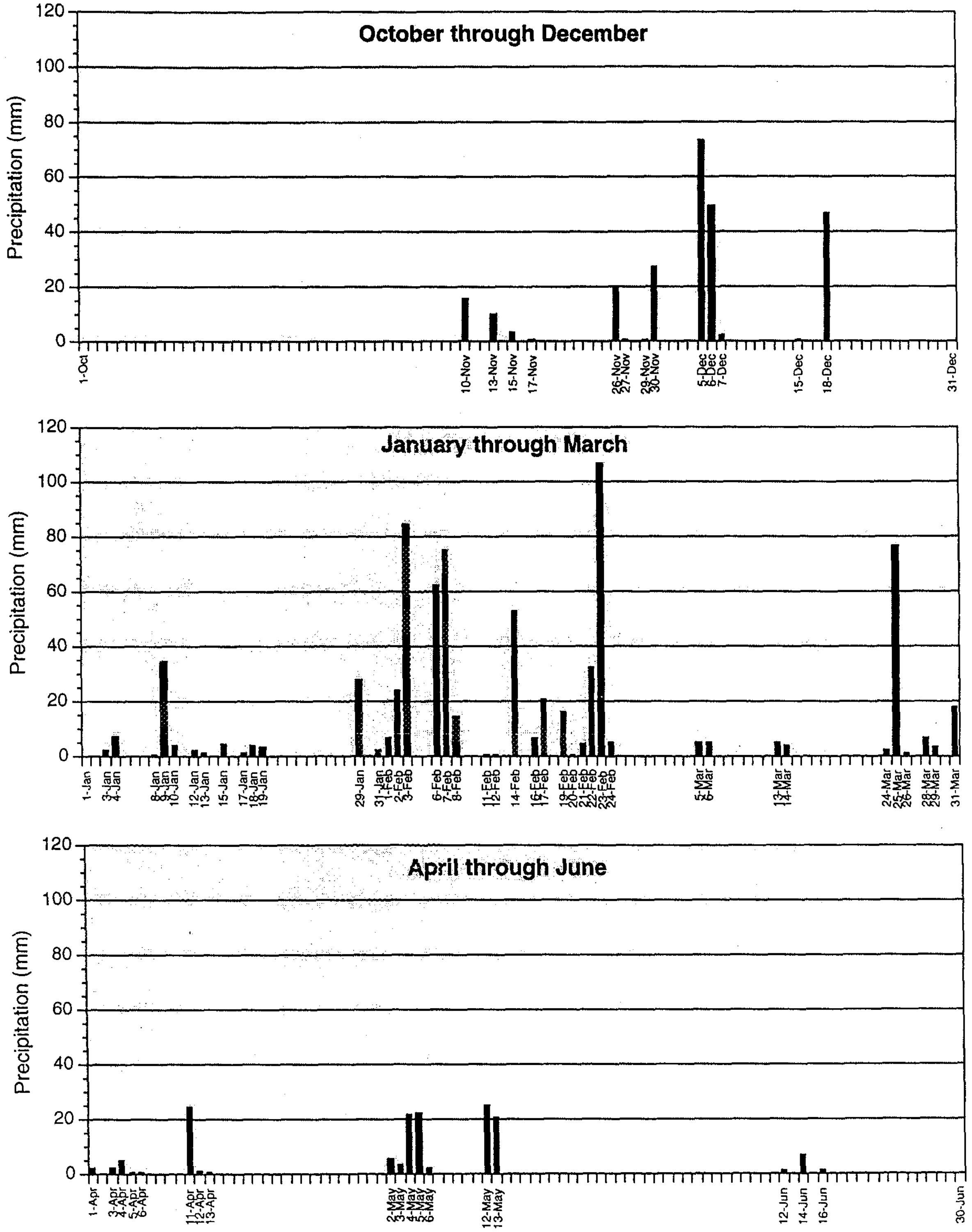
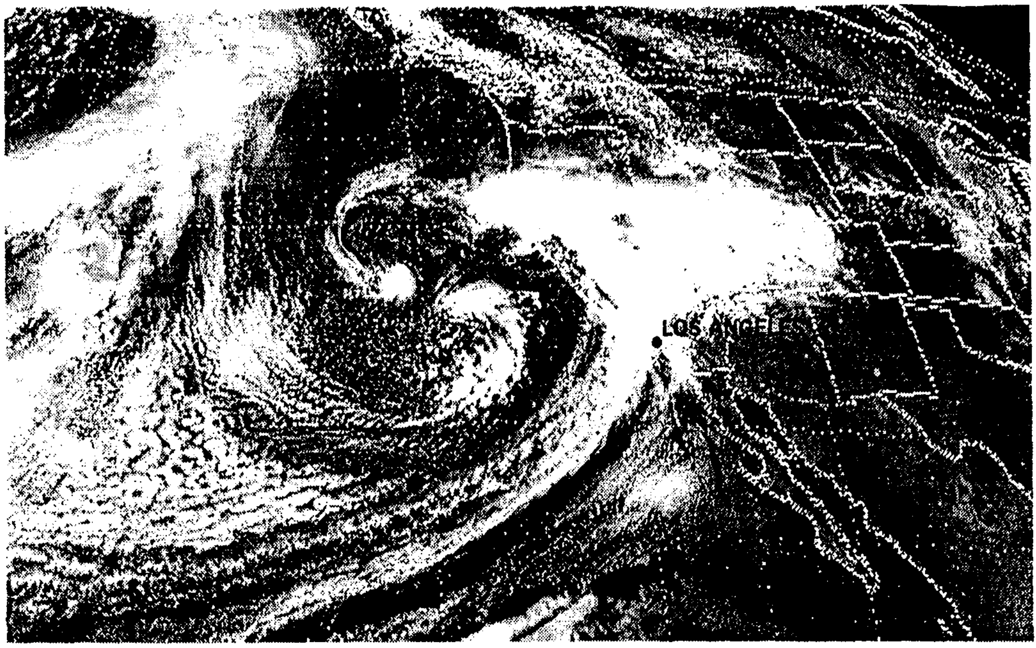


Figure 2-16 Malibu Creek Watershed precipitation 1997-98



Taken at 2 p.m. Monday — National Oceanic and Atmospheric Administration/WeatherData, Inc.

A tap of tropical moisture fed into a powerful storm centered just off the coast of California on Monday. Heavy surf associated with this storm, coupled with high astronomical tides, may generate minor tidal overflow today along the Southern California beaches.

Figure 2-17 Satellite image of Pacific storm hitting California on Monday March 23, 1998 *(Los Angeles Times Feb. 24, 1998)*

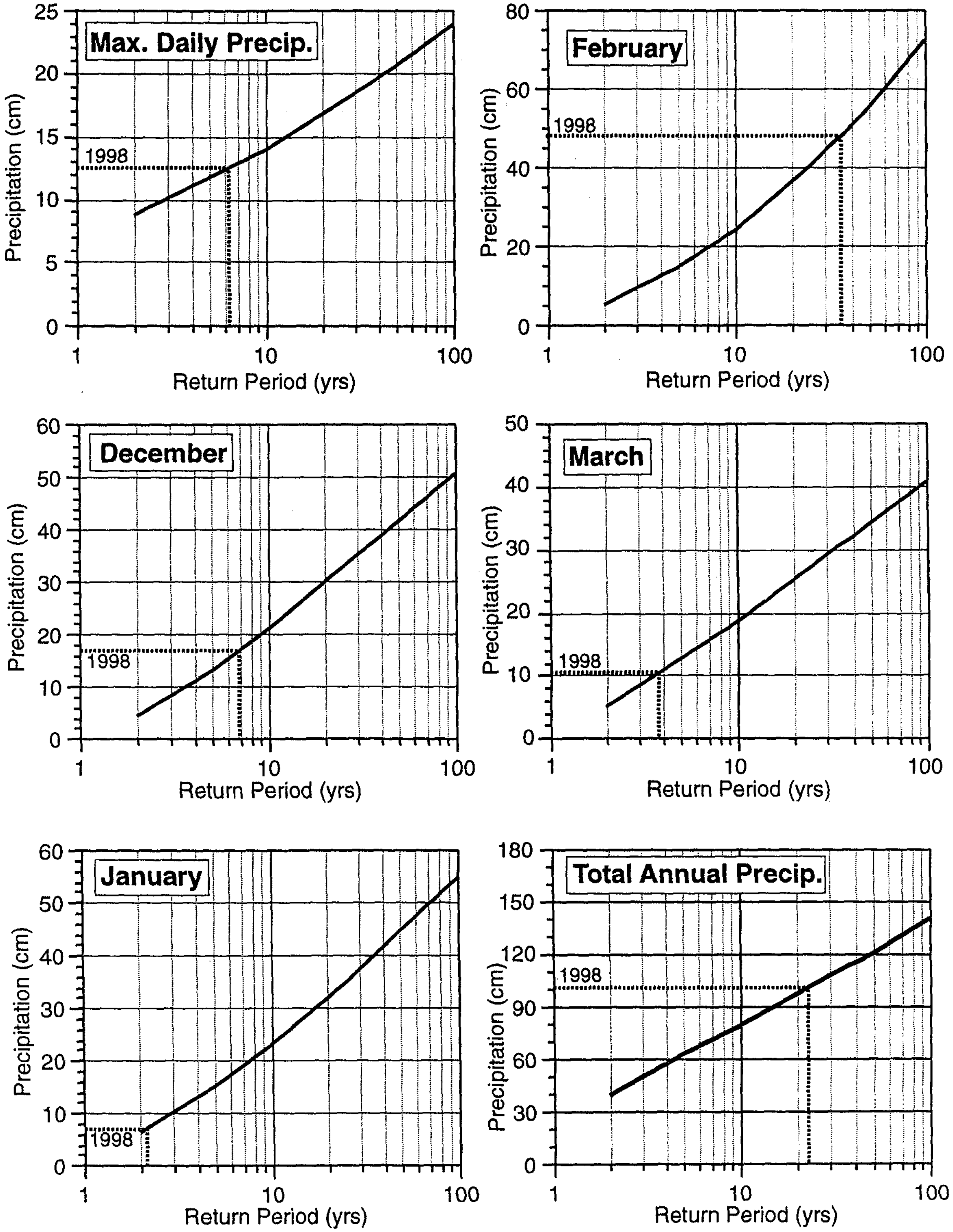


Figure 2-18 Precipitation frequency analysis at Agoura station

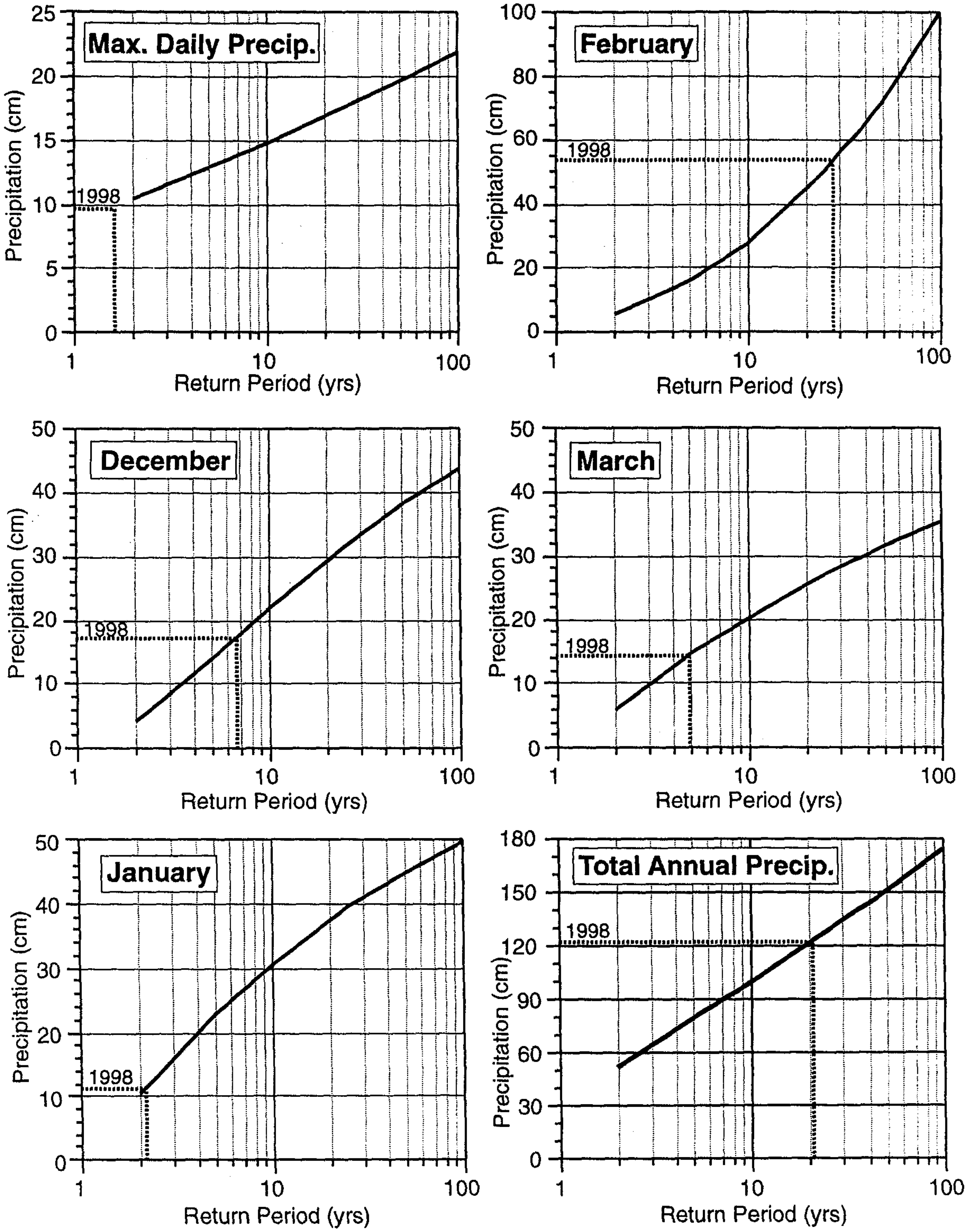


Figure 2-19 Precipitation frequency analysis at Monte Nido station

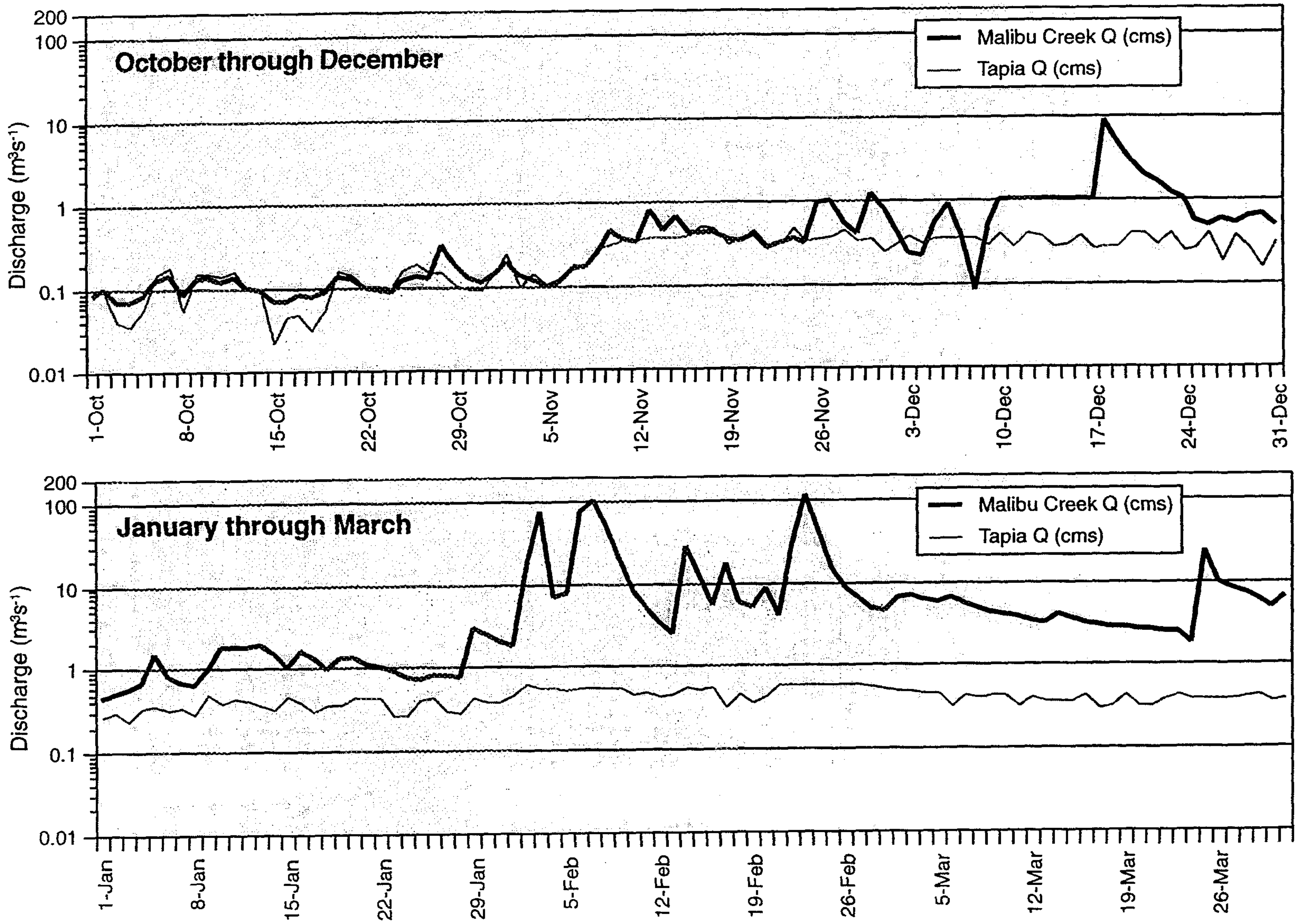


Figure 2-20 Mean daily discharge Malibu Creek, October 1997 - March 1998

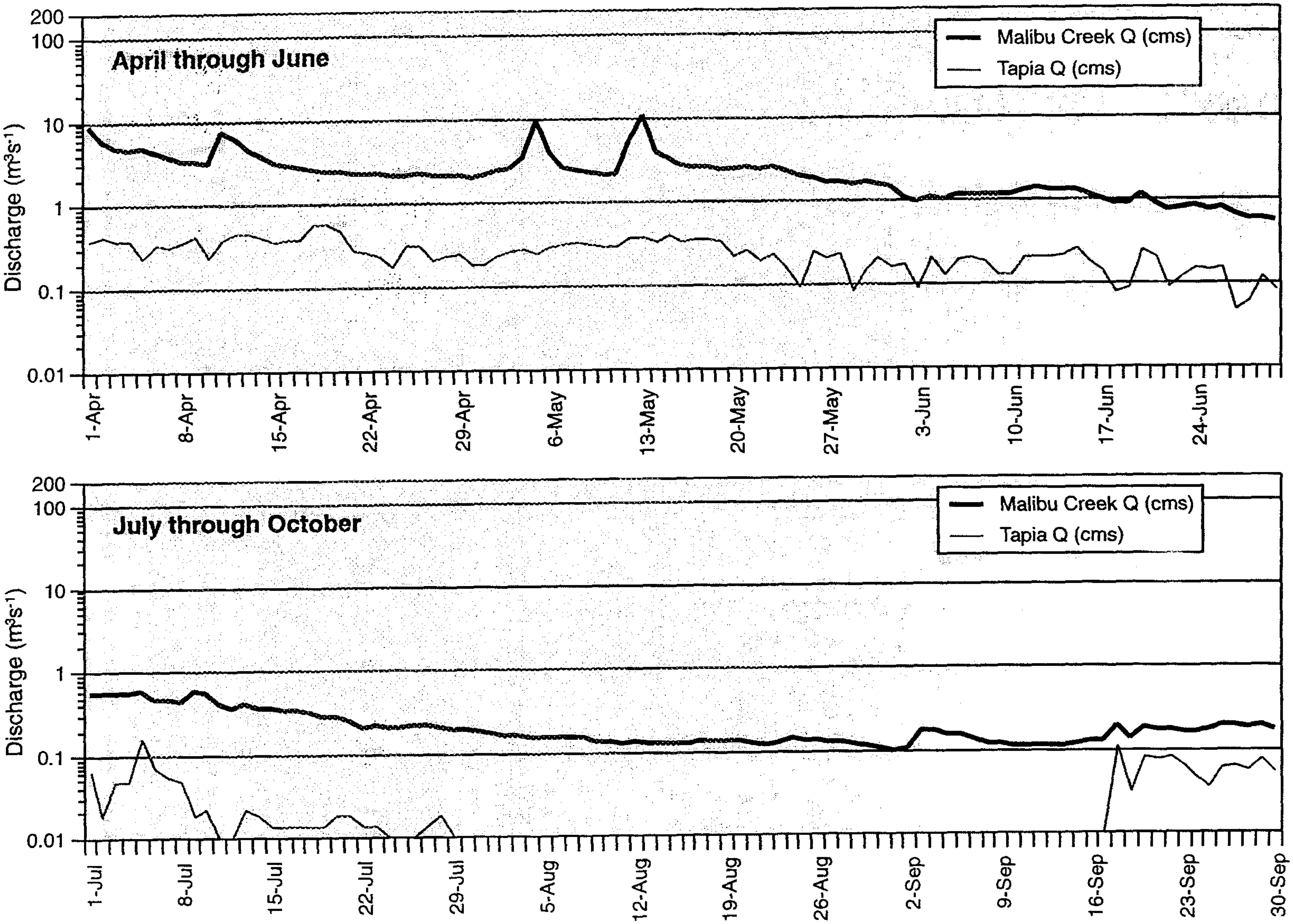


Figure 2-21 Mean daily discharge Malibu Creek, April 1998 - October 1998

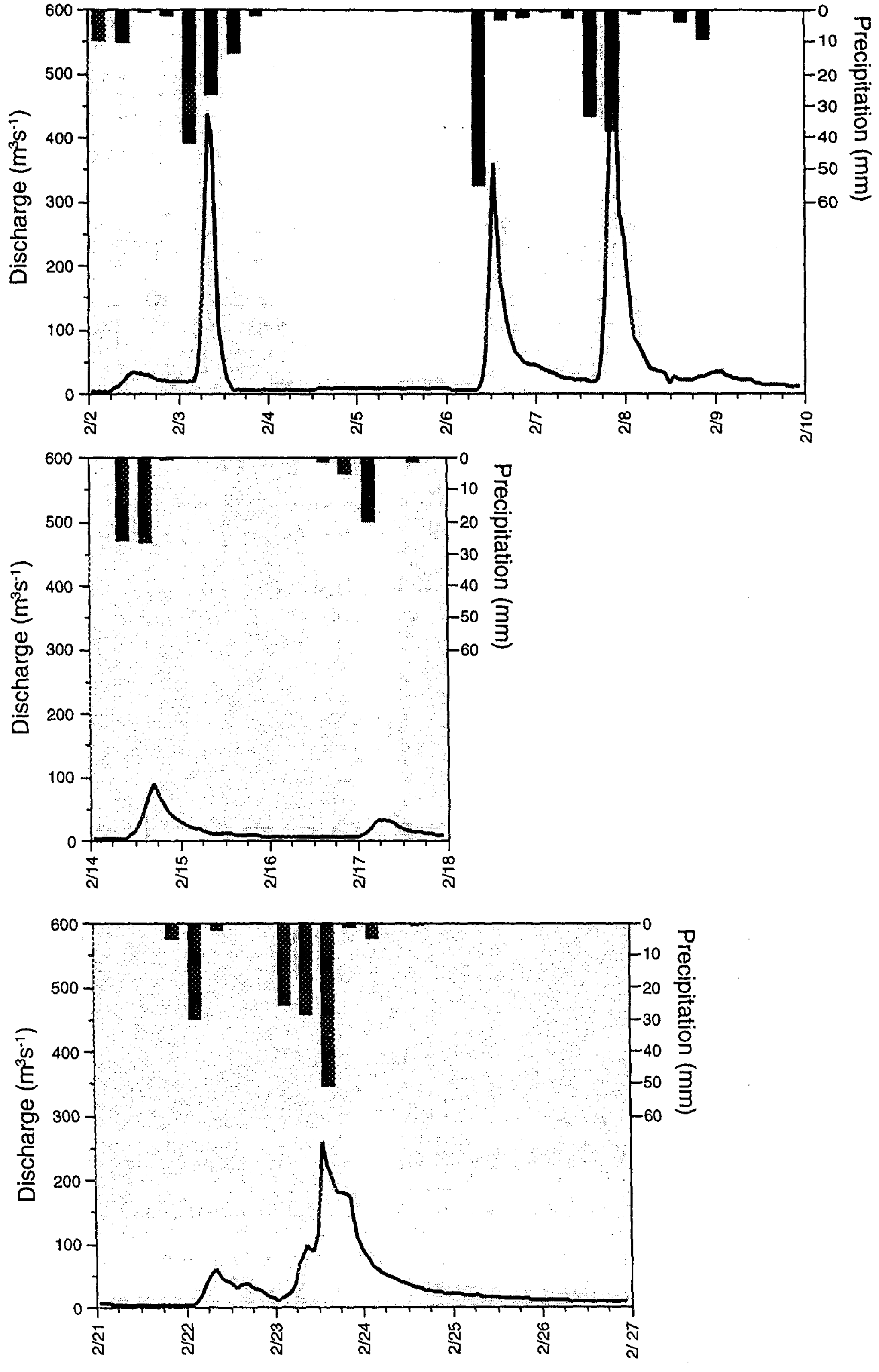
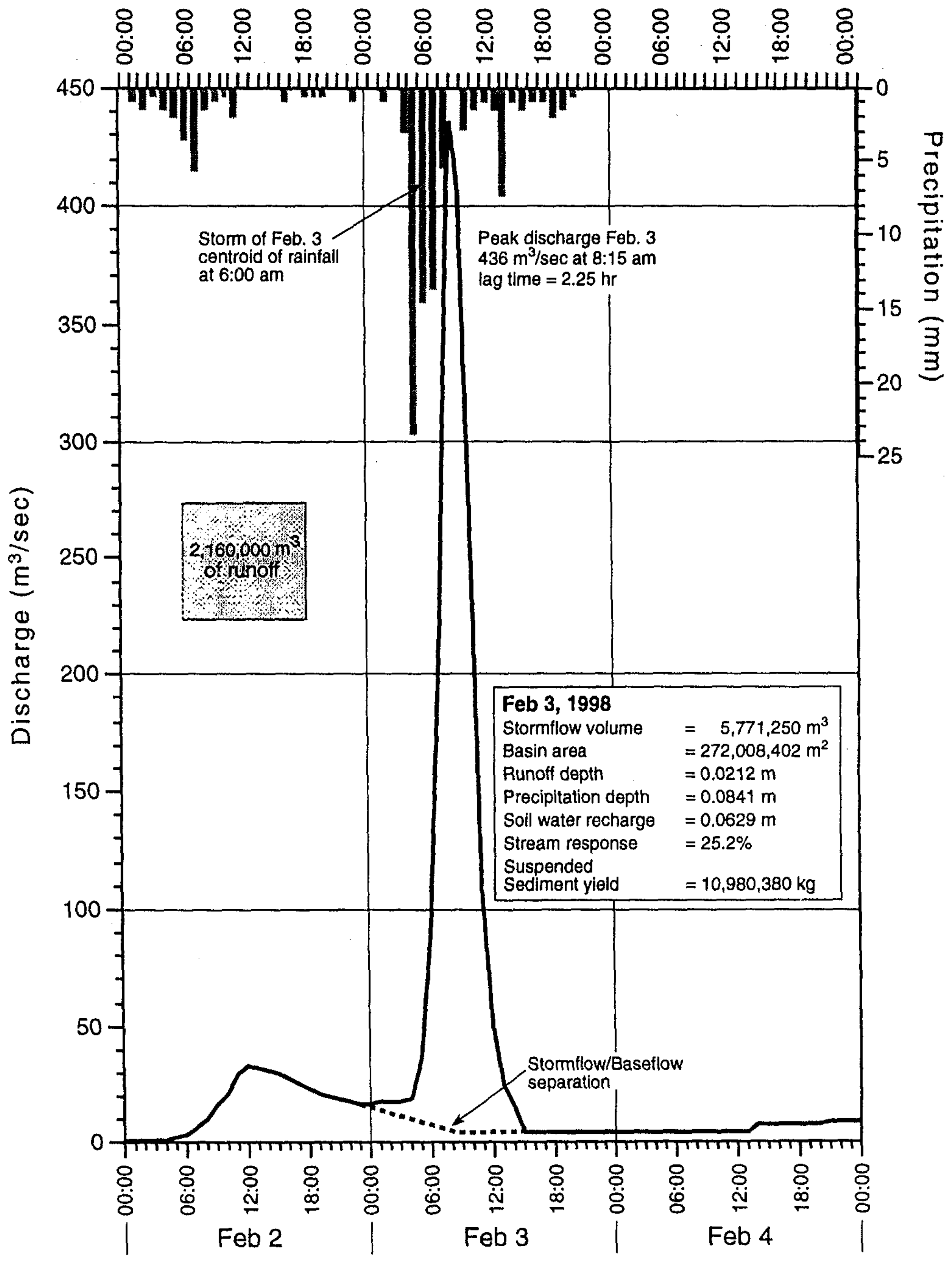
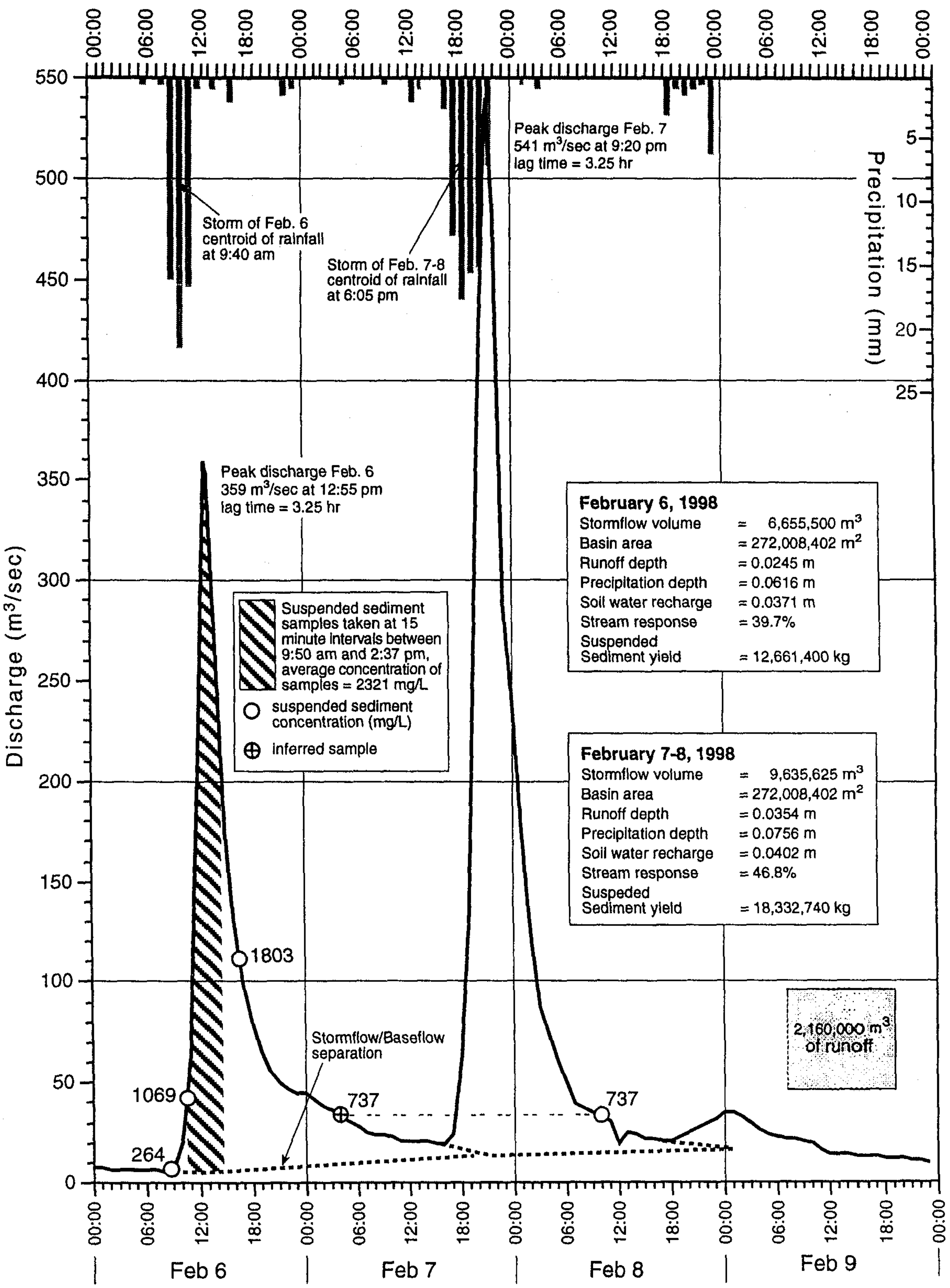


Figure 2-22 Hydrographs and hyetographs of February 1998 storms



Feb 3, 1998	
Stormflow volume	= 5,771,250 m³
Basin area	= 272,008,402 m²
Runoff depth	= 0.0212 m
Precipitation depth	= 0.0841 m
Soil water recharge	= 0.0629 m
Stream response	= 25.2%
Suspended Sediment yield	= 10,980,380 kg

Figure 2-23 Hydrograph and hyetograph, February 2 - 4, 1998



February 6, 1998

Stormflow volume	= 6,655,500 m^3
Basin area	= 272,008,402 m^2
Runoff depth	= 0.0245 m
Precipitation depth	= 0.0616 m
Soil water recharge	= 0.0371 m
Stream response	= 39.7%
Suspended Sediment yield	= 12,661,400 kg

February 7-8, 1998

Stormflow volume	= 9,635,625 m^3
Basin area	= 272,008,402 m^2
Runoff depth	= 0.0354 m
Precipitation depth	= 0.0756 m
Soil water recharge	= 0.0402 m
Stream response	= 46.8%
Suspeded Sediment yield	= 18,332,740 kg

Figure 2-24 Hydrograph and hyetograph, February 6 - 9, 1998

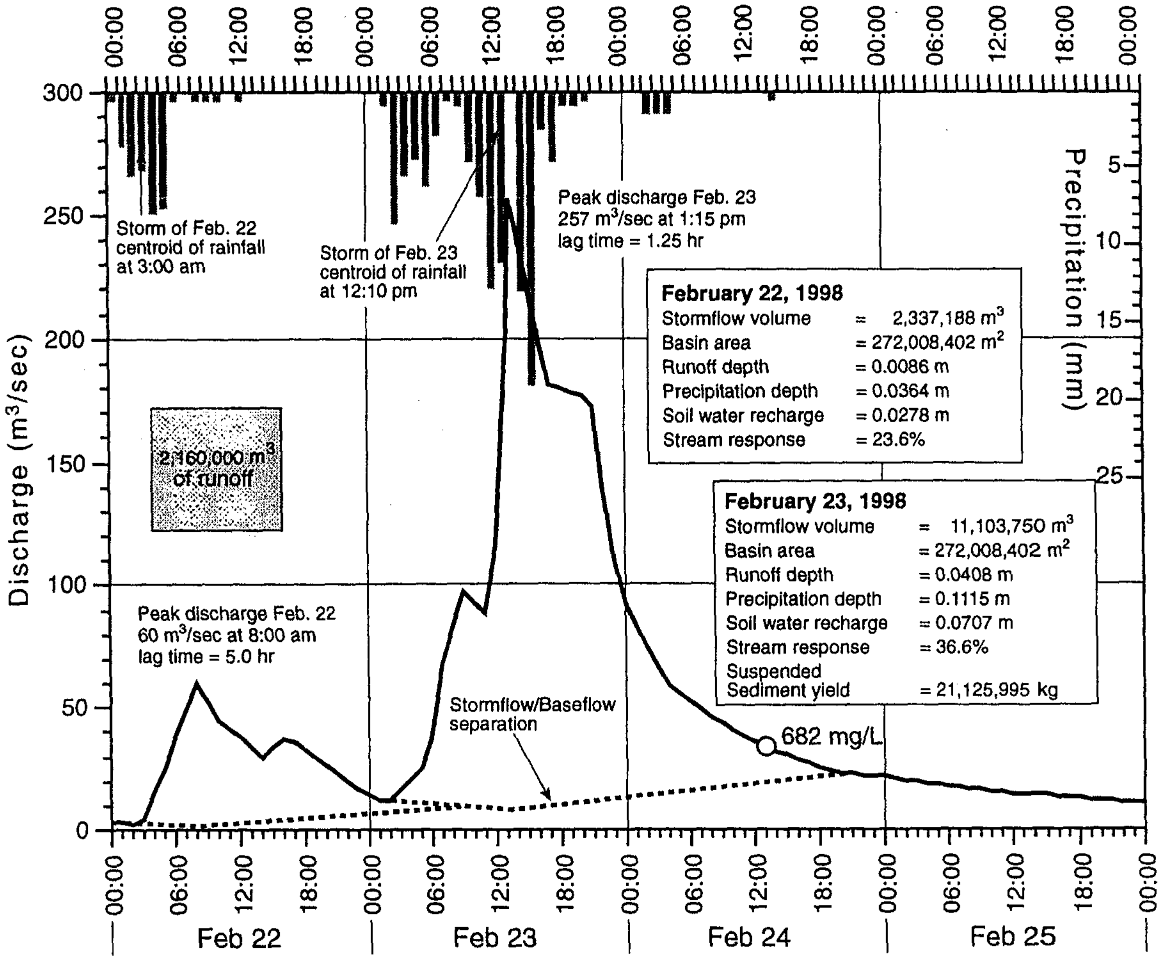
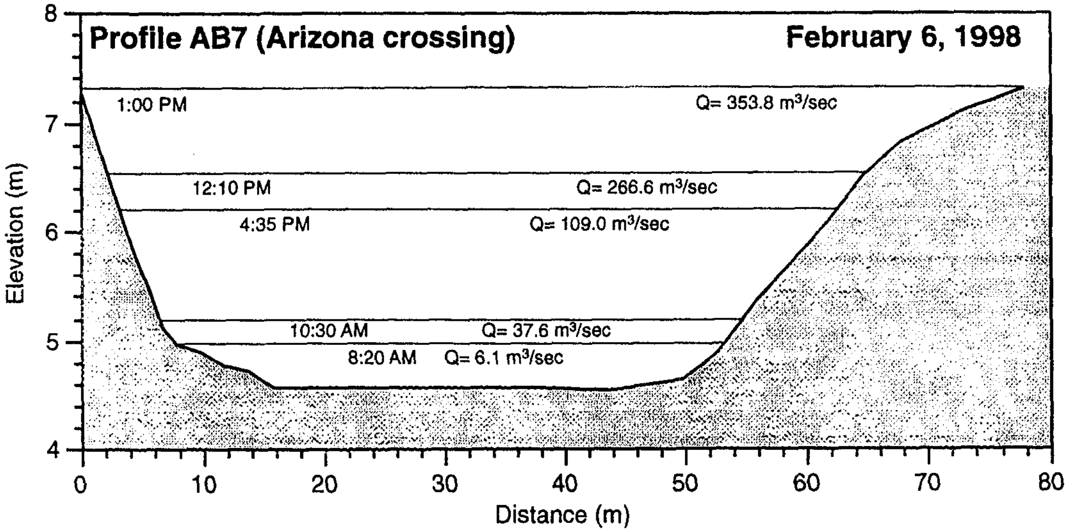


Figure 2-25 Hydrograph and hyetograph, February 22 - 25, 1998



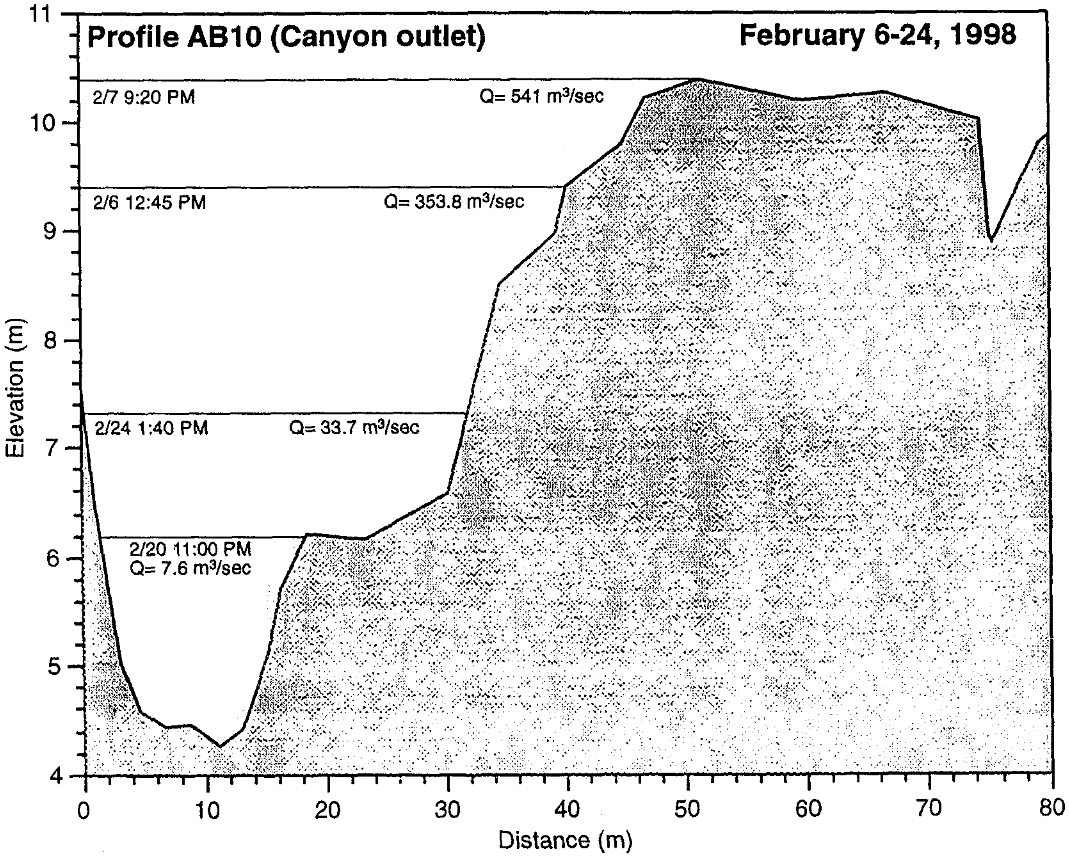


Figure 2-26 Wetted perimters of selected February 1998 stormflows across profiles in lower Malibu Creek

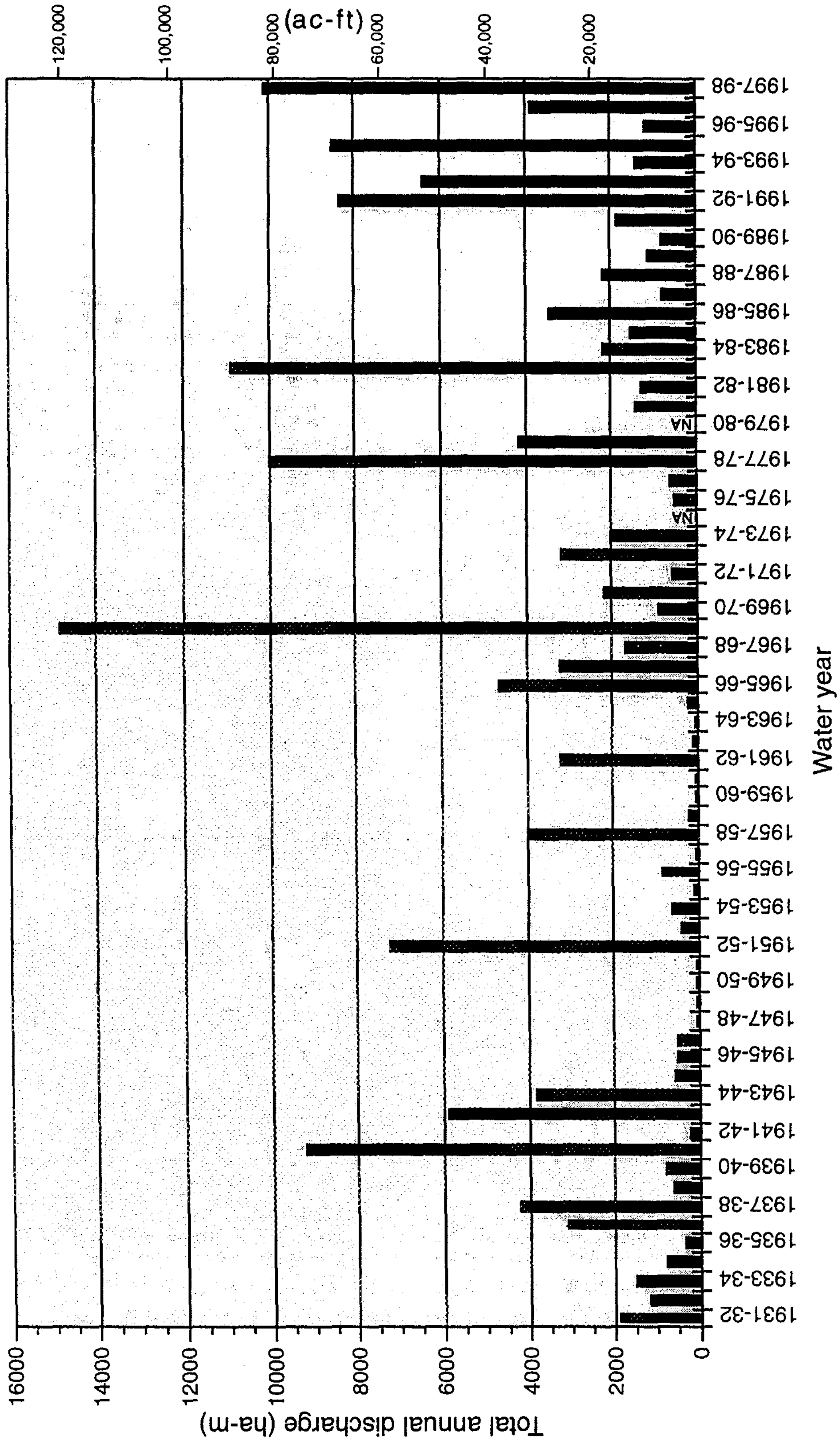


Figure 2-27 Total annual discharge at Malibu Creek

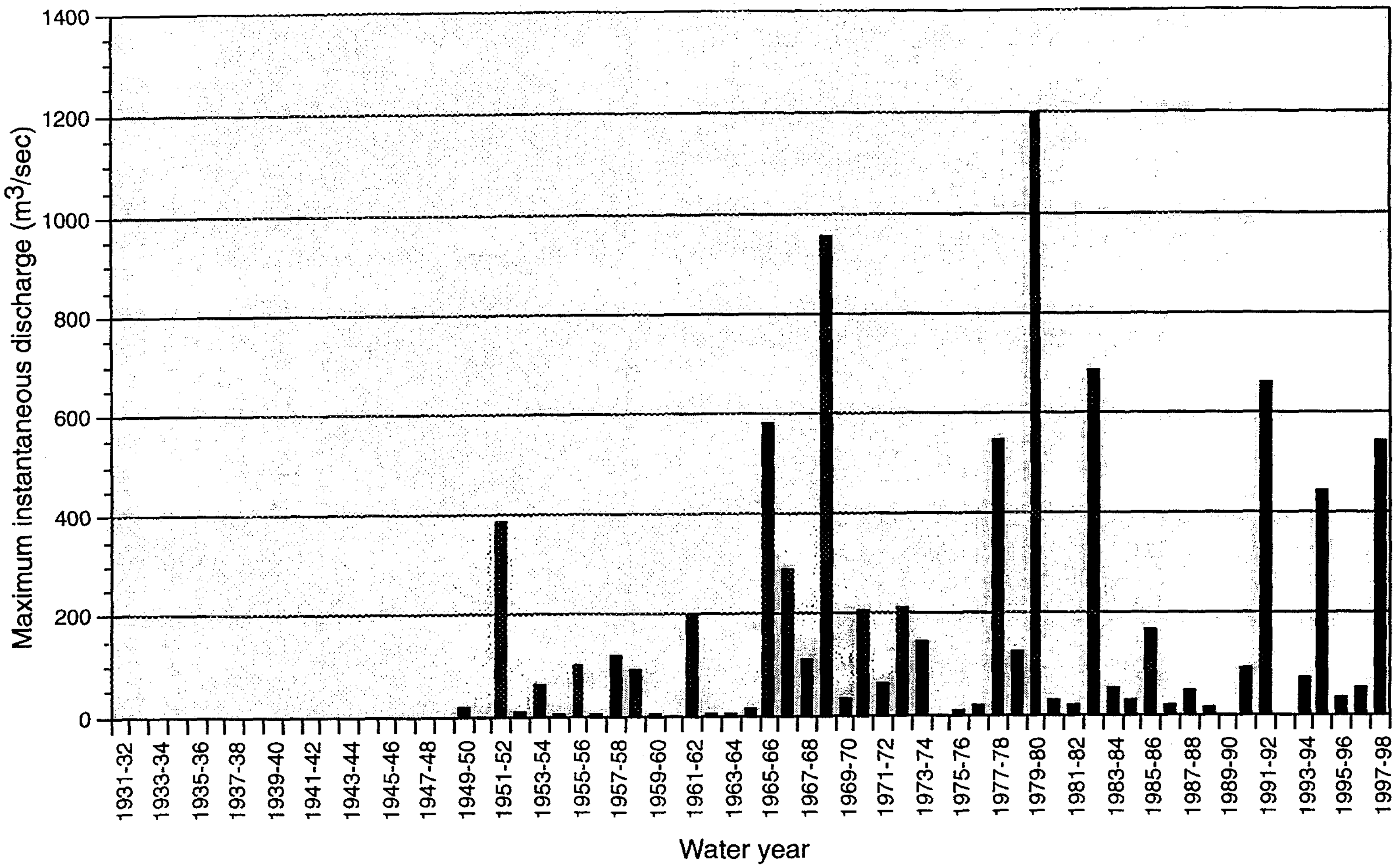


Figure 2-28 Maximum instantaneous discharge at Malibu Creek

Table 2.2
Malibu Creek Gauge Historical Discharge Values

Year	Total Annual Discharge (ha-m)	Total Annual Discharge (ac-ft)	Maximum Instantaneous Discharge (cms)	Maximum Instantaneous Discharge (cfs)	Month of greatest flow	Total Monthly Discharge (ha-m)	Mean Monthly Discharge (cms)	Mean Monthly Discharge (cfs)
1931-32	1873.7	15189.9						
1932-33	1132.0	9177.2						
1933-34	1505.9	12208.6						
1934-35	766.2	6211.8						
1935-36	291.3	2361.3						
1936-37	3078.1	24954.2						
1937-38	4182.9	33911.3						
1938-39	573.8	4651.6						
1939-40	771.2	6251.8						
1940-41	9224.0	74779.6						
1941-42	224.5	1820.2						
1942-43	5857.2	47485.1						
1943-44	3794.8	30764.9						
1944-45	533.1	4321.6						
1945-46	467.4	3789.5						
1946-47	473.6	3839.5						
1947-48	22.2	180.0						
1948-49	11.1	90.0						
1949-50	59.0	478.1	19.1	674	Feb	25.7	0.11	3.8
1950-51	6.9	56.3	0.1	3	Feb	1.1	0.01	0.2
1951-52	7180.3	58211.3	385.1	13600	Mar	3447.7	12.87	454.6
1952-53	361.9	2934.0	9.1	322	Dec	130.4	0.49	17.2
1953-54	615.6	4991.1	63.7	2250	Feb	267.9	1.11	39.1
1954-55	93.5	757.8	1.3	45	May	24.4	0.09	3.2
1955-56	797.5	6465.1	101.9	3600	Jan	455.6	1.70	60.1
1956-57	54.8	444.4	1.3	46	Mar	21.8	0.08	2.9
1957-58	3907.0	31674.6	120.6	4260	Apr	1758.1	6.78	239.5
1958-59	186.5	1511.6	90.0	3180	Feb	103.9	0.43	15.2
1959-60	62.2	503.9	2.4	84	Jan	11.8	0.05	1.6
1960-61	12.3	99.4	0.2	8	Jan	2.3	0.01	0.3
1961-62	3226.0	26153.8	199.9	7060	Feb	2912.6	12.04	425.2
1962-63	86.6	702.2	2.9	104	Mar	21.7	0.08	2.9
1963-64	47.3	383.5	1.8	65	Jan	11.5	0.04	1.5
1964-65	191.7	1554.3	14.8	521	Apr	155.1	0.60	21.1
1965-66	4629.1	37528.7	583.2	20600	Dec	2214.4	8.27	292.0
1966-67	3174.4	25735.2	288.8	10200	Jan	1335.8	4.99	176.1
1967-68	1657.1	13434.0	108.4	3830	Mar	565.2	2.11	74.5
1968-69	14791.5	119916.0	957.0	33800	Jan	10330.5	38.56	1362.1
1969-70	887.6	7196.3	32.6	1150	Mar	427.9	1.60	56.4
1970-71	2134.0	17300.5	209.2	7390	Dec	1079.9	4.03	142.4
1971-72	523.0	4239.7	60.0	2120	Dec	261.0	0.97	34.4
1972-73	3133.2	25401.0	211.8	7480	Feb	1786.0	7.38	260.7
1973-74	1962.6	15911.1	144.4	5100	Jan	1233.3	4.60	162.6
1974-75								
1975-76	481.9	3907.0	9.6	339	Feb	127.7	0.51	18.0
1976-77	614.8	4984.2	16.9	597	Jan	233.6	0.87	30.8
1977-78	9990.6	80995.1	549.3	19400	Mar	4672.0	17.44	616.0
1978-79	4121.9	33416.3	125.1	4420	Jan	1188.2	4.45	157.0
1979-80			1193.9	42170				
1980-81	1212.9	9833.5	25.8	910	Mar	434.9	1.62	57.3
1981-82	1237.5	10032.8	19.1	676	Mar	293.4	1.10	38.7
1982-83	10874.5	88160.4	685.2	24200	Mar	4602.6	17.19	607.0
1983-84	2148.0	17413.8	52.1	1840	Jan	308.7	1.15	40.7
1984-85	1480.6	12003.3	24.9	880	Mar	157.3	0.65	23.0
1985-86	3439.5	27884.4	166.5	5880	Feb	1137.9	4.70	166.0
1986-87	769.4	6237.3	18.5	653	Jan	159.7	0.60	21.1
1987-88	2138.8	17339.6	47.6	1680	Jan	409.1	1.53	53.9
1988-89	1095.0	8877.3	12.5	441	Feb	216.9	0.90	31.7
1989-90	749.4	6075.8			Feb	208.9	0.86	30.5
1990-91	1836.9	14892.2	89.2	3150	Mar	1162.2	4.34	153.3
1991-92	8306.2	67339.3	659.7	23300	Feb	4747.8	18.94	669.0
1992-93	6375.2	51684.7			Feb	3015.5	12.46	440.0
1993-94	1368.4	11093.6	69.4	2450	Feb	546.0	2.26	79.7
1994-95	8475.5	68711.5	444.5	15700	Jan	3109.6	11.61	410.0
1995-96	1159.1	9396.8	34.5	1220	Feb	474.0	1.89	66.8
1996-97	3846.3	31182.2	51.0	1800	Jan	1291.5	4.81	170.0
1997-98	10079.4	81714.4	540.5	19108	Feb	5799.9	23.98	847.0

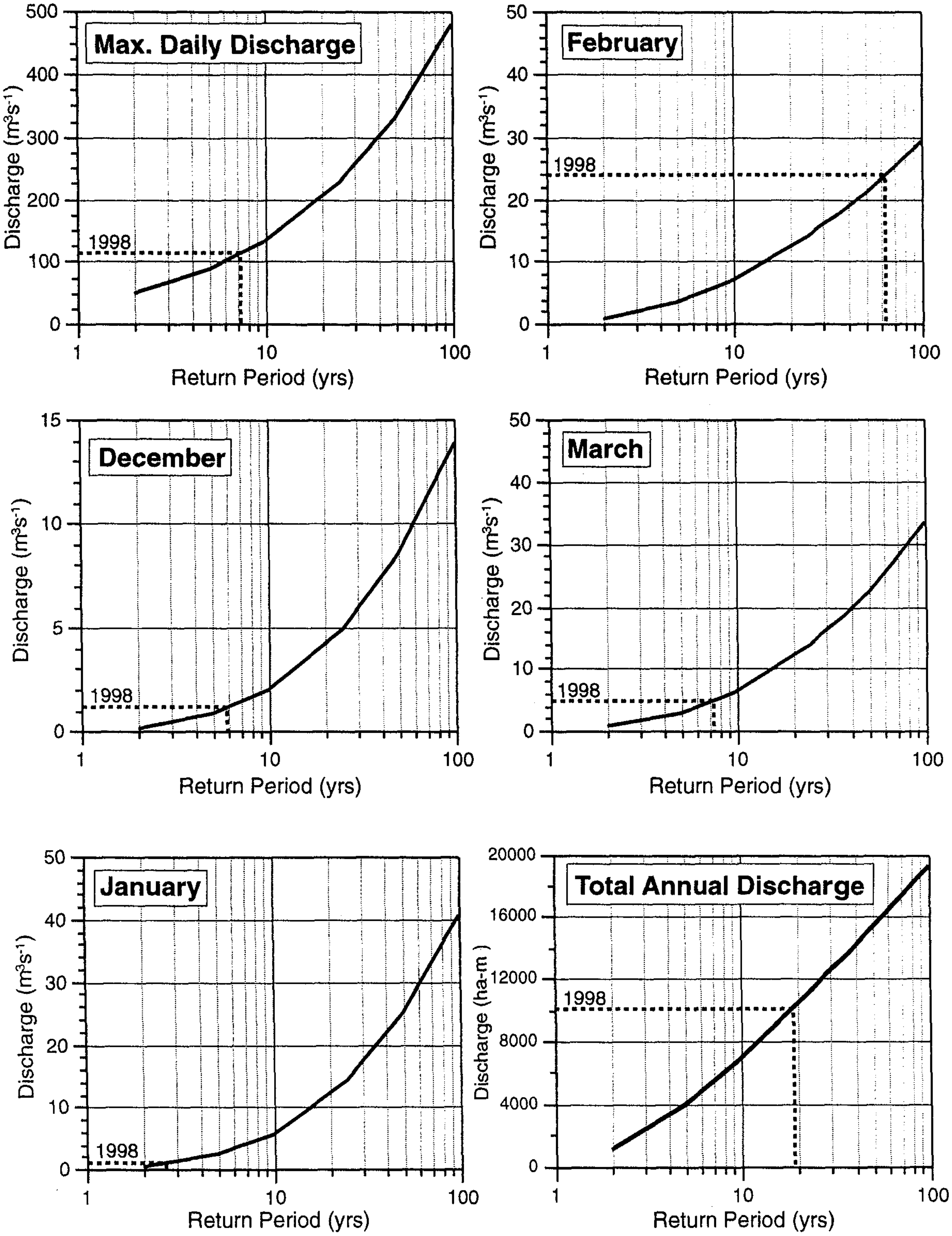


Figure 2-29 Discharge frequency analysis at Malibu Creek

Table 2.3

Sample	Location	Time	Discharge (m^3/sec)	Flow Condition (pre/post peak)	Sample Volume (ml)	Sediment Weight (mg)	Sediment Concentration (mg/L)
Dec. 1 1997	LA Co. gauge (R-13)	1:00 PM	0.74	post	440	82	186.36
Dec. 1 1997	LA Co. gauge (R-13)	1:00 PM	0.74	post	450	85	188.89
Dec. 1 1997	Arizona (R-4)	2:00 PM	0.74	post	300	81	270.00
Dec. 5 1997	LA Co. gauge (R-13)	3:00 PM	0.85	pre	390	200	512.82
Dec. 5 1997	Arizona (R-4)	3:35 PM	1.02	pre	325	130	400.00
Dec. 5 1997	LA Co. gauge (R-13)	4:08 PM	1.05	peak	440	464	*1054.55*
Dec. 5 1997	Arizona (R-4)	4:40 PM	1.05	post	340	122	358.82
Dec. 7 1997	Arizona (R-4)	10:00 AM	0.37	post	370	107	289.19
Dec. 7 1997	LA Co. gauge (R-13)	10:35 AM	0.37	post	415	107	257.83
Jan. 29 1998	Arizona (R-4)	9:20 AM	1.81	pre	340	181	532.35
Jan. 29 1998	Tidal channel at beach	1:22 PM	1.84	peak	395	600	1518.99
Jan. 29 1998	Arizona (R-4)	2:40 PM	7.64	post	415	222	534.94
Jan. 29 1998	Tidal channel at beach	3:20 PM	6.90	post	390	483	1238.46
Feb. 6 1998	Arizona (R-4)	8:20 AM	6.06	pre	360	95	263.89
Feb. 6 1998	Arizona (R-4)	10:30 AM	37.66	pre	432	462	1069.44
Feb. 6 1998	Arizona (R-4)	4:40 PM	107.59	post	380	685	1802.63
Feb. 8 1998	Arizona (R-4)	10:00 AM	33.41	post	415	306	737.35
Feb. 12 1998	Arizona (R-4)	10:30 AM	3.14	post	268	86	320.90
Feb. 20 1998	Arizona (R-4)	10:07 AM	8.04	post	360	103	286.11
Feb. 24 1998	Arizona (R-4)	1:00 PM	33.69	post	408	264	647.06
Feb. 24 1998	Arizona (R-4)	1:00 PM	33.69	post	353	253	716.71
Feb. 27 1998	Arizona (R-4)	2:25 PM	7.13	post	425	107	251.76
Mar. 13 1998	Arizona (R-4)	10:40 AM	3.09	post	439	78	177.68
Mar. 23 1998	Tidal channel at beach	2:33 PM	2.43	post	323	87	269.35
Mar. 26 1998	Arizona (R-4)	12:15 PM	8.95	post	355	92	259.15
Mar. 26 1998	Tidal channel at beach	1:05 PM	8.95	post	455	133	292.31
Mar. 26 1998	Tidal channel at beach	3:05 PM	8.95	post	372	109	293.01
Apr. 1 1998	Arizona (R-4)	1:50 PM	7.05	post	418	96	229.67
Apr. 1 1998	Tidal channel at beach	3:20 PM	7.13	post	360	96	266.67
Apr. 6 1998	Tidal channel at beach	12:30 PM	4.22	post	370	80	216.22
Apr. 6 1998	Tidal channel at beach	1:10 PM	4.22	post	425	82	192.94
Apr. 6 1998	Arizona (R-4)	5:37 PM	4.16	post	390	80	205.13

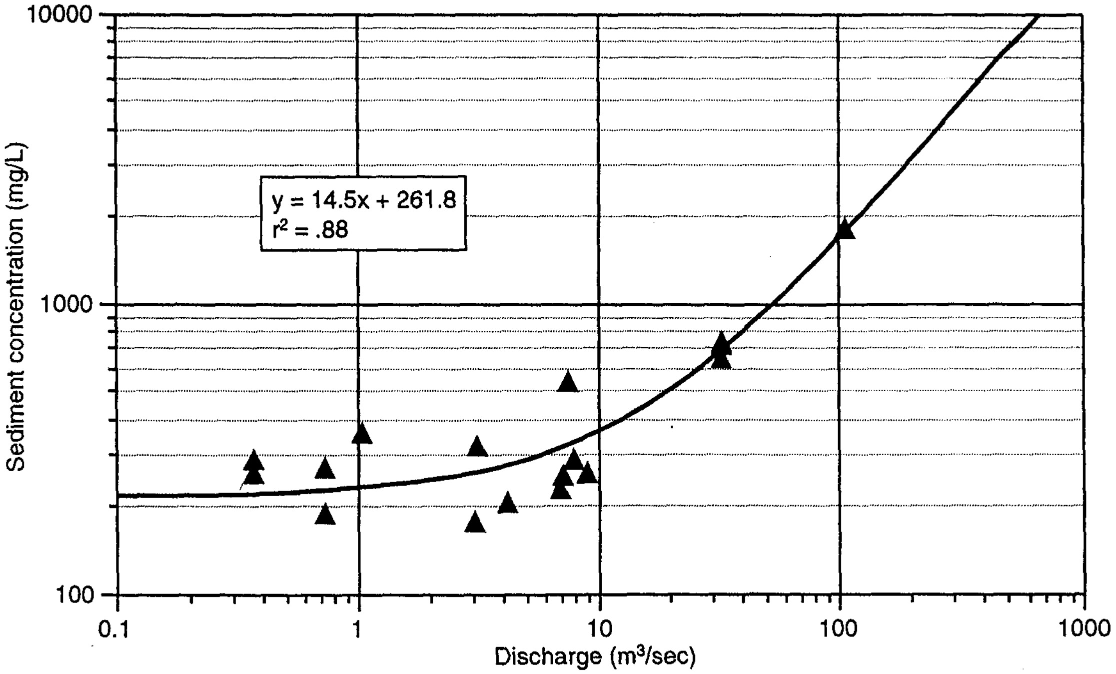


Fig 2.30 Suspended sediment concentration (mg/L) as a function of discharge

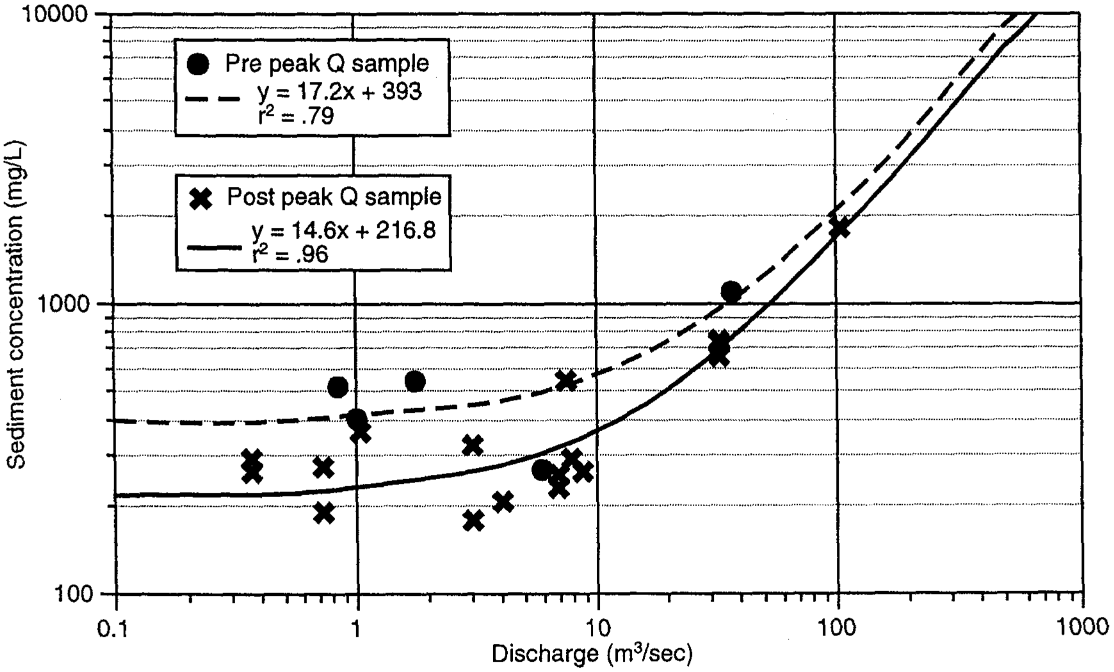


Fig 2.31 Suspended sediment concentration (mg/L) as a function of discharge, distinguished by pre preak discharge and post peak discharge sampling

Table 2.4

Suspended sediment concentrations (mg/L) collected by LVMWD			
Date	R-13 (gauge)	R-4 (Arizona)	R-11 (lagoon)
10/7/97	3.4	1	16.8
11/10/97	1.1	2.2	10
12/1/97	16.8	33.8	70.4
1/6/98	8.2	6.4	18
2/4/98	130	180	170
3/3/98	24	19	20
4/14/98	1.2	5	10.2
5/12/98	4.9	2.8	24.3
6/9/98	3.7	4.3	4.6
7/7/98	1	1	18.5
8/4/98	4	4	6.2
9/1/98	5.6	3.8	11.2

Table 2.5

Suspended sediment concentrations (mg/L) collected by LA Co.		
Date	R-13 (gauge)	
12/5/97	403	
12/18/97	742	
12/21/97	14	
1/9/98	394	
1/29/98	160	
2/2/98	197	
2/6/98	2321	
note- 2/6/98 composite sample taken at 15 min. intervals (9:50 am -2:37 pm)		

2.4 Barrier-Beach Morphodynamics

Under typical Mediterranean-type conditions, the mouth of Malibu Creek varies seasonally between two extremes - from an open estuary during winter flood events to a closed lagoon behind a barrier beach during summer drought. The duration of these extreme states reflects the relative strength and persistence of stream flows from the watershed and of constructive wave power directed against the river mouth from the adjacent ocean basin. A range of conditions exists between these extremes but, normally, the barrier breaches quickly during the first major floods of the winter rainy season and reforms slowly during the following spring and summer dry season. During winter, breaches may be sealed during low flow intervals, only to reopen during subsequent floods. The spring and summer recovery period for barrier reconstruction may occur swiftly with constructive wave activity and minimal creek discharge favoring onshore bar migration, or be delayed by continuing high discharge and destructive wave activity. Closure of the barrier during periods of continuing moderate discharge may also promote high lagoon levels which again breach the barrier, notably during late summers following unusually wet winters. Indeed several cycles of barrier breaching and at least partial reconstruction may occur during a typical year.

The above scenario responds also to tidal forcing from the adjacent ocean, but tidal effects are compensating rather than cumulative. The natural system is, however, confounded by human impacts, ranging from unnaturally high or prolonged creek discharges to mechanical breaching of the barrier when lagoon levels are perceived to be unreasonably high or unhealthy during the later summer. In short, the mouth of Malibu Creek is a dynamic seasonal system subject to a predictable range of natural conditions, confounded by human activity.

Because of their significance to the functions and behavior of Malibu's estuarine lagoon, barrier-beach morphodynamics were examined throughout the 1997-98 water year. This investigation involved frequent monitoring of the changing river mouth and barrier beach, and of environmental factors thought to play significant roles in barrier formation and destruction. Survey techniques involved the use of a Nikon or Topcon total station to measure precise positions, distances, angles, and elevations within the river mouth. The resulting data were then used to generate contour maps and profiles of the changing river mouth and barrier beach. Sediment characteristics were also sampled at frequent spatial and temporal intervals along and across the barrier. Environmental variables evaluated included tidal regime, wave climate, and creek discharge. Although the forces which drive major changes at this land-ocean interface are confounded by human interference and access problems during flood and storm events, the barrier process-response system is relatively easy to understand.

The following discussion focuses on the seasonal morphodynamics of the barrier beach, relates observed changes to forcing environmental variables, and concludes with an interpretation of the system as it evolved during the year. Because of the recurrence of El Niño-Southern Oscillation effects, the 1997-98 water year within the Malibu Creek basin was unusual for its above average precipitation and persistent discharge, but this did not abrogate the detectable principles involved in barrier breaching and reconstruction. The spatial focus of the discussion is the active barrier beach, between the eastern end of the Malibu Colony and Los Angeles County Lifeguard Station No. 2 near the Adamson property east of the estuarine lagoon. Beyond these limits, as discussed in Chapter 1.4, the barrier has been stabilized by housing and related development during the past century, although still prone to wave impacts and high water levels during storm and flood events.

2.4.1 *Seasonal Morphodynamics*

Monitoring of barrier-beach and river-mouth morphodynamics and related environmental variables began on August 15, 1997, focused on the water year, October 1, 1997, to September 30, 1998, and has continued since. For ease of interpretation, the following discussion is based on the 1997-98 water year, on monthly or bimonthly intervals according to the nature of the observed changes, and referenced to selected maps developed from the field surveys. The datum for elevations is the National Geodetic Vertical Datum of 1929 (NGVD), which is 0.80 m above Mean Lower Low Water. Delineation of subaqueous barrier form is based on the marked reduction in slope observed between the barrier and the lagoon floor to landward, and the nearshore bottom bathymetry to seaward. This change in slope coincides with a transition from barrier sand and gravel to lagoonal muds and fluvial gravels to landward, and to finer sands to seaward, although there is also much interfingering of facies. Fluvial gravels from preceding flood events, observable in the nearshore at low tide, provide the foundations for the barrier and these in turn rest westward on shallow, emergent bedrock reefs.

2.4.1.1 October and November 1997

When the water year began on October 1, 1997, the barrier beach had not been breached, either naturally or artificially, for over 100 days. The first detailed survey revealed a subaerial barrier 300 m long, parallel to the shore, and broadening eastward from 75 to 125 m wide normal to the shore (Figure 2-32, October 1997) The barrier beach plan described a shallow arc, convex seaward. Elevations along the barrier descended gradually from 2.5 m in the west to 2 m in the east. The seaward western end of the barrier was steeper and narrower than its broader, more gently shelving eastern end, which did however steepen at the lagoon interface. Shoreface declivity ranged from 0.05 to 0.1. The back-barrier lagoon was shallow, rarely exceeding depths of -0.25 m. The relatively smooth interface of beach and lagoon reflects the absence of overwash lobes and estuarine bars during the preceding weeks.

After 107 days of closure, the barrier was breached on October 12, 1997, probably manually, at its narrowest part at the western end of the active beach. Lagoon waters flowed directly seaward through this breach, incising and widening the outlet through erosion and slumping. Lagoon levels dropped rapidly but, within a few days, outflow velocities decreased and the outlet channel became more sinuous. Thereafter, this channel migrated eastward across the barrier as incident wave action from the south, oblique to the beach face, began moving modest bars onshore and overwash lobes impacted the barrier backslope. The shore-normal alignment of the outlet channel was thus short-lived and was replaced by an increasingly oblique alignment over the next several weeks.

2.4.1.2 <u>December 1997</u>

The breach initiated on October 12 remained open for the remainder of 1997 but migrated progressively eastward in response to incident wave-forcing at the beach face. A repeat survey of December 30, 1997, showed that the outlet channel thalweg had migrated ENE some 200 m, or two-thirds the length of the active barrier, at a net rate of 2.53 m/day over the preceding 79 days (Figure 2-32, December 1997). The 50-m wide outlet channel now exited the estuarine lagoon at a strongly oblique angle. To the west, the reconstructed barrier was 175 m long and 65 m wide, tapering eastward and descending from >2 m to <1 m towards the channel. The eastern beach was 75 m long, 75-85 m wide, reached 2 m over smaller areas due to winnowing, and descended steeply over undercut banks to the outlet channel. Both western and eastern beaches had moderately steep foreshore slopes, from 0.08 on the western beach face to 0.05 on the east. On the landward side of the western beach, a prominent overwash lobe extended lagoonward for 25 m. Excepting the breach, overall beach plan was now linear, the prior convex-seaward arc having been trimmed by storm waves.. The back-barrier lagoon remained shallow, rarely more than -0.25 m, thus limiting the tidal prism as an effective force.

2.4.1.3 <u>January 1998</u>

As the outlet channel continued its eastward migration, it threatened to undermine Lifeguard Station No. 2. Accordingly, on January 9, 1998, lifeguards cut a new breach in the approximate center of the barrier. As anticipated, following its creation, estuarine outflow abandoned the old channel, whose path was subsequently sealed with overwash sand. The new channel in turn began to migrate eastward. No other unpredictable changes occurred during this period.

2.4.1.4 <u>February 1998</u>

In late January 1998, southern California began experiencing the full effects of a series of storms associated with renewed warming of the northeast Pacific Ocean and repeated cyclonic activity related to El Niño-Southern Oscillation. Frequent precipitation events generated abundant basin runoff which in turn increased discharge, often rapidly, towards the mouth of Malibu Creek (see section 2.3 and accompanying figures). Discharge attained several major peaks during early and late February, and continued at modest levels with occasional storm peaks during late winter and spring.

Following heavy basin precipitation on February 3 and again on February 6, 1998, the evening of February 6 saw the Malibu barrier beach completely removed by storm discharge. Initially, the existing channel, which had migrated eastward from its location on January 9, accommodated this early February discharge, widening westward in response to increasing bank erosion. As discharge increased, however, the entire active barrier was swept seaward and its place taken by a friction-dominated estuary.

A repeat survey of February 13, 1998, showed that the active portion of Malibu's barrier beach had largely disappeared, excepting its distal ends, protected in the west by revegetated dunes and in the east by the Adamson property (Figure 2-32, February 1998). On the western end of the former barrier, a small sandy beach remained. This remnant was approximately 50 m long, 75 m wide, rose to 2.5 m, and terminated to the ESE in a small newly constructed lobe, 35 m across but rarely above zero datum. Elevation fell to -0.5 m at the seaward base of this western beach, the slope of which averaged 0.06. The active channel spanned 215 m at its mouth, rising from depths of >-0.50 m in its deeper channels onto several intertidal, middle ground bars that reached above 0.25 m and extended seaward of the former barrier. East of the river mouth, a 50-m wide active beach, arcuate in shape and with a seaward slope of 0.035, was entirely welded onto the backshore.

Almost immediately, however, wave action, tidal forces and associated currents began reworking the sediment and organic debris introduced to the nearshore zone. These processes made little initial impact because of the dominance of stream discharge, but slowly and erratically the materials were reworked into numerous small, discrete subtidal bars, troughs, and hollows. The estuary remained open throughout February and March.

2.4.1.5 March 1998

A repeat survey of March 23-26, 1998, showed that the estuary was still largely open but had been subject to significant and continuing change (Figure 2-32, March 1998). Although the western, dune-protected barrier remnant and the eastern welded beach survived, much modified, a massive longshore bar system had now formed immediately offshore from the former barrier crest, with indications of further subtidal bars to seaward. Although formed in response primarily to the reworking of fluvial sediment by waves and currents, the broad seaward arc of the main longshore bar continued to be shaped by estuarine (stream plus tidal) discharge. Accordingly, the bar crest was discontinuous, reaching above 1.5 m in two insular locations and at its eastern end but separated by four distinct estuarine distributaries. Of the latter, the westernmost, 70 m wide, carried the greatest discharge and was scoured to depths exceeding -0.75 m at the former shoreline. The west-central and east-central distributaries were scoured to depths of nearly 0.25 m and 0.50 m respectively, the more easterly being a sandy shelf which submerged along a broad front at high tide. Although most estuarine discharge passed through the western distributary at all tidal stages, water also passed ENE north of the entire longshore bar system at high water, reaching towards Malibu Pier through the easternmost distributary beyond the former location of Lifeguard Station No. 2. At this stage, although the foundations of a new barrier beach were observable in the discontinuous longshore bar, the system as a whole still functioned as a river-dominated estuary subject to additional tidal forcing and some constriction.

2.4.1.6 April 1998

By the time of the next repeat survey, on April 23, 1998, the nascent barrier observable in March had begun to weld onto the residual face of the former back-barrier beach (Figure 2-32, April 1998). The western remnant of the former barrier had prograded eastward some 65 m, with a beach-face slope of 0.05 and a backslope of 0.04, and ranged from 100 m to 40 m at its distal end which trended ESE as sand sought to close the outlet. The outlet channel was 30 m wide and scoured to -0.5 m at its narrowest point. To the east of this outlet, the earlier longshore bar system was welding to the former backshore towards its eastern end and forming a more continuous barrier farther west. The largely emergent barrier east of the outlet measured 290 m in length, 20-60 m in width, 1.25 m in height, with a beach-face slope of 0.04 to 0.07 and a backslope of 0.02, and descended only 0.75 m into the now shallow outlet channel. The former easternmost outlet towards Malibu Pier had been sealed by barrier welding but the abandoned channel survived as a longshore corridor, 0.25 to 0.75 m in elevation, between the barrier and the backshore. The barrier crest described a broad arc, convex seaward, with a sharper landward inflexion at its western end that had developed as estuarine discharge weakened in face of oblique wave construction from the south. Deposition during a recent tidal cycle had generated a low 4000 m^2 ebb-tidal delta between -0.75 m and -1.0 m off the channel outlet. Modest ebb-tidal and flood-tidal deltas were frequently observed during successive observation periods as tidal forcing moved sediment through narrowing outlets.

2.4.1.7 May and June 1998

The above pattern persisted throughout May and June but the outlet, once it had been restricted to a single channel by barrier growth, began to migrate eastward. In general terms this eastward migration was similar to that observed in late 1997, indicating the recurrence of comparable restorative forces following disruption of the system. In detail, however, the migration pattern was not uniform but marked instead by short-term oscillations in channel angle relative to the barrier, and by distinct "jumps" or episodes of rapid channel movement separated by relatively stable periods when the channel was more or less anchored. This behavior is explained later.

The repeat survey of June 18, 1998, revealed the barrier beach to be firmly in place, landward of its April location, but the outlet channel remained open, though now located centrally to the estuarine lagoon (Figure 2-32, June 1998). The western part of the barrier was 170 m long, 25-45 m wide, and undulated from 0.80 m to 2.10 m in elevation. The eastern part was 180 m long, 25-45 m wide, and from 0.90 m to 1.75 m high. The low narrow passes across the undulating crests of these barrier arms coincided with former estuarine distributaries. From west to east, foreshore slopes ranged from 0.10 to 0.08 , and lagoonward slopes from 0.07 to 0.05. The intervening outlet was 18 m wide and its thalweg, now raised 0.50-0.75 m above datum, dried at low water. However, the landward and seaward ends of this outlet revealed flood-tidal and ebb-tidal deltas, respectively, indicating a continuation of effective tidal currents and estuarine outflow during higher tidal stages. Nevertheless, the deepest part of the adjacent lagoon, almost -1 m below datum, still lay against its western shore, landward of its April outlet now buried beneath beach sand.

2.4.1.8 July 1998

The remaining outlet channel continued to shift erratically eastward during late June and July, until it impinged on and was arrested by the sand mass already welded onto the shoreface by barrier migration. Thereafter, with stream discharge much diminished and tidal influx inhibited by barrier growth, the outlet channel filled with sand. The outlet was finally closed and the barrier sealed during the night of July 31-August 1, 1998. Thus, from its broad opening by floodwaters on February 6, it had taken 175 days for a barrier to reform and seal under prevailing conditions. This type of information is important for the future management of the estuarine lagoon. Additionally, owing to prior human interference with the barrier, the lagoon had maintained some link with the ocean for 290 days, since October 12, 1997.

2.4.1.9 August and September 1998

Once the barrier sealed, the level and volume of water in the lagoon increased progressively, attributable to continuing stream discharge from the basin and to effluent flows from nearby groundwater sources. Water level rose until, at Higher High Water at 13.40 h on August 12, the lagoon was only 10 cm below the barrier crest and the barrier was only 5 m wide. With a further rise of water level, overspill was inevitable and that evening, at 20.30 h the barrier was breached at its western end, more or less in line with the deepest channel thalweg through the lagoon. The lagoon largely emptied within 12 hours revealing the remnants of middle-ground bars from the previous winter's estuary, thinly mantled in mud and other waste. A large ebb-tidal delta formed temporarily on the seaward side of the breach but was progressively reworked by wave action over the next few days. Therafter, for the rest of the water year, the barrier remained breached and the lagoon again responded to a combination of stream discharge, groundwater effluent, and tidal stage (Figure 2-32).

2.4.2 *Environmental Conditions*

The principal environmental variables influencing river-mouth and related beach dynamics are stream discharge, tidal regime, and wave climate. These are now reviewed briefly for the 1997-98 water year, preparatory to evaluation of their impact on barrier morphodynamics.

2.4.2.1 Stream Discharge

Stream discharge from Malibu Creek's upper basin for the 1997-98 water year, as gauged below the Cold Creek confluence, is discussed in section 2.3.2. Because the 12 km^2 canyon section downstream from this gauge represents only a small portion of the 284 km^2 basin and has no significant tributaries, discharge is only modestly increased through the canyon, mainly by direct runoff from steep slopes during and immediately after rain events. Thus the data presented in figures accompanying section 2.3.2 are largely indicative of hydrographs at the river mouth.

In terms of discharge, the 1997-98 water year divided into four principal periods. First, from October 1 through November 9, 1997, discharge of around 0.1 m^3 s^{-1} reflected baseflow contributions from groundwater storage towards the close of the dry season, depleted by evapotranspiration but augmented by undefined discharge from human sources. Second, from November 10, 1997, through January 31. 1998, discharge rose, at times above 1.0 m^3 s^{-1}, responding to less evapotranspiration and several early winter rain events which recharged groundwater and increased throughflow and surface runoff. Third, from February 1 to February 28, 1998, a succession of winter storms increased peak discharge, on three occasions above 350 m^3 s^{-1}, and shed much mineral and organic debris towards the river mouth. Finally, from March 1 to September 30, 1998, the general trend was toward diminishing discharge, offset during March, April and May by modest rain events which served to maintain above-average flow rates into the summer months, even as evapotranspiration reasserted the basin's negative summer water balance.

2.4.2.2 Tidal Regime

Ocean tides at Malibu are mixed and mesotidal with a maximum observed range of 3.22 m since 1933, and of 2.70 m during the 1997-98 water year (Figure 2-33). They are mixed in that the diurnal and semidiurnal constituents common to all tides differ significantly in magnitude locally so that the resultant tidal regime usually has two high waters of different magnitude and two low waters of different magnitude daily. With higher high water normally preceding lower low water, there is a significant seaward gradient between the estuarine lagoon or beach face and the ocean during the larger of the semidiurnal ebbs (Figure 2-33).

Table 2-6 presents tidal elevations for the period 1933-1998 at Santa Monica Pier, 16 km east of Malibu, referenced to Mean Lower Low Water and to the National Geodetic Vertical Datum of 1929 commonly employed for regional surveys and used in this study. The highest observed water level of 2.43 m MLLW occurred during the strong El Niño effect of 1982-83. During the 1997-98 El Niño event, the highest observed water level, in November 1997, reached 2.31 m MLLW, although the predicted highest tide should have been only 2.07 m. The difference was due in part to low atmospheric pressure associated with weak frontal passage. The highest and lowest tides of the 1998 calendar year, 2.16 m and -0.43 m MLLW respectively, are predicted for December 3, 1998, but it remains to be seen whether water levels are augmented or suppressed by ocean-atmosphere forcing.

Based on the 66-year record to date, water levels of 2.43 m and 2.31 m MLLW have recurrence intervals of 100 and 7 years respectively. Whereas such effects are not strictly predictable, it is reasonable to incorporate tidal oscillations of 2.5 m above MLLW into coastal management scenarios, to which should be added the relative apparent secular rise of sea level of 1.8 mm per year, discussed in section 1.4.1, and probable tsunami effects.

The tide wave that generates the above oscillations propagates northward along the California coast. However, because tidal current velocities are directly related to tide amplitude and distance from shore, and inversely related to tide period and water depth, the north-flowing flood current and the south-flowing ebb current are unlikely to exceed 0.03 m s^{-1} immediately off Malibu. In the absence of significant nearshore relief, these modest currents can be ignored for most coastal management purposes, although they may assist other processes in redistributing fine sediment offshore.

2.4.2.3 Wave Climate

Ocean waves range in frequency from tide waves, with periods measured in hours, to capillary waves with periods of <1 s generated by transient surface wind stress. The waves of most importance to barrier-beach formation and destruction are those generated by winds of sufficient duration blowing over water bodies of sufficient fetch to create a wave train. These are the wind waves, with periods usually <10 s, generated by local winds, and swells with periods of 10-20 s which have traveled beyond their source area. The impact of wind waves and swells on the coast is related to ocean wind regime, coastal orientation and nearshore bathymetry, variables that produce the local wave climate.

The wave climate of the California coast is influenced primarily by ocean-atmosphere interaction over the north Pacific Ocean. Clockwise atmospheric circulation around the pulsating Hawaiian high pressure cell and anticlockwise flows around eastward-moving low pressure cells generate most of the storm waves and swells that approach the coast from between

Table 2-6. Tidal Elevations in Meters at Santa Monica, California, 1933-98

	To MLLW	To NGVD
Highest Observed Water Level (January 28, 1983)	2.43	1.63
Mean Higher High Water (MHHW)	1.65	0.85
Mean High Water (MHW)	1.42	0.62
Mean Sea Level (MSL)	0.85	0.05
National Geodetic Vertical Datum of 1929 (NGVD)	0.80	0.00
Mean Low Water (MLW)	0.29	-0.51
Mean Lower Low Water (MLLW)	0.00	-0.80
Lowest Observed Water Level (December 11, 1933)	-0.79	-1.59

Source: NOAA National Ocean Service, Santa Monica station 9410840

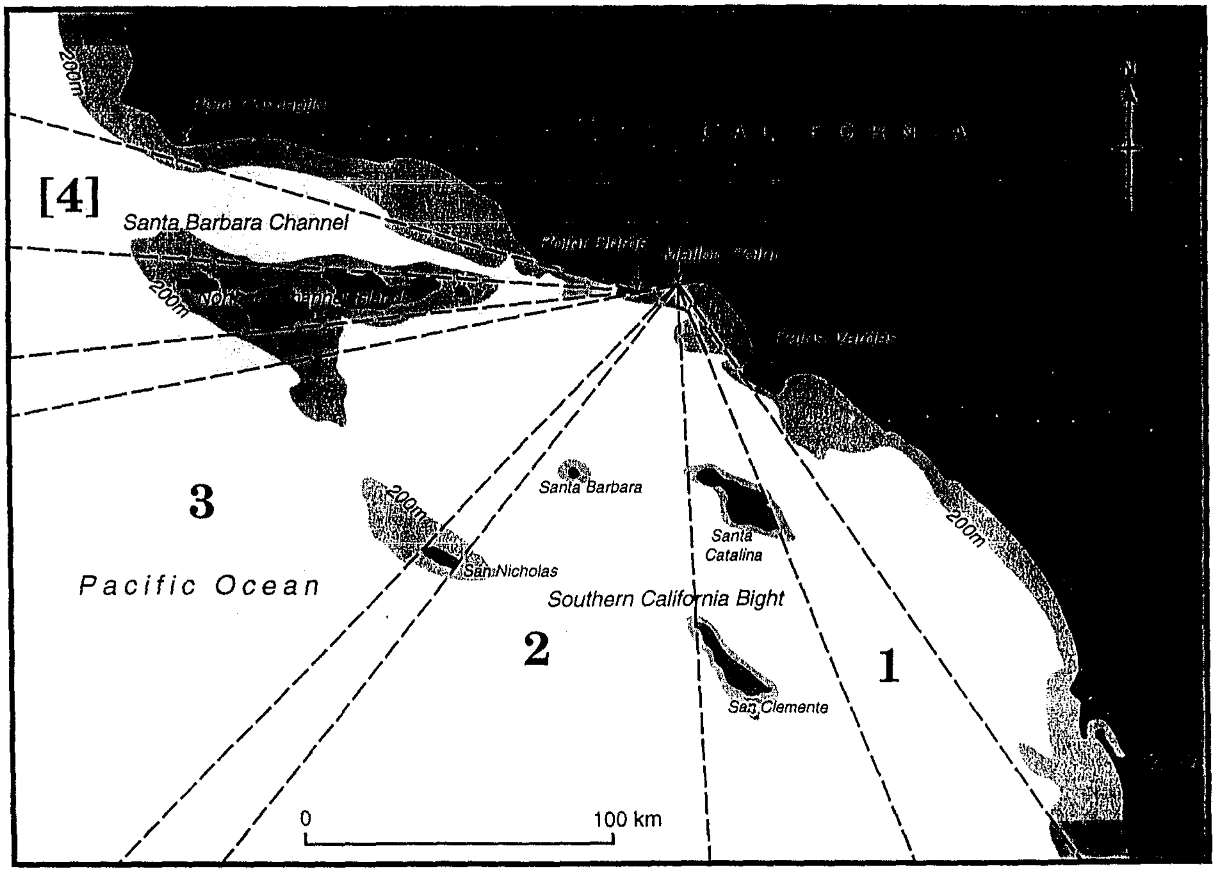


Figure 2-34 Ocean-swell exposure at Malibu. Numbers 1-4 refer to windows discussed in section 2.4.2.3, Wave Climate.

northwest and southwest. Indeed, north of Point Conception, 45% of swells approach from the northwest and a further 45% from west-northwest or west (Orme, 1985). South of Point Conception, however, changing coastal orientation, offshore islands, and complex nearshore bathymetry cause 70% of all swells to pass up the Santa Barbara Channel from due west, while 80% of all swells reaching the Malibu coast approach initially from west-southwest and southwest.

Wind waves and swells also approach the Malibu coast from the south, attributable to three principal forcing mechanisms. First, local storm activity and thermal forcing within the Southern California Bight, up to 100-300 km from shore, may generate wind waves 1-2 m in height with periods of 5-8 s which, superimposed on swells of more distant origin, make for a confused and potentially destructive sea at the coast. Second, from August to November, powerful southerly swells are commonly generated by tropical cyclones that form off the west coast of Mexico and Central America and may grow to hurricane strength before dissipating as they travel northwestward into the cooler waters of the north Pacific Ocean. Exceptionally, as in September 1939, such storms will bring strong winds and high wind waves with 9-11 s periods to the Malibu coast. Third, extratropical storms in the southern hemisphere, forming between Antarctica and New Zealand, generate waves which reach the Malibu coast as low southerly swells with long periods of 15-22 s. Because such storms are strongest and pursue more northerly tracks in the southern winter, these swells are most common locally during the northern summer, although their impact is often masked by swells from other sources. Nevertheless, such swells may cause considerable erosion along south-facing shores, as evidenced by the 10 m breakers of September 1934 and the strong swells of August 1983.

Figure 2-34 shows how swells most commonly approach Malibu. There are four windows of approach between offshore islands and the mainland: **1** between the Palos Verdes peninsula and Santa Catalina Island, **2** between San Clemente and San Nicolas Island, **3** between San Nicolas and the northern Cannel Islands, and **[4]** through the Santa Barbara Channel. Of these, **1** is unimportant because local storms pass swiftly through this narrow window and more distant swells are refracted by the mainland coast. Window **[4]** is also unimportant to Malibu because, although powerful westerly swells and storm waves may progress eastward up the Santa Barbara Channel, most of their energy is expended in refraction and shoaling against the Ventura County coastline, while the offshore islands and Point Dume ensure that little residual energy reaches Malibu. Thus most wave energy is directed through windows **3** and **4**, through a broad expanse of water between south and west that is only slightly modified by San Nicolas Island and its adjacent submarine bank.

Deep-water wave conditions for the 1997-98 water year are illustrated in Figures 2-35 and 2-36. The graphs are derived from data obtained by the

Redondo Beach and Catalina Ridge buoys as provided to the National Data Buoy Center. The Catalina Ridge buoy (46025) lies in water 860 m deep at 33.75^0N and 119.08^0 W, 55 km due southwest of Malibu Point (bearing 225^0 true), on the south margin of window **3** just north of Santa Barbara Island (Figure 2-34). Because it records deep-water waves approaching centrally to Malibu's exposure windows **2** and **3**, it is the preferred buoy for present purposes, but was inoperable from October to December 1997. The Redondo Beach buoy (46045), used for October-December 1997 data, lies in water 77 m deep at 33.84^0N and 118.45^0W, 31 km due southeast of Malibu Point (bearing 135^0 true), and sheltered by the Palos Verdes peninsula and Santa Catalina Island from waves approaching from the south. This buoy does however, provide good proxy information for waves approaching through windows **2** and **3**. The graphs refer specifically to significant wave height (H_s), the highest one third of all wave heights during successive 20-m sampling intervals, and dominant wave period (T_d), the period with maximum wave energy.

Data on significant wave height and period are the preferred indicators for defining the magnitude and frequency of deep-water wave energy approaching Malibu, subject to refraction and shoaling by coastal orientation and nearshore bathymetry. This modified energy is in turn directed against the nearshore approaches and seaward face of the Malibu barrier beach, redistributing nearshore sediment and constructing or eroding the shoreface. Predictably, there is much noise in the data, attributable in part to the merging or crossing of two or more wave trains of differing characteristics, and to local wind effects. Nevertheless, some important generalizations may be made.

In terms of significant wave height and wave period, the 1997-98 water year may be divided into ten intervals, each of which could be anticipated to yield a distinctive response at Malibu (Figures 2-35 and 2-36).

(1) October 1 - 13, 1997, saw continued late summer swell activity with two episodes of short-period 5-10 T_d swells approaching 3 m H_s attributable to tropical cyclone forcing off western Mexico.

(2) October 14 - November 8 was a quiescent interval with H_s <1 m and waves of variable T_d.

(3) November 9 - December 9 was a more variable interval with H_s of 2-3 m and T_d of 10-15 s as swells generated by north Pacific storms and weak fronts reached the coast. Storm passage saw wind waves of 5-10 s T_d and 2.5-3 m H_s.

(4) December 10 - January 3, 1998, saw the return of relatively quiescent conditions with the approach of mostly low, relatively long-period swells.

(5) January 4 - 29 witnessed a trend towards increasing wave height of around 2-3 m H_s and 15 s T_d as mid-winter storm activity became well established over the north Pacific Ocean.

(6) January 30 - February 28 represented a month of frequent local wind-wave activity superimposed onto larger swells related to repeated storm generation. Hs reached 4-5 m on several occasions with T_d ranging around 10-15 s, with a brief lull February 9-13 between storms. Impacts at the coast were, however, muted because these waves were superimposed in turn on relatively low high water levels (averaging 1.98 m MLLW) and significantly lower low water levels (averaging -0.31 m MLLW). Although these relationships are complex, it appears that the peak high water levels associated with El Niño had already passed during the preceding four months, unlike the 1982-83 El Niño event when peak high water levels coincided with peak winter storm wave activity.

(7) March 1 - April 13 saw a return to more variable conditions with higher shorter waves, of H_s locally >3 m and T_d <10 s, associated with late winter storms, notably from March 24 to April 4.

(8) April 14 - June 3 saw a relaxation of wave energy as early summer conditions became established in the relative absence of strong storm activity in the north Pacific Ocean. Weak frontal activity was reflected in low peaks in the wave spectrum but these never exceeded 3 m H_s.

(9) June 4 - August 15 was represented by high summer conditions with modest long period swells of <1 m H_s and 15-20 s T_d most typical, interrupted occasionally by shorter-period effects probably attributable to merging wave trains from distant sources, including the southern hemisphere.

(10) August 15 - September 30 saw the cycle close with a return to conditions typical of interval 1 when tropical cyclone activity off western Mexico again superimposed higher swells onto the modest long-period swells of summer.

The above outline is useful because several intervals more or less coincide with precipitation events, and thus with storm forcing of both the local wave climate and discharge regime. The water year could be further simplified into three intervals - the February period of frequent strong storms, high waves, and abundant discharge, preceded and followed by more variable or quiescent conditions. The wave climate is unrelated to the tidal regime.

Finally, no tsunami effects were observed locally during 1997-98. Indeed the probability of damaging tsunamis along the Malibu coast is small, owing to the east-west coastal orientation away from primary tsunamigenic foci in the north Pacific Ocean, and to the protection afforded by offshore islands. Though more exposed to events generated in the south Pacific, a long travel distance ensures that such tsunamis would have impacts similar to southern hemisphere swells. Tsunami run-ups of 1.5-3 m and 5 m have predicted recurrence intervals of 100 and 500 years respectively. The probability of locally generated seismic sea waves or landslide-induced water waves remains, related to submarine disturbances in the Southern California Bight, but no unambiguous historic record exists for such events.

2.4.3 Morphodynamics in Environmental Context

Stream discharge and tidal regime form the principal components of the river mouth's water budget, augmented by gains from wave overwash and groundwater effluent, and depleted by losses to evapotranspiration and groundwater recharge. When gains from stream inputs, flood tides, wave overwash and groundwater effluent exceed losses, water levels rise within the estuarine lagoon and, given sufficient gradient to the ocean, a net seaward flow results. In the absence of a barrier beach, water flows directly seaward, its velocity influenced by hydraulic gradient, namely its head relative to tidal stage. With a partial barrier, flow is constrained by breach dimensions and falling water level may lag behind falling tidal stage. Outflow then reshapes the hydraulic geometry of the outlet channel in association with incident wave energy and tidal forcing until some form of dynamic equilibrium develops between flow conditions and channel shape. With a continuous barrier beach, the estuarine lagoon fills with water until the head is sufficient to overtop and breach the barrier. Assuming that a continuous barrier blocks tidal inputs, if stream inputs, wave overwash and groundwater effluent are less than evapotranspiration from the estuarine lagoon, the lagoon may eventually desiccate, although this is presently unlikely owing to the discharge of imported water. Salt-water influx beneath the barrier crest elevates fresh and brackish water levels in the lagoon, further complicating the water budget.

The barrier beach is thus critical to the behavior of the river-mouth system as a whole. Its presence inhibits the exchange of water between the lagoon and the ocean. Its absence facilitates such exchange. Its many intermediate states, representing a wide spectrum of possible outlet geometries, generate a comparable range of exchange conditions. This discussion defines the range of barrier morphodynamic states measured relative to environmental variables during the 1997-98 water year, including the propensity for positive and negative feedback within the system. The discussion focuses on barrier states and beach-face behavior. The morphodynamics of the tidal channel and the variable-exchange scenarios across and through the barrier between the ocean and the lagoon are discussed in Section 2.5 and illustrated in Figures 2-37 through 2-50 and in Table 2.7.

During the 1997-98 water year, the Malibu barrier beach exhibited one of seven morphodynamic states at any one time, namely stationarity, onshore migration, longshore migration, seaward progradation, beach-face erosion, partial breach, or wholesale removal. This may be regarded as a spectrum of possible scenarios, even a cycle, that begins with removal of a prior barrier and ends with establishment of a new barrier that remains in place until removed by subsequent floods or storm waves. In reality, the barrier is rarely stable and human activity can severely disrupt the cycle.

Stationarity implies a barrier in equilibrium with environmental forces. It is associated typically with low wave energy, neap tidal conditions, and prolonged absence of stream discharge. Storm waves are absent and low swells typically dissipate on the nearshore rock and cobble, reaching the shore as low ineffective surges that are reflected from the beach face. Except for brief intervals in early October 1997 and early August 1998, this state was rarely seen during the 1997-98 water year because stream discharge always threatened barrier integrity. Such a condition could develop during a prolonged drought but enhanced runoff from urbanization in the upper Malibu basin now renders this scenario unlikely.

Onshore migration implies landward construction of the barrier under the influence of constructive high magnitude, long period waves during high tidal and minimal discharge stages. Nearshore dissipation of wave energy is insufficient to prevent onshore sediment transport by spilling breakers and related currents, resulting in overwash during higher tidal stages. As sediment is removed from the beach face to the landward side of the barrier, the net result is onshore barrier migration. This condition was observed frequently during 1997-98, for example after the breaching events of mid-October 1997 and mid-August 1998. More significantly, onshore migration of nearshore longitudinal bars was partly responsible for the gradual formation of the new barrier during the spring and early summer months of 1998.

Longshore migration implies a net downdrift movement of barrier form under the influence of wave, tide, and discharge conditions similar to those associated with onshore migration, but with the added component of an effective littoral drift promoted by strong wave refraction. Whereas longshore migration is apparent in the migration of tidal channels through the barrier, it also involves the slow net movement downdrift of part of the barrier mass, compensated by updrift replenishment. This condition was demonstrated during the 1997-98 water year by the migration of the October 1997 tidal channel between October 12 and January 9, 1998, by the migration of the January 9 mid-barrier breach during the remainder of that month, by the episodic downdrift migration of estuarine outlets in spring and early summer 1998, and by the migration of the August 12, 1998, breach.

Seaward progradation of the barrier occurs under the influence of constructive low magnitude, long period waves associated with neap tidal stages. Sediment is moved onto the beach face but not removed farther. If Malibu Creek discharges modestly through the barrier, fluvial debris is added to the nearshore sediment supply. This condition was rare during the 1997-98 water year, occurring briefly towards the barrier's eastern end between longer periods of onshore and longshore migration, notably in June and July 1998.

When beach-face erosion is the corollary of onshore migration there is little or no net change in barrier mass. The barrier simply migrates en masse. However, when beach-face erosion occurs against a stationary barrier, a net loss of mass occurs. This condition is favored by destructive high magnitude, short period waves, especially by plunging breakers at higher tidal stages. Sediment is removed from the beach face, either into offshore bars, in which case negative feedback dampens subsequent wave impacts, or downdrift in which case positive feedback prolongs the loss of mass. Whereas small beach-face changes occur more or less continuously, more prolonged erosion was noted mainly during June and July 1998 when the western barrier beach face was severely eroded by a secondary circulation cell and the material removed downdrift (Figure 2-32). This effectively narrowed the barrier here and set up conditions favorable for breaching on August 12, 1998.

A partial breach of the barrier may occur during storm-wave activity but, owing to the active barrier's sheltered location in the lee of a rock and cobble reef, this is rare. More commonly, breaching occurs as a result of high lagoon levels associated with continued discharge into the lagoon behind a continuous barrier. Such breaching may also be encouraged by human interference. Whatever the cause, the resultant breach will remain open while there is sufficient discharge from the lagoon to counter constructive wave activity at the beach face. During the 1997-98 water year, the barrier was partially breached on three occasions, artificially on October 12 and January 9, and naturally as a result of high lagoon levels on August 12. A partial breach effectively relieves pressure and thixotropic potential on the landward side of the barrier, and flushes barrier and lagoonal sediment into the nearshore zone where it may be available for transfer back to the beach face. A partial breach thus causes fairly rapid morphological changes along the entire beach face while the system seeks a new dynamic equilibrium.

Wholesale removal of the barrier typically accompanies major flood discharges and occurs to a greater or lesser extent during most winters with at least average precipitation. As previously noted, during the 1997-98 water year, wholesale removal of the remaining partial barrier occurred on February 6 and a new barrier was not sealed across the estuary until July 31, 1998. The dimensions of the removed sediment, or conversely of the estuary thus formed, are mostly a function of the magnitude of discharge. The duration of the estuarine state is a reflection of flood frequency and persistence in the face of constructive wave and current activity.

Under prevailing conditions, with enhanced discharge from the upper Malibu basin, it is likely that the barrier will be more unstable than in the historic past. Whereas the variability of the wave climate, current conditions, and tidal forcing have not changed significantly, discharge into the lagoon has probably become more persistent, leading in turn to more frequent natural breaching or the perceived need to breach more frequently.

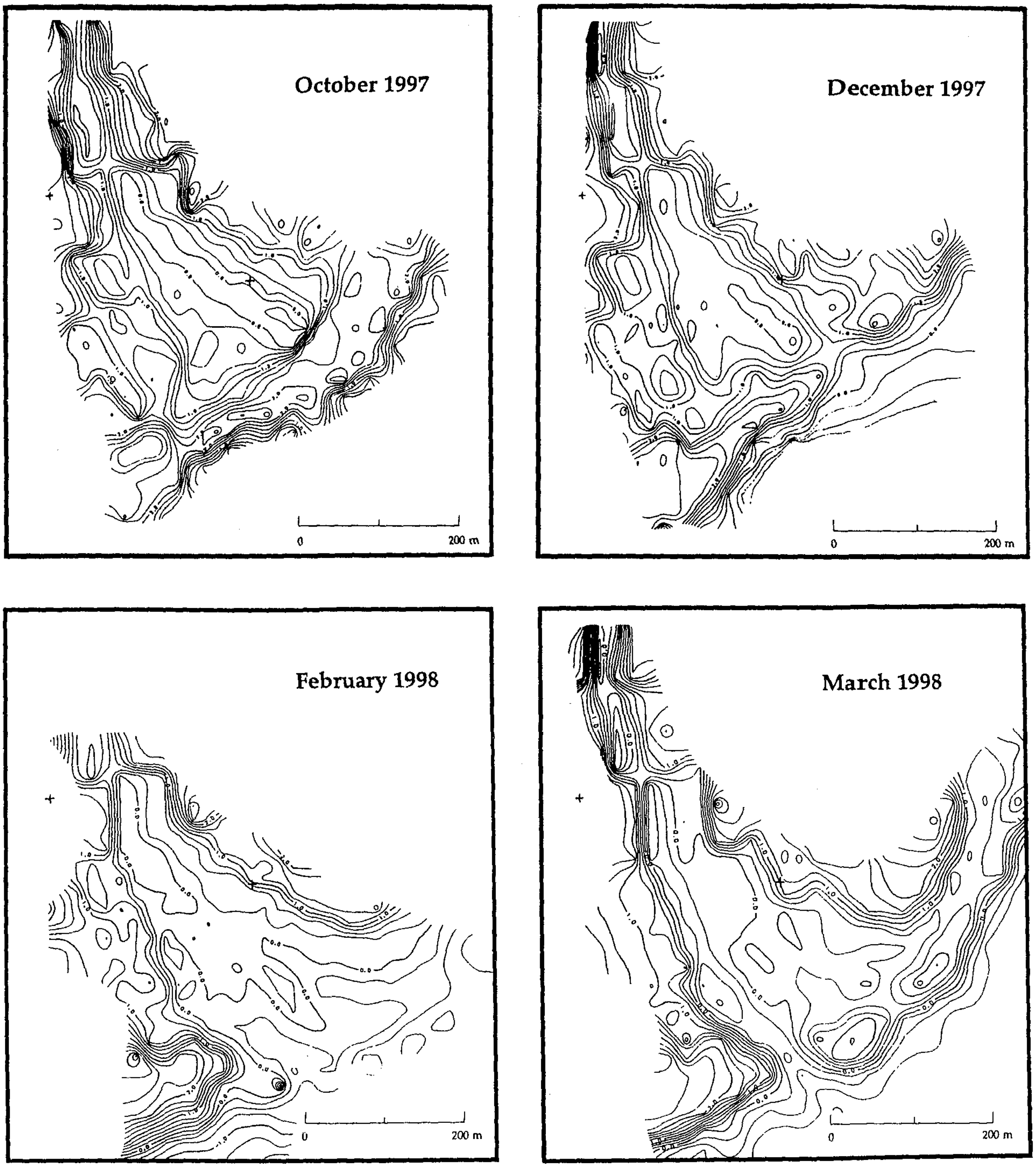


Figure 2-32 Seasonal morphodynamics of Malibu barrier beach and estuarine lagoon during 1997-98, based on repeat surveys. Contours are drawn at 0.25 m intervals above and below zero datum (NGVD 1929).

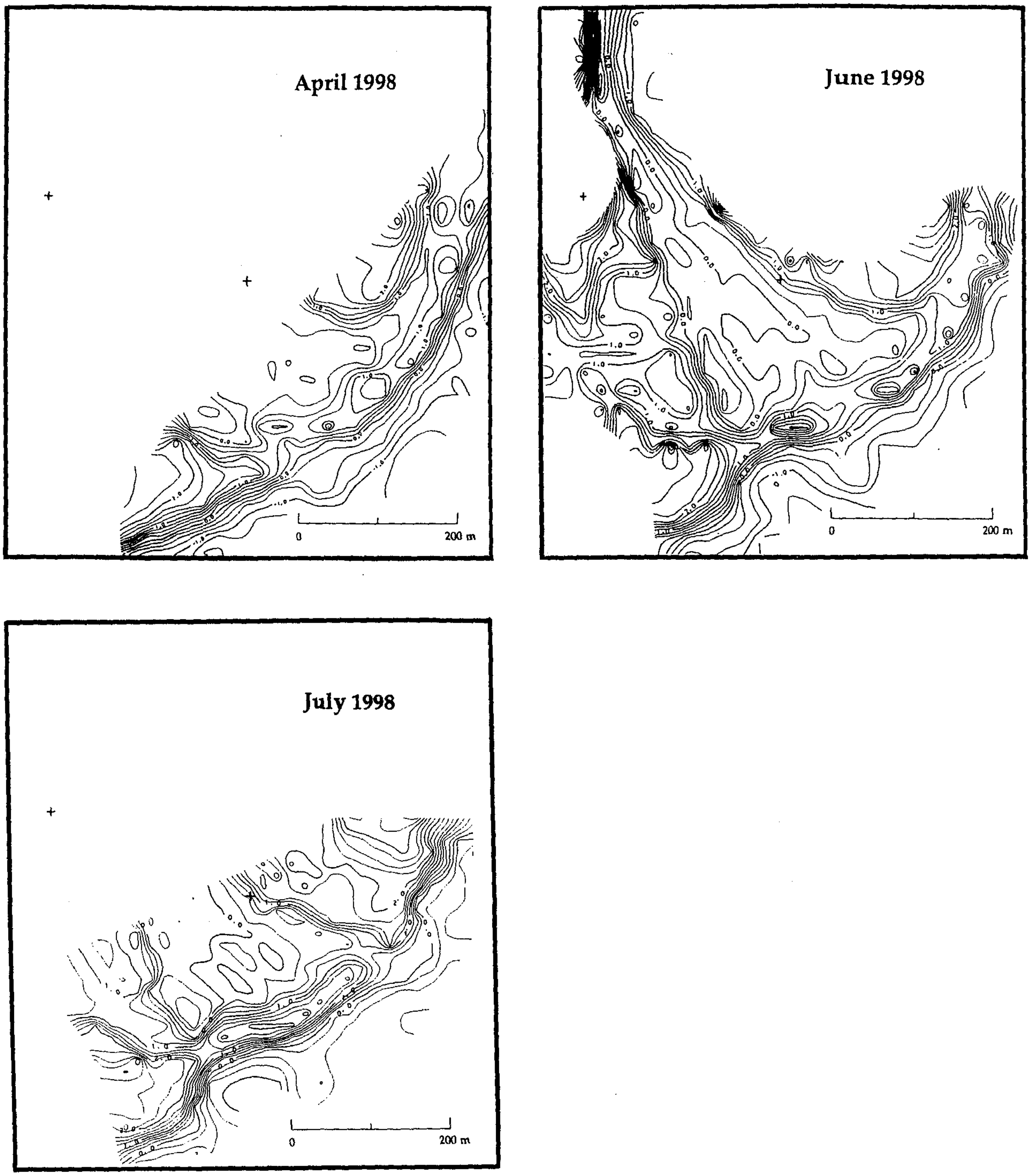


Figure 2-32 (continued) Seasonal morphodynamics of Malibu barrier beach and estuarine lagoon during 1997-98, based on repeat surveys. Contours are drawn at 0.25 m intervals above and below zero datum (NGVD 1929).

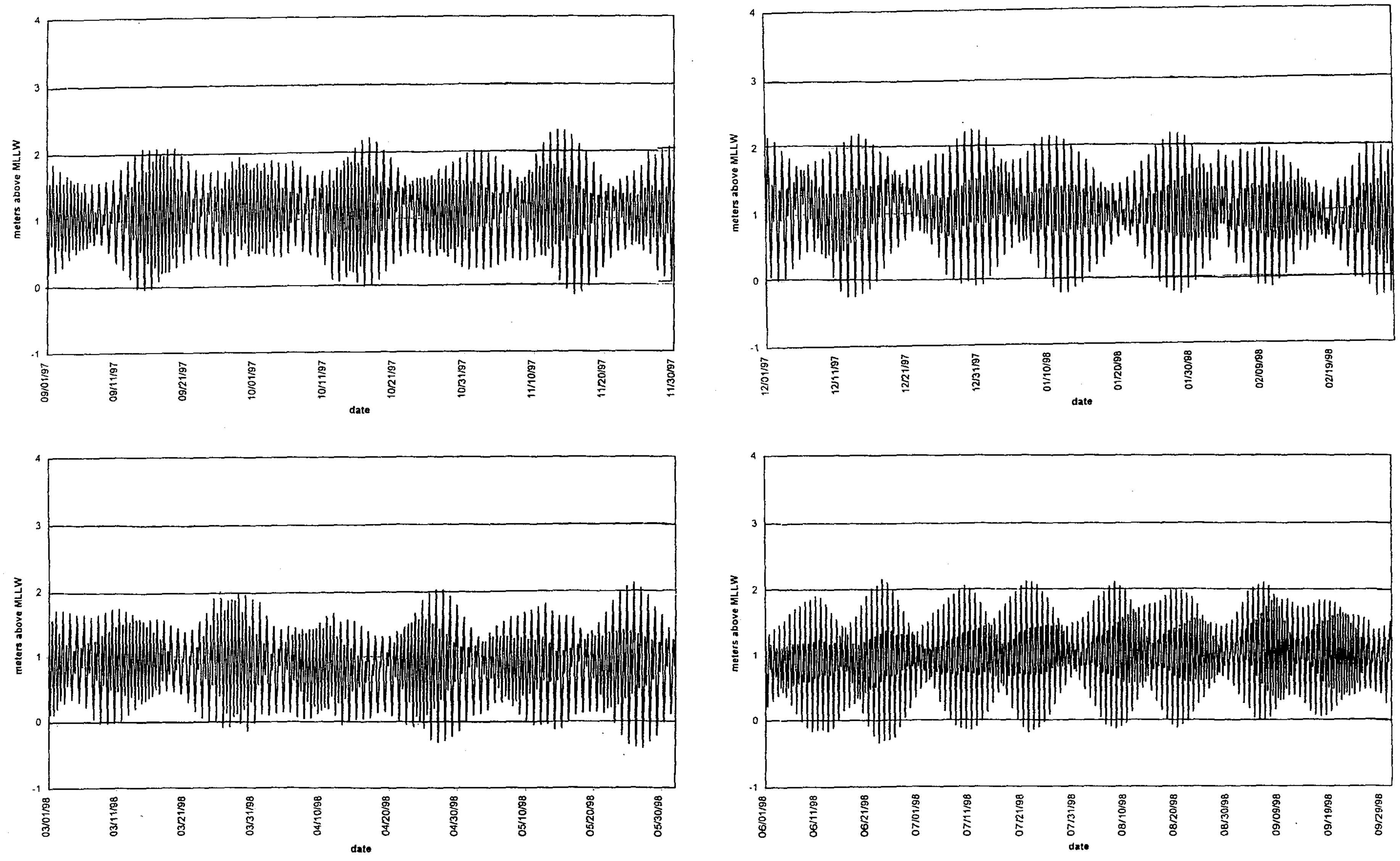


Figure 2-33 Ocean levels for 1997-98 water year observed at the tide-gauge station maintained by the National Ocean Service at Santa Monica Pier. Zero datum is Mean Lower Low Water (-0.80 m NGVD 1929).

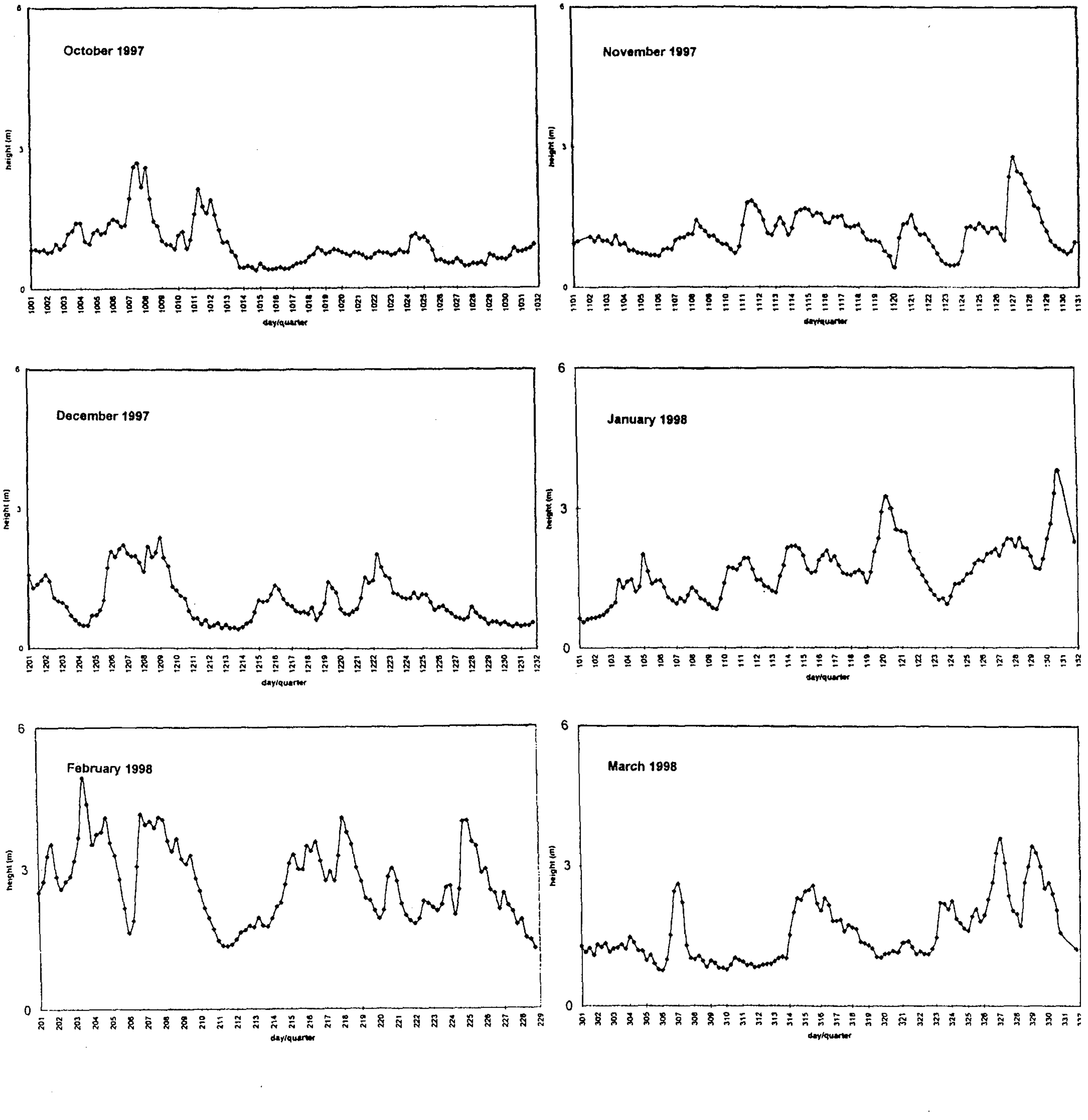


Figure 2-35 Significant deep-water wave heights recorded off the Malibu coast during the 1997-98 water year (courtesy National Data Buoy Center). Data for October-December 1997 are derived from the buoy off Redondo Beach (46045), and for January-September 1998 from the Catalina Ridge buoy (46025, inoperable during the preceding period).

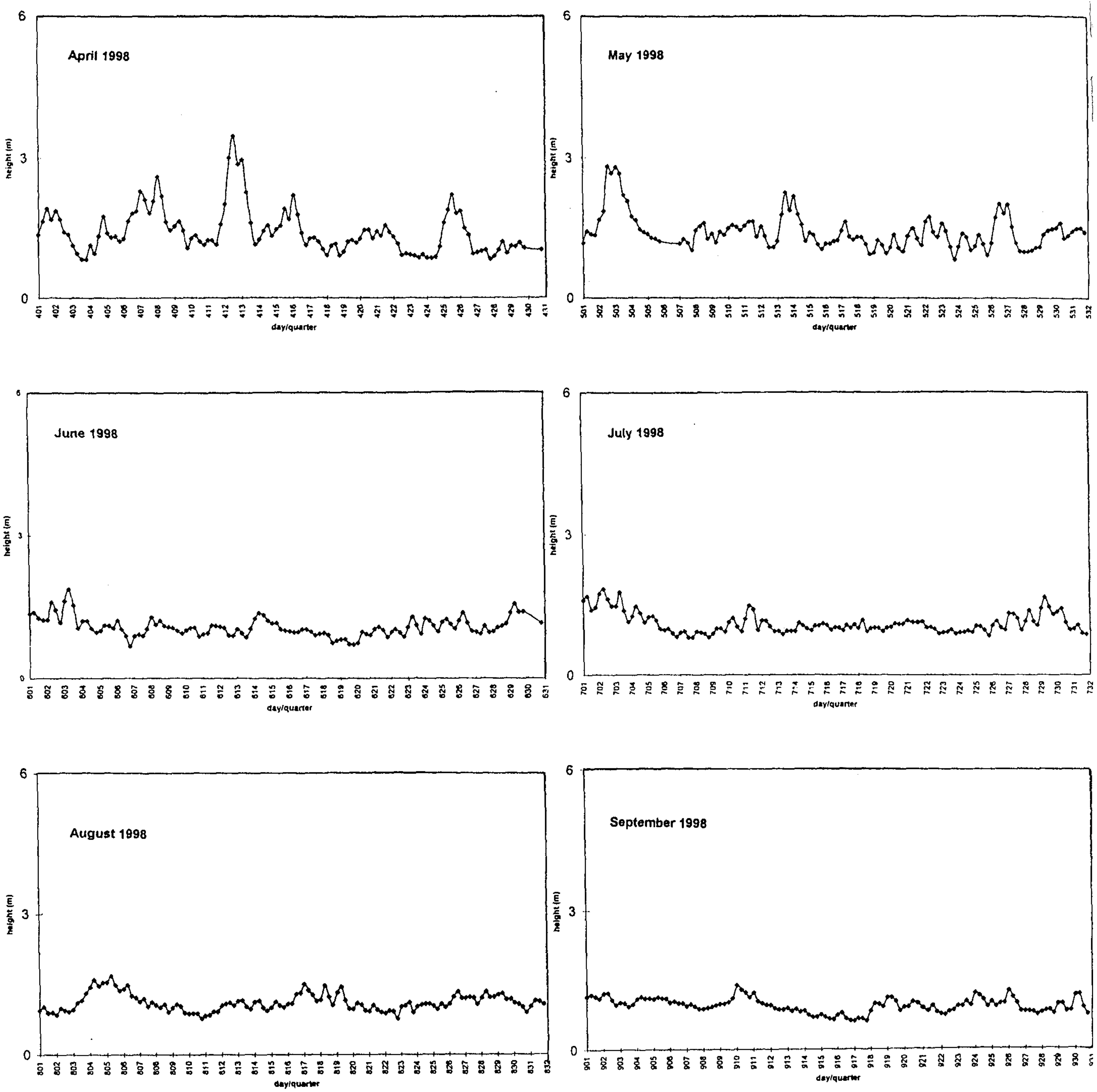


Figure 2-35 (continued) Significant deep-water wave heights recorded off the Malibu coast during the 1997-98 water year (courtesy National Data Buoy Center). Data for October-December 1997 are derived from the buoy off Redondo Beach (46045), and for January-September 1998 from the Catalina Ridge buoy (46025, inoperable during the preceding period).

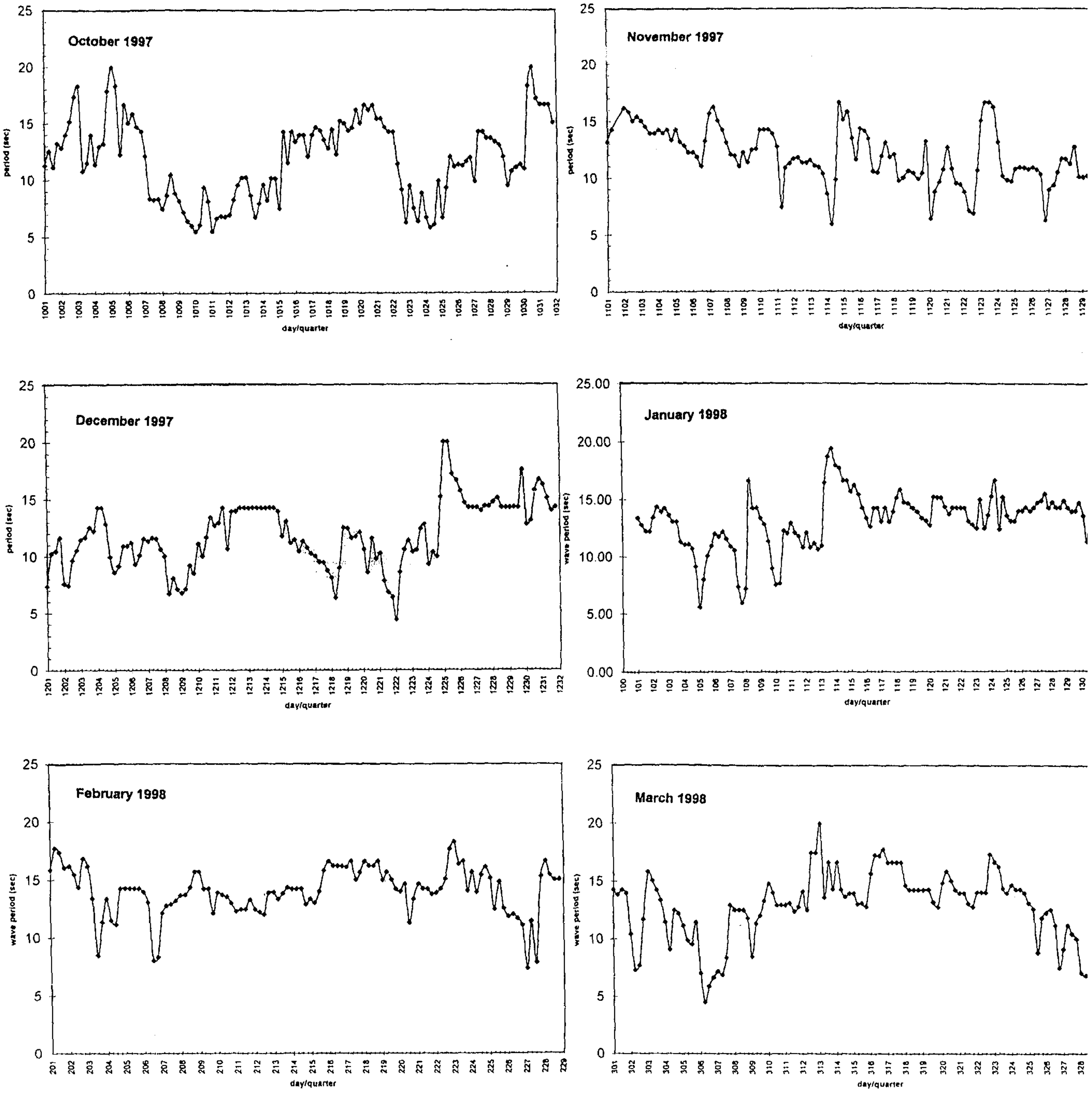


Figure 2-36 Dominant deep-water wave periods recorded off the Malibu coast during the 1997-98 water year (courtesy National Data Buoy Center). Data for October-December 1997 are derived from the buoy off Redondo Beach (46045), and for January-September 1998 from the Catalina Ridge buoy (46025, inoperable during the preceding period).

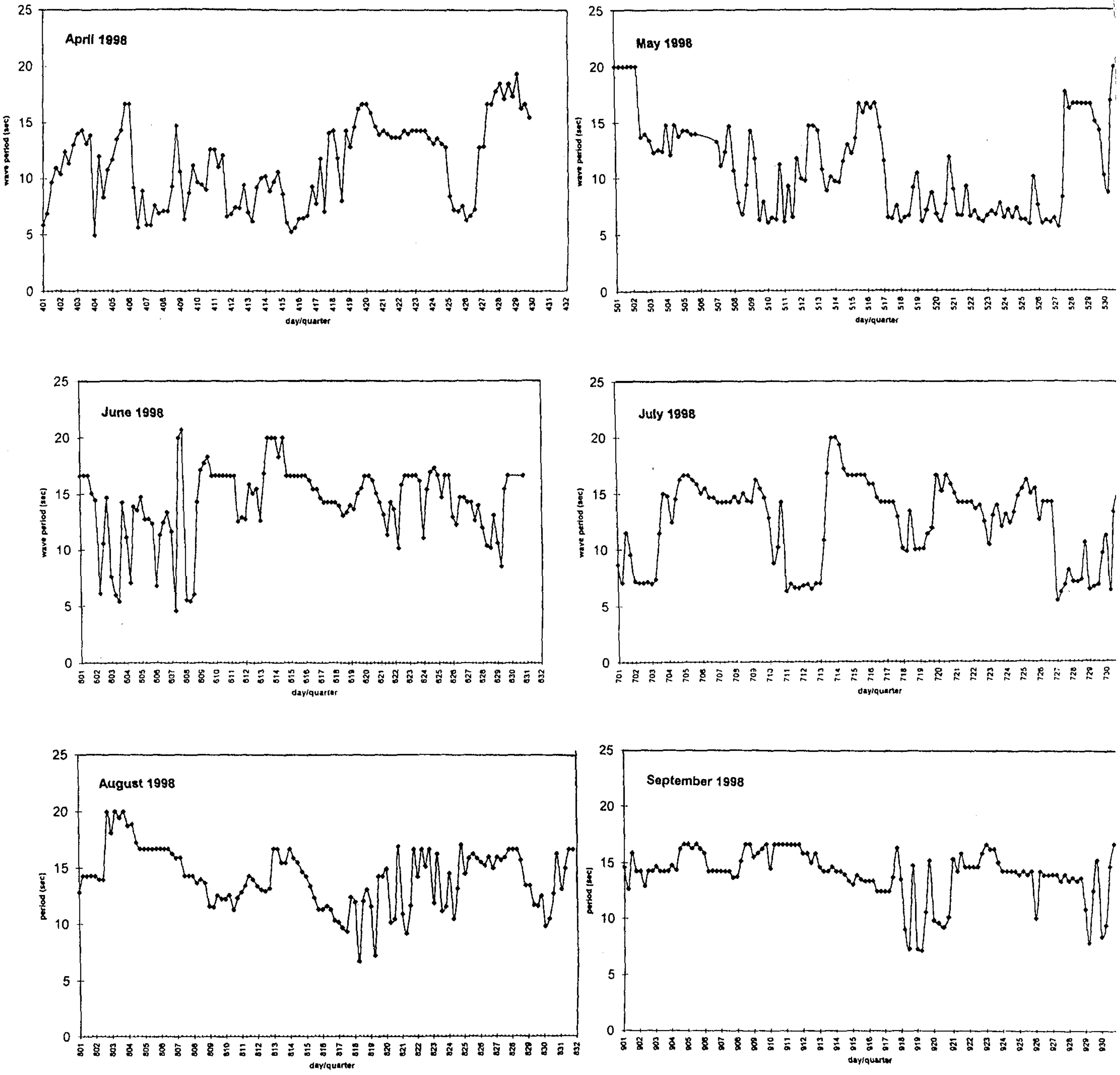


Figure 2-36 (continued) Dominant deep-water wave periods recorded off the Malibu coast during the 1997-98 water year (courtesy National Data Buoy Center). Data for October-December 1997 are derived from the buoy off Redondo Beach (46045), and for January-September 1998 from the Catalina Ridge buoy (46025, inoperable during the preceding period.

2.5 Estuary-Lagoon-Barrier-Ocean Relations

2.5.1. *Tidal Channel Hydrodynamics*

The terminus of Malibu Creek functioned in a variety of forms during the 1997-98 water year ranging from a completely closed lagoon to an open estuary. However, for the majority of the water year the system operated as a semi-restricted lagoon where a single tidal channel breached the barrier beach. Although this dynamic channel migrated continuously, several diagnostic geomorphic features remained constant. As a hydraulic conduit between river and sea, the velocity and volume of water in the tidal channel was dependent upon immediate discharge, tide, and wave conditions.

Table 2-7 presents an elementary water balance comparing lagoon inflow and outflow during ebb tide conditions when a single channel drained the lagoon. On January 16, 1998, four outflow measurements taken on the falling tide indicated that rates of outflow through the tidal channel decreased as the tide fell. During periods of high water prior to the ebb the lagoon cannot drain through the tidal channel and therefore upstream inflow to the lagoon contributes towards an increased storage volume. Additionally, depending on tide and wave conditions, sea water enters the lagoon either through the tidal channel or by way of barrier overwash and also increases lagoon storage. At the beginning of the receding tide, the enlarged hydraulic head in the lagoon following high water exerts itself and rates of outflow through the tidal channel are high. Outflow rates decline as the tide continues to fall and the lagoon hydraulic head decreases. On January 22 the channel was monitored during the tidal nadir after the lagoon has drained for 5-6 hours, at which time rates of outflow had decreased below inflow. Conditions during the ebb tide on January 29 were similar to January 16 in that outflow decreased as the tide fell. Interestingly, inflow rates on January 29 also decreased with time but this was due to the recession of stormflow from earlier in the day.

Open estuarine conditions during February and March prevented any field measurement of tidal channel outflow. Data were collected again on March 23 and 26 when a single tidal channel returned. On these days during intermediate tide levels a near balance between lagoon inflow and outflow existed. The absorptive role of the lagoon as a reservoir during moderate runoff events was noted on April 1 when a swollen lagoon released storm water that had been 'backed up' during high water. Additional tests in April and May taken during various stages of the ebb tide showed, to varying degrees, that outflow generally outpaced inflow during falling tides.

Until tide and wave conditions are strong enough to reverse flow direction into the lagoon, oceanward flow may be maintained during much of the flood tide. Under this condition, discharge rates from the lagoon continue to decrease during much of the flood tide because hydraulic gradients in the tidal channel decrease as ocean levels rise. For example, on June 18 at 3:30 pm the tide was rising in the nearshore zone, but oceanward flow was maintained from the lagoon (Table 2-7). This outflow (0.81 m^3/sec) had diminished below the rate of input to the lagoon from the stream (0.91 m^3/sec). This situation was also observed on June 30, July 15, and July 29 when measurements taken well after lower low water indicated that oceanward flow was maintained, although it was diminished. Rates of inflow to the lagoon from the Malibu Creek source gradually diminish throughout the dry summer months. On August 26 and September 8, outflow rates of 1.03 and 1.37 m^3/sec respectively are far greater than inflow rates of 0.14 and 0.13 m^3/sec measured during higher low water. In these cases, the lagoon was not primarily discharging streamflow that had been held as storage in the lagoon, but was removing a mass of seawater that had been introduced during higher high water through a channel whose geometry and orientation enhanced lagoonward flow (Figures 2-45, 2-46).

Field measurement of seawater discharge into the lagoon through the tidal channel during stages of high water was problematic. During flood tides, water entering the lagoon came as surges associated with individual waves propagating upstream through the tidal channel. As these wave surges passed, channel velocities and cross-sectional areas changed rapidly, and theis prevented any accurate calculation of discharge. Examples of changing channel geometry during flood tides will be addressed below. In contrast to the field approach, a water-balance approach which considers changes in lagoon storage minus upstream inputs to the lagoon can be used to estimate the contribution of sea water to the lagoon.

In Figures 2-37 to 2-41 instantaneous velocities are graphed taken at 20-second intervals in the tidal channel during flood tides between April and July 1998. Positive velocities indicate seaward flow while negative velocities depict lagoonward flow. Data from April 6 reveal the alternating nature of positive and negative flow associated with wave surges during a flood tide (Figure 2-37). Whether waves are successful or not in funneling through the channel and reaching the lagoon is a complex function of tide stage, wave height, wave period, wave speed, and the orientation of the channel to the approaching wave sets. Measurements from April 23 and May 7 show a decreasing frequency of positive seaward flow with the arrival of the first flood bores into the lagoon. The data from June 1, taken just after higher high water illustrate how even during periods of continuous lagoonward flow, velocities pulse according to wave conditions (Figure 2-37).

On June 18 flows surveyed, ranged from being completely ocean-directed to being entirely lagoon-directed during the advent of the flood tide (Figure 2-38) The first lagoonward pulses were low in magnitude, occurring nearly 4 hours after low water around 3:52 pm. Interestingly, the seaward velocities following these first flood bores (>0.6 m/sec) exceeded the outflow velocities measured around 3:30 pm prior to any inflow. This happens because much of the water carried by the first flood bores only advances minimally upstream into the lagoon. After reaching its terminal lagoonward limit, the plume of water becomes instantaneously stationary, and then returns seaward at a faster rate due to an increased elevational gradient. By 4:15 pm flow is still bi-directional, although it is flowing increasingly towards the lagoon. At one hour prior to higher high water, flow is entirely lagoonward. Peak inflow velocities during high tide (~1.0 m/sec) not only exceed the outflow velocities measured earlier during the flood tide around 3:40 pm (~ 0.50 m/sec) but are comparable to the higher outflow velocities (~1.0 m/sec) measured earlier in the morning of June 18 (Table 2-7). Even as the high water mark was approaching, several gaps between wave sets allowed lagoonward flow velocities to diminish (~ -0.18 m/sec). At the time of high water on June 18 around 5:45 pm, flow no longer entered the lagoon solely as channelized flow within the banks of the tidal channel but swept over the flood tidal lobes of the barrier adjacent to the channel (Figure 2-43).

Similar to the conditions of June 18, on June 30 lagoonward flow did not begin until over 4 hours into the flood tidal phase (Fig 2-39). Unlike June 18 though, entirely lagoonward flow was never maintained during the time of high water on June 30. Less seawater entered the lagoon on this day because the maximum tide height on June 30 (1.31 m) was less than high tide on June 18 (1.65 m). Interestingly, channel orientation and geometry on June 30 were more favorable to flood tide penetration into the lagoon than on June 18 (Figure 2-44), yet these factors, although important, are often not as influential as the more independent variables of tide and wave magnitude.

Data from July 15 show that lagoonward flow was already dominant more than 2 hours prior to high tide, with velocities exceeding 1.0 m/sec into the lagoon (Figure 2-40). One cause of this strong marine influx was stronger wave energy than on previous sample days. Wave heights on this day were moderate (0.9-1.5 m), although due to a south swell, occasional sets did exceed 2.2 m. Two hours following high tide on July 15, flow was primarily oceanward, where large waves were successful in reversing flow. On July 29, lagoonward flow began even earlier in the flood tidal phase, arriving more than 2.75 hours prior to high tide (Figure 2-41). On this day, however, wave heights were not very large (0.6-0.9 m) and high tide (1.34 m) was also below the level of July 15 (1.49 m). Furthermore, channel geometry and orientation were not advantageous to marine influx on this day because the channel bed had heightened, constricted, and was fairly oblique across the barrier (Figure 2-44).

What then enabled seawater to enter the lagoon under these unfavorable conditions? Field observations and experience suggest another reason for why seawater entered the lagoon successfully on July 29. By the end of July, the tidal channel had migrated to the far eastern margin of the barrier (Figure 2-44). In fact, on August 1, the beach would completely seal at this eastern boundary. In relation to the shape and overall setting of the barrier beach the channel was located at an important inflection point along the beach where the coastline begins to bend northward (Figure 2-1). This location is also distant from the coastal inflection updrift at the east end of Malibu Colony. The positioning of the tidal channel in this specific location has several implications in terms of wave energy and approach. At the far eastern barrier, the nearshore is subject to more wave energy compared to locations to the west which are more sheltered in the lee of the Malibu Colony headland. Wave energy due to refraction is also greater at the eastern barrier and this also contributes to the focusing of wave energy at this inflection point.

A more detailed examination of the shape, elevation, location, and orientation of the tidal channel between January and October 1998 is offered in Figures 2-42 to 2-46. In early January 1998, prior to the large storms of February 1998 marine-dominated forces had constructed a high barrier beach which had advanced well into the lagoon. The tidal channel had migrated eastward along the barrier beach to a position impacting Lifeguard Station #2 at the eastern side of the beach. Beach managers excavated a new tidal channel on January 9 in the central portion of the barrier. This channel was deep, short, and oriented more or less normal to the barrier and approaching wave sets. Throughout the rest of January (Figure 2-42) the channel maintained a relatively symmetrical profile and southward orientation (azimuth = 140°). The throat of the tidal channel was 155 m north of a reference point on the western barrier and the base elevation of the channel was roughly 0 m. The profile from January 29 reveals initial stages of eastward channel migration. Soon after these surveys was made, the heavy rains of the first week of February 1998 would remove nearly the entire barrier beach.

Channelized flow returned with the emergence of a new barrier several weeks after the stormflows. As surveyed in late March and early April, the bed elevation of the tidal channel (~ -1.0 m), was roughly 1 m below levels observed in January, and the throat of the tidal channel was only 30-40 m north of the reference point. Throughout April, constructive beach forces and littoral drift resulted in a heightened barrier whose tidal channel had elevated (~ -0.75 m), migrated eastward, and became increasingly oblique in orientation. Measured water levels from April 23 indicate how wetted perimeter increases with the flood tide, as well as, the correspondence between channel form water stage (Figure 2-42).

A larger scale map of the barrier and tidal channel for April 23, 1998, including geomorphic features and sediment textures, is given in Figure 2-43. In this perspective, two large longitudinal bars that were deposited during friction-dominated stormflows include very coarse cobbles and small boulders along their perimeters. The western edge of the eastern spit of the barrier beach is aligned and overrides the western fluvial cobble bar. The eastern bank of the tidal channel comprises coarse cobbles derived from the fluvial cobble bar. A sandy flood tidal delta projects lagoonward resting over gravels deposited during the winter floods. Offshore, a symmetrical ebb tidal delta radiates from the tidal channel along several braided paths. The onlapping barrier bisects the eastern fluvial cobble bar into lagoonal and offshore components. Field observations detected an important process in which these fluvial structures helped anchor the tidal channel in place. The migration of the tidal channel eastward beyond the western fluvial bar occurred as a series of jumps during a phase of large spring tides (2.3 m) the last week of April.

By mid-May 1998, the tidal channel had continued to elevate (~ -0.5 m) and had shifted nearly 30 m eastwards in the 21 day interval since April 23 (Figure 2-44). In the following two weeks to June 1, the channel migrated eastward another 11 m without aggradation, although notable changes in channel form did occur during this period. The previously incised high water channel form of May 14 had broadened. Steep banks were replaced with gently sloping overwash ramps at the ends of the western and eastern spits. The western edge of the eastern spit is seen as a rounded peninsula around which flood tides sweep sand. An incised low water channel still remained on June 1. Between June 1 and June 18, the channel rose over 0.8 m, lengthened somewhat, and became increasing oblique (azimuth 105°). The higher and steeper western bank of the June 18 profile demonstrates how the channel migration process may produce asymmetrical banks, where the updrift bank ploughs towards the downdrift bank. The June 18 map of Figure 2-43 shows the new position of the tidal channel between the fluvial cobble bars and the lobes flanking the channel which are swept by high tides. An important textural change in the sediments of the main body of the lagoon occurred between April and June when the winter's gravels were overlain by fines settling out of suspension.

Between June 18 and June 30 the tidal channel shifted quickly eastward (Figure 2-44). Large spring tides (2.5 m) during June 23-25 in combination with stronger wave energy (1.5-2 m sets) from a south swell between June 26-30 combined to help move the tidal channel another 56 m east. High tides and powerful surf successfully pushed the lobe of the western spit up and over the secondary eastern fluvial cobble bar. Without this combination of wave and tidal energy, the eastern cobble bar would have anchored and impeded channel migration, as had occurred updrift of the western cobble bar. As observed earlier in the year, the downdrift ploughing of sand creates an asymmetrical channel profile on June 30. The relative recency of the June 30 channel is also indicated by its more southerly orientation (azimuth 145°) and curvilinear shape when observed in plan view. Interestingly, the June 30 channel bed had dropped (0.35 m) in net elevation compared to June 18. The deeper channel may be attributed to increased outflow velocities and competency due to shortened channel length and a steeper gradient.

Over the next two weeks, littoral drift again pointed the tidal channel more easterly (azimuth 105°) and also raised the channel slightly. The nature of channel movement during a single tidal cycle is portrayed in the profiles from July 15 (Figure 2-44). During the flood tide the upper portions of the banks are eroded and the base of the updrift bank bulges with new deposition. The net movement of material is downdrift. The barrier map from July 15 shows previous channel throats as indentations west of the active channel. Repeat surveys during a flood tide cycle on July 29 also indicate downdrift migration and infilling. By the end of July the tidal channel had reached the eastern margin of the barrier. In the four month period between the surveys of March 23 and July 29, the throat of the tidal channel had migrated over 167 m east and 122 m north. By July 29 thalweg height (~ 0.0 m) had returned to an elevation similar to that recorded earlier in January 1998. Only two days after the July 29 survey, in the early morning hours of August 1, 1998, the barrier beach sealed for the first time since October 12, 1997. Tide and wave conditions during the final days of July were mild, although strong enough to pinch the tidal channel against the upland beach zone east of the barrier and fill it to closure.

Malibu Barrier Beach remained sealed for the first 12 days of August 1998. Lagoon level rose as a large volume of water was impounded behind the barrier. By the evening of August 12, the lagoon surface (elevation 2.05 m) had risen on the backshore of the barrier to less than 10 cm below the crest of the narrow western barrier (Figure 2-44, use barrier map from July 29 as reference during closure). A series of large waves struck the vulnerable neck of the western barrier around higher low water at 8:30 pm on August 12. Initial overspill quickly deepened into a large breach as the head of water in the lagoon, 1.86 m above seawater to drained seaward by gravity. Surveys from the following day, August 13, revealed a channel with the largest cross sectional area measured throughout the year (Figure 2-45). Impressive scour set the thalweg to a depth of -1.7 m, which was 1.7 m below the bed elevation of the July 29 channel prior to barrier closure. Channel width during higher high water of August 13 was over 30 m at the surface.

Geomorphic recovery towards a new dynamic equilibrium began immediately with the redistribution of nearshore sands by wave and tidal energy. By August 26 a new tidal lobe on the western spit filled much of the area eroded by the breach. The bed of the tidal channel had risen over 1.7 m in less than two weeks. The steep western bank of the channel was replaced by a more gently sloping ramp of sand. As had been observed consistently throughout the monitoring year, littoral drift built a sand lobe along the western margin of the tidal channel which forced the channel to a more easterly orientation.

The westward elongation of the eastern spit is strongly pronounced by September 8 (Figures 2-45, 2-46). Outflow during tidal ebb is carried by a lengthy, narrow, and circuitous low flow channel (<6.0 m) which snakes around the eastern spit. The influx of marine water to the lagoon does not take such an indirect route. Flood tides may flow directly into the lagoon over the lobes of the eastern and western spits or, during particularly high tides, overwash the central barrier. At some point between September 20 and 22 the meander bend around the eastern spit was cut-off by a shorter, more southerly flowing channel (azimuth 150°). The profile of the new September 22 channel indicates banks high enough to contain much of the lagoonward flow during high water and a nested smaller low flow channel. Bed elevation at the channel throat scoured 0.3 m between September 8 and 22. This is attributed to channel regulation due to increased gradient with a shorter channel and is very similar to the conditions observed with the June 30 channel described above.

At the close of the monitoring season in October 1998, the elevation of the bed of the tidal channel had risen again to around 0.0 m. This 0.0 elevation, routinely observed throughout the water year, appears to represent a quasi-equilibrium for the throat of the tidal channel. By October 21 (Figure 2-46) relict meanders survive along the backshore of the western spit, while the newer flood tidal delta masks the previous winter's longitudinal cobble bar. Offshore, a large field of cobbles and small boulders is revealed along the base of the foreshore. The channel profile from October 21 indicates a return to familiar channel form, in which the western, updrift bank is a sloping lobe due to flood tidal constructive processes and the eastern, downdrift bank is more vertical because of cut-bank erosion during ebb tidal outflows.

2.5.2. Estuarine Lagoon Water Levels, Volumes, and Tidal Exchange

The degree to which Malibu estuarine lagoon fills and drains according to daily tidal cycles is perhaps the most fundamental hydrologic parameter of the physical system. The tidal exchange of water into and out of the system determines water temperature and salinity, sediment concentration and distribution, and general biological resources. Multiple factors are responsible for the exchange of water between the estuarine lagoon and the open ocean. These factors are complex and often interact with both positive and negative feedbacks. Besides the relative balance of freshwater discharge, wave climate, and tidal magnitudes, the geomorphic nature of the barrier, and more specifically, the hydraulic geometry of the tidal inlet-outlet channel are critical in governing the system.

In Figures 2-47 to 2-50, tidal range, range in elevation of the water surface in the estuary or lagoon, and volume of water exchange in the system are given for specific days in the study period. For the tides, the daily extremes of higher high water and lower low water are graphed in meters based on predicted tidal information. Daily extremes of the height of the water surface were monitored by a recording stilling well and also by field measurements. The volumes of water exchanged within the lagoon-estuary were calculated based on the relationships graphed in Figure 2-11, where the September 1997 curve was used to calculate volumes through January 1998, the June 1998 curve was used from February 1, 1998 to September 22, and the October 1998 curve was used for the remaining days in October. The term tidal-prism is avoided because, strictly speaking, measures of the tidal prism account for and subtract volumes of freshwater discharge.

During late September and early October 1997 a completely closed barrier beach sealed the lagoon (Figure 2-32). During this period, diurnal fluctuations of lagoon levels were very small, less than 0.1 m, even though tidal range was greater than 1.5 m throughout the period (Figure 2-47). The role of seepage through the barrier is detected during this closed phase when lagoon water levels fell with the tide between September 24 and 26 and then rose with the tide from September 26 through October 3. Evaporation from the free water surface and transpiration from surrounding vegetation are important hydrologic withdrawals during warm long summer days. However, the ability to calculate the role of evapotranspiration in the lagoon's water balance under these conditions is extremely difficult because at the time there was no contributing surface streamflow from Malibu Creek, the degree of groundwater inflow was unknown, and the rate of seepage through the barrier was uncertain.

The barrier beach at Malibu was breached on the night of Sunday, October 12, 1997, probably through human interference. This breach resulted in a wide and deep channel at the western end of the barrier which was oriented normal to the shore. Overnight the lagoon transformed from a stagnant water body to a dynamic system where water levels rose and fell over 1.5 m and water volumes gained and lost over 110,000 m^3 during single tidal cycles. During higher tides coastal waves entered through the breach and propagated directly upstream beyond the PCH Bridge towards Profile AB2. Refracted incoming waves circulated sea water through the reconstructed channels of the western lagoon.

For the remainder of October, November, and December lagoonal range diminished compared to the days immediately following the breach (Figure 2-47). The principal cause of this restriction in flow was a self-regulating geomorphic response. Powerful flood tidal and ebb tidal flows distributed sands into lobes and fans that reshaped the new tidal channel, previously wide and deep, into a shallower narrower passage, resulting in reduced exchange between the lagoon and open ocean. Additionally, littoral drift pushed the western spit eastwards, which effectively sheltered the tidal channel from directly approaching waves (Figure 2-32). All of these aspects of geomorphic recovery were very similar to the events described above following the later August 1998 breach. The strong lagoonal exchange observed on November 14 was caused primarily by a high tidal range but also by changes in tidal channel geometry which favored greater circulation. On December 5 and December 18 the ranges of lagoon water levels were very small, only 0.3 m and 0.48 m respectively, considering the tidal range on these days. Runoff from two early season storms entered the lagoon during falling tides and prevented lagoon levels from dropping (Figures 2-16, 2-20).

The form, location, and orientation of the newly excavated January 9 channel in the central barrier (Figure 2-42) increased tidal circulation. Lagoonal range and tidal exchange observed on January 16 was greater than previous days in December 1998 with similar tidal conditions (Figure 2-48). The geomorphic response to the new January 9 channel was similar to the events following the earlier October breach, even though environmental conditions were somewhat different, as there was more runoff entering the lagoon in January. This geomorphic recovery entailed general channel infilling and migration due to the deposition of flood tide and ebb tide sand lobes which resulted in a more limited lagoonal range. The fairly narrow range of lagoon levels observed at the end of January is due both to these changes in channel geometry and also to the role of runoff following the January 29 storm.

Hydrologic and geomorphic conditions in the barrier-lagoon system were extensively altered by the arrival of the large storms of February 1998 (Figures 2-22 and 2-32) and this is sharply reflected by intriguing patterns in the lagoonal range data (Figure 2-48). The rains and stormflow of February 6 kept the lagoon fairly high, even throughout the time of low water, and also eroded much of the eastern and central barrier. The following day's flood removed what was remaining of the western barrier such that by February 8 a completely open estuary existed at the mouth of Malibu Creek (Figure 2-32). For example, during February 11-13 the range of water levels in the estuary closely matched the projected tidal elevations for those days. The derived volumetric exchange of water in the open estuary between high and low tides on February 11 (125,000 m^3) exceeded the volumes following the breach in October 1997. Similar to the flood of February 6, the high discharge of Tuesday, February 23, maintained elevated lagoon water levels throughout the day. By Friday February 27, stormflows had receded and open estuarine conditions returned. During the flood tide the sea penetrated far upstream, past the area of Profile AB2, and during the ebb tide the surface water level dropped over 1.65 m exposing the recently deposited cobble bars.

For the remainder of March the mouth of Malibu Creek continued to operate under estuarine conditions, yet a transition was beginning to occur. March 1998 was a fairly dry month, especially when compared to the previous month, and while there was continued baseflow discharge, there was only one true stormflow event, on March 25 (Figure 2-20). With a relaxation of the friction-dominated flow conditions, sands from swash bars deposited offshore following the February floods began to move onshore and weld onto the storm-deposited longitudinal cobble bars (Figure 2-32). Thus a nascent beach was beginning to form. This beach, though, was no barrier, and being quite low in elevation it was easily overtopped by many daily high tides. By the last days of March and the beginning of April a critical height was attained by much of the new beach such that it rightfully began to operate as a barrier, restricting flow both seaward and lagoonward (Figure 2-32). These important changes in beach morphology are reflected clearly in Figure 2-49 for lagoonal water elevations during the spring months April, May, and June. In general, lagoon water levels varied less than 1 m, and often less than 0.5 m. Only one monitoring day in this period, May 27, which had a particularly high tide, had a significantly large volume of tidal exchange. Beside the essential function of the barrier, the consistency of lagoon water levels and the resulting low exchange volumes during this period may also indicate the important role of baseflow discharge which helped maintain a continuous input to the lagoon.

As explained above, during July 1998 the tidal channel became more narrow, shallow, and oblique to wave approach as it continued to migrate eastward along the barrier. On July 29, lagoon-ocean exchange involved around 20,000 m^3 of water (Figure 2-50), where the ability of seawater to enter the lagoon was somewhat influenced by wave energy as focused by refraction. Once the barrier sealed on August 1, water immediately began to rise in the lagoon. Lagoon elevation had reached 1.74 m by 8:30 am on the morning of August 6. By 5:30 pm on August 6, the lagoon had risen another 2.4 cm regardless of evaporation, tidal fluctuation, or seepage through the barrier. In the ensuing days, lagoon levels continued to rise, although at a slower rate probably due to the combined effect of increased evaporative loss, attributable in large measure to increased surface area to volume ratio in the lagoon at higher levels, and increased seepage through the barrier.

The lagoon reached its maximum elevation (2.05 m) during the early evening of August 12, when it held a volume of nearly 195,000 m^3 (Figure 2-50). The dramatic breach occurred around 8:30 pm during a mild flood tide. Even though seawater was rising, the tide was still far beneath the high lagoon which was quickly draining. A race occurred between the rate at which the lagoon could drain through the new channel versus the rate at which the tide rose. The volume of lagoon water discharged through the breach on the evening of August 12 was estimated to be 170,000 - 180,000 m^3. It is important to keep in mind that the sealed lagoon of August 1998 had a much greater storage capacity than the closed lagoon of October 1997 because of extensive erosion during February 1998.

The geomorphic recovery following the August 1998 breach (Figures 2-45, 2-46), which led to the replacement of a deep wide channel with a smaller, more oblique conduit, mitigated lagoonal exchange within several days. On August 26, lagoon-ocean exchange was a moderate 35,000 m^3 for a tidal range of roughly 1.0 m. Large tides (>2.0 m) on September 5, the initial day of a four-day series of spring tides, raised the flood tidal lobes along the western and eastern spits of the barrier beach and also constricted the outflow channel to a more limited cross-sectional area. The hydrologic outcome of these geomorphic changes was that during the remaining high and low tides from September 5 to 8, the lagoon did not fill as high nor drain as low as that measured on the first day of the series (Figure 2-50).

An interesting distinction is noted in Figure 2-50 comparing the measurements from September 20 and 22. These two days had similar wave, tidal, and creek inflow conditions, yet September 22 had nearly twice the volume (60,000 m^3) of lagoon-ocean circulation. The cause of this discrepancy is found in the channel changes occurring between the two days when the lengthy meandering outflow channel was replaced by a wider, shorter, and more southerly flowing channel (Figure 2-46). Once again, geomorphic alterations of the tidal channel had important hydrologic implications for the entire lagoon system.

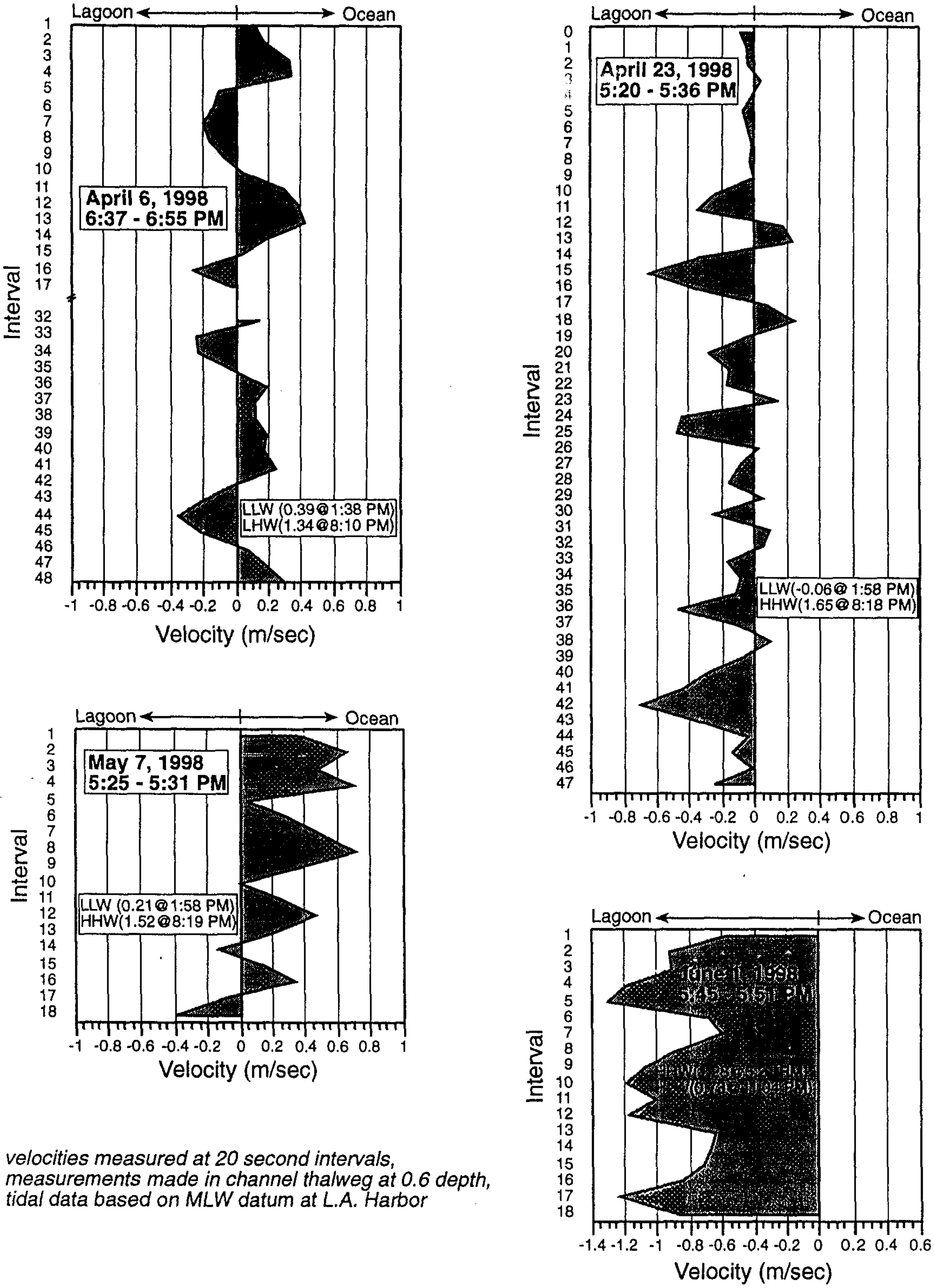
Between October 6 and 8, spring tides comparable in magnitude to those occurring at the beginning of September resulted in rates of lagoonal exchange around 60,000 m^3 (Figure 2-50). As the new cut-off channel of late September underwent the expected modifications, circulation between the lagoon and sea was restricted. Evidence of this process is found in comparing exchange volumes from early October, during strong tides, which are very similar to those from September 22 during much smaller tides. The final measurements made during slightly smaller spring tides on October 20 and 21 indicate the continued dampening of tidal circulation as the channel heightened, lengthened, and became more oblique (Figures 2-45, 2-46, 2-50).

Table 2.7

Elementary Water Balance Under Outflow Condtitions

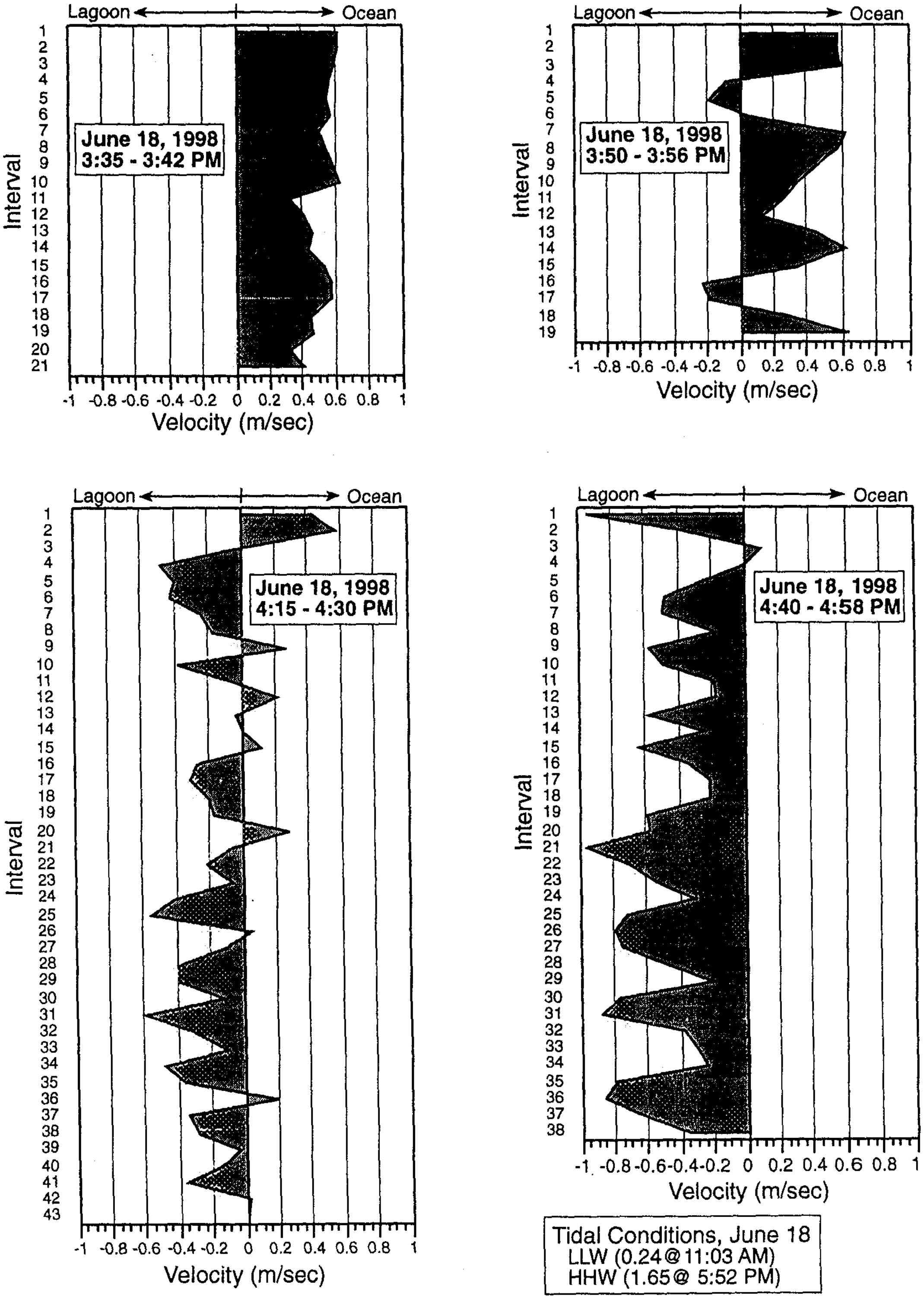
Date	Time of Measurement	Inflow (cms)	Outflow (cms)	Daily Tidal Conditions
1/16/98	11:30 AM	1.64	11.7	HHW(1.52 @10:53 AM)
	12:15 PM	1.64	11.98	LLW(0.06 @ 5:52 PM)
	1:25 PM	1.67	5.24	
	2:45 PM	1.67	3.59	
1/22/98	1:40 PM	0.96	0.78	LLW(0.31@12:15 PM) LHW(1:00@7:16 PM)
1/29/98	1:50 PM	8.5	13.23	HHW(1.95@9:35 AM)
	3:30 PM	6.6	10.72	LLW(-0.34@4:29 PM)
3/23/98	2:25 PM	2.44	2.44	LLW(-0.06@12:21 PM) LHW(1.22@6:55 PM)
3/26/98	2:50 PM	8.95	8.51	LLW(-0.24@2:14 PM) LHW(1.62@8:28 PM)
4/1/98	2:45 PM	7.05	21.66	LHW(1.07@1:27 PM) HLW(0.61@6:25 PM)
4/6/98	12:05 PM	4.22	6.25	HHW(1.40@6:54 AM) LLW(0.00@1:38 PM)
4/13/98	3:45 PM	4.22	5.05	LHW(1.22@11:11 AM) HLW(0.40@4:42 PM)
4/23/98	3:30 PM	2.29	2.55	LLW(-0.06@1:58 PM) HHW(1.65@8:18 PM)
5/7/98	4:00 PM	2.63	3.6	LLW(0.21@1:57 PM) HHW(1.52@8:18 PM)
5/14/98	4:00 PM	3.71	4.82	LHW(1.04@12:42 PM) HLW(0.70@5:10 PM)
6/1/98	9:20 AM	1.33	1.6	LHW(1.22@2:54 AM) LLW(0.15@10:05 AM)
6/18/98	9:35 AM	1.05	1.01	LHW (1.16@4:56 AM)
	3:30 PM	0.91	0.81	LLW(0.30@11:02 AM) HHW(1.65@5:51 PM)
6/30/98	8:00 AM	0.51	0.97	LLW(0.24@8:58 AM)
	12:50 PM	0.54	0.64	HHW(1.31@4:09 PM)
7/15/98	7:20 AM	0.34	1.07	LHW (1.37@1:49 AM)
	11:00 AM	0.37	0.74	LLW(0.18@8:28 AM) HHW(1.49@3:22 PM)
7/29/98	7:00 AM	0.21	0.6	LHW (1.25@1:15 AM)
	11:30 AM	0.22	0.5	LLW(0.40@7:51 AM) HHW(1.34@2:44 PM)
8/26/98	7:10 PM	0.14	1.03	HHW(1.43@12:41 PM) HLW(0.58@6:55 PM)
9/8/98	2:25 PM	0.13	3.39	HHW(1.77@11:25 AM)
	5:05 PM	0.13	1.37	HLW(0.15@5:35 PM)
	7:15 PM	0.11	0.82	LHW(1.65@11:42 PM)

Tidal elevations given in meters based on Mean Low Water datum at Los Angeles Harbor. Tide times are adjusted (+7 min) for Malibu. HHW = higher high water, LHW = lower high water, HLW = higher low water, LLW = lower low water.



velocities measured at 20 second intervals, measurements made in channel thalweg at 0.6 depth, tidal data based on MLW datum at L.A. Harbor

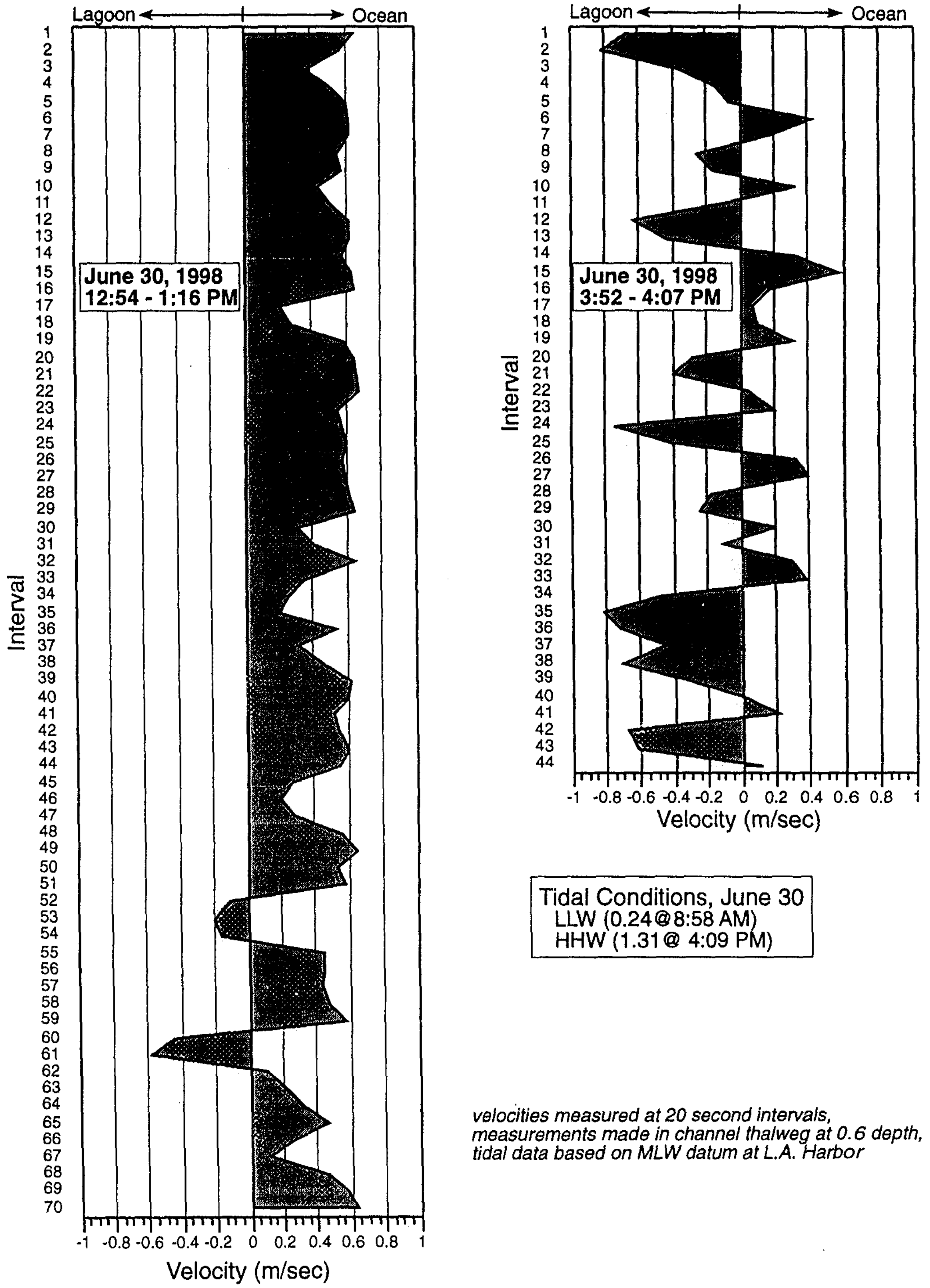
Figure 2-37 Tidal channel velocities during inflow conditions, April 6 - June 1, 1998



Tidal Conditions, June 18
LLW (0.24@11:03 AM)
HHW (1.65@ 5:52 PM)

velocities measured at 20 second intervals,
measurements made in channel thalweg at 0.6 depth,
tidal data based on MLW datum at L.A. Harbor

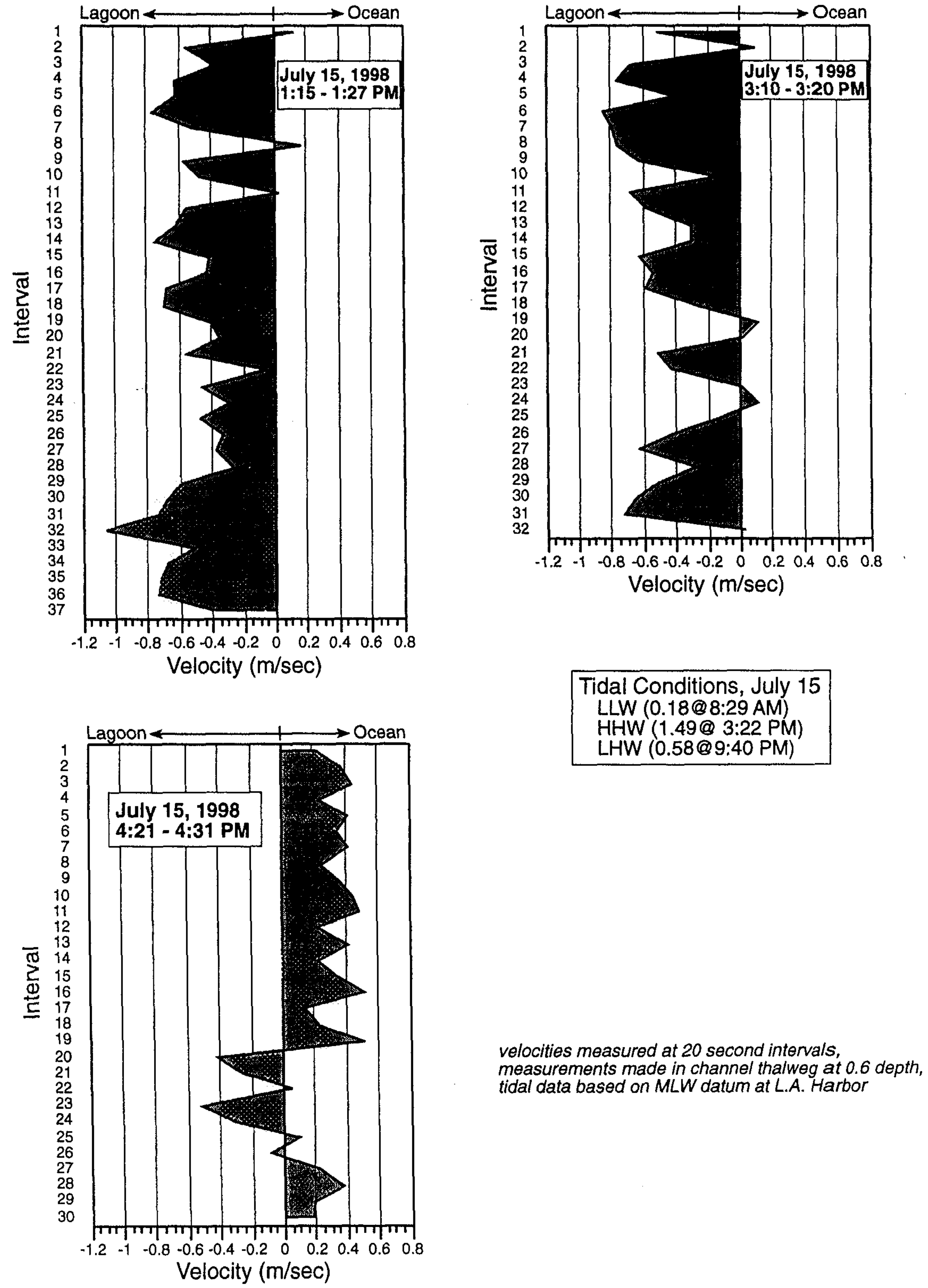
Figure 2-38 Tidal channel velocities during inflow conditions, June 18, 1998



Tidal Conditions, June 30
LLW (0.24@8:58 AM)
HHW (1.31@ 4:09 PM)

velocities measured at 20 second intervals, measurements made in channel thalweg at 0.6 depth, tidal data based on MLW datum at L.A. Harbor

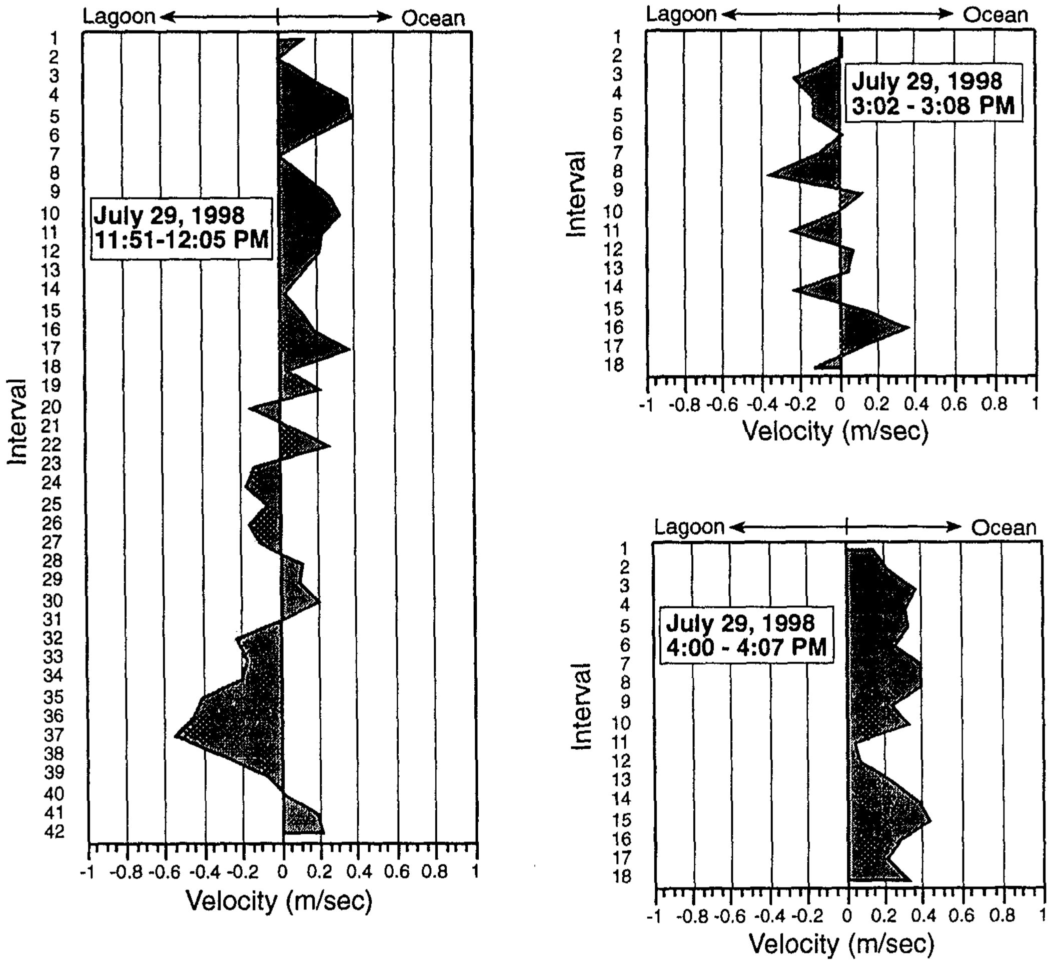
Figure 2-39 Tidal channel velocities during inflow conditions, June 30, 1998



Tidal Conditions, July 15
LLW (0.18@8:29 AM)
HHW (1.49@ 3:22 PM)
LHW (0.58@9:40 PM)

velocities measured at 20 second intervals, measurements made in channel thalweg at 0.6 depth, tidal data based on MLW datum at L.A. Harbor

Figure 2-40 Tidal channel velocities during inflow conditions, July 15, 1998



Tidal Conditions, July 29
LLW (0.40@7:51 AM)
HHW (1.34@ 2:44 PM)
HLW (0.73@8:58 PM)

velocities measured at 20 second intervals,
measurements made in channel thalweg at 0.6 depth,
tidal data based on MLW datum at L.A. Harbor

Figure 2-41 Tidal channel velocities during inflow conditions, July 29, 1998

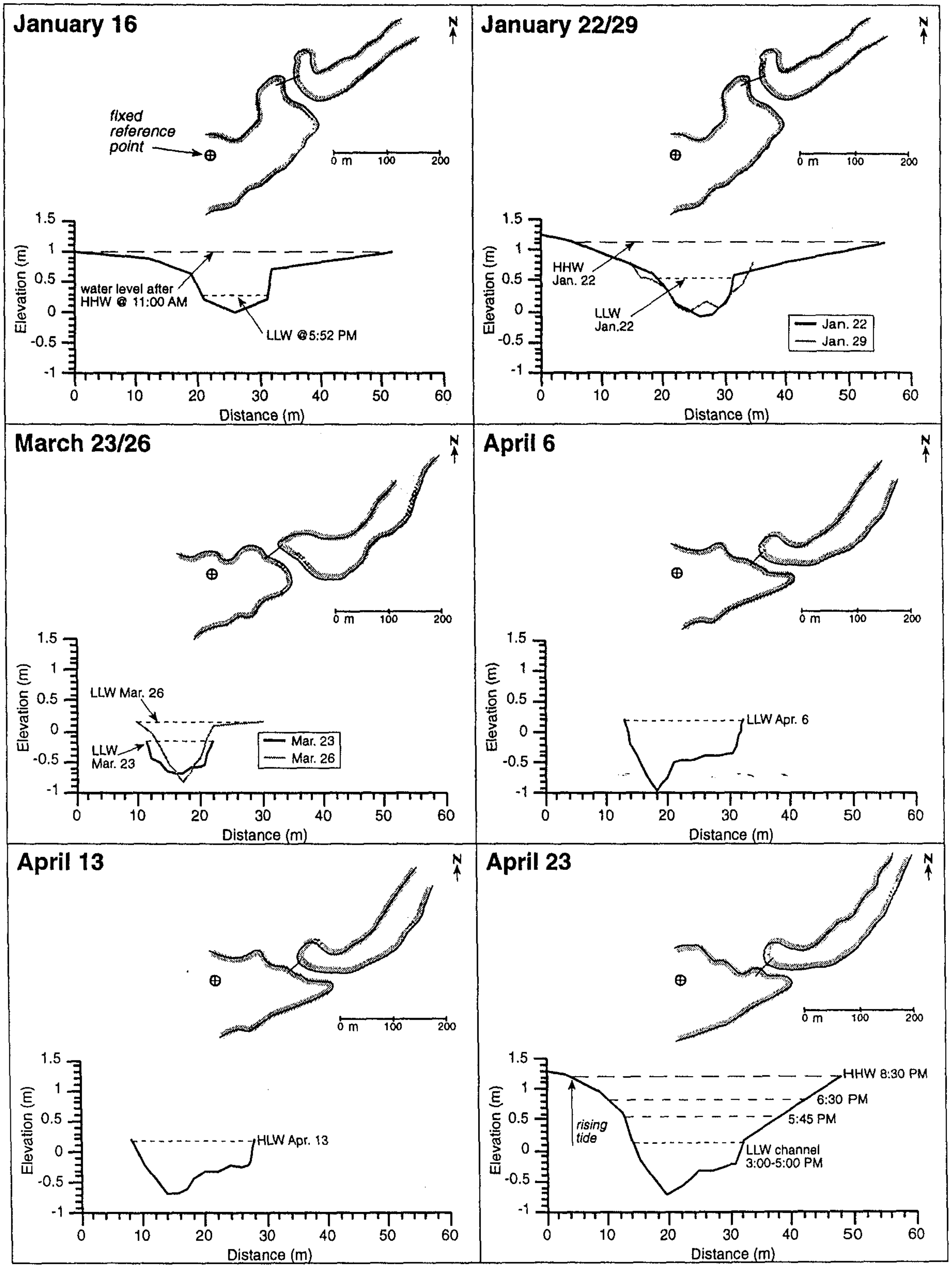


Figure 2-42 Tidal chanel profiles and locations, January 16 - April 23, 1998

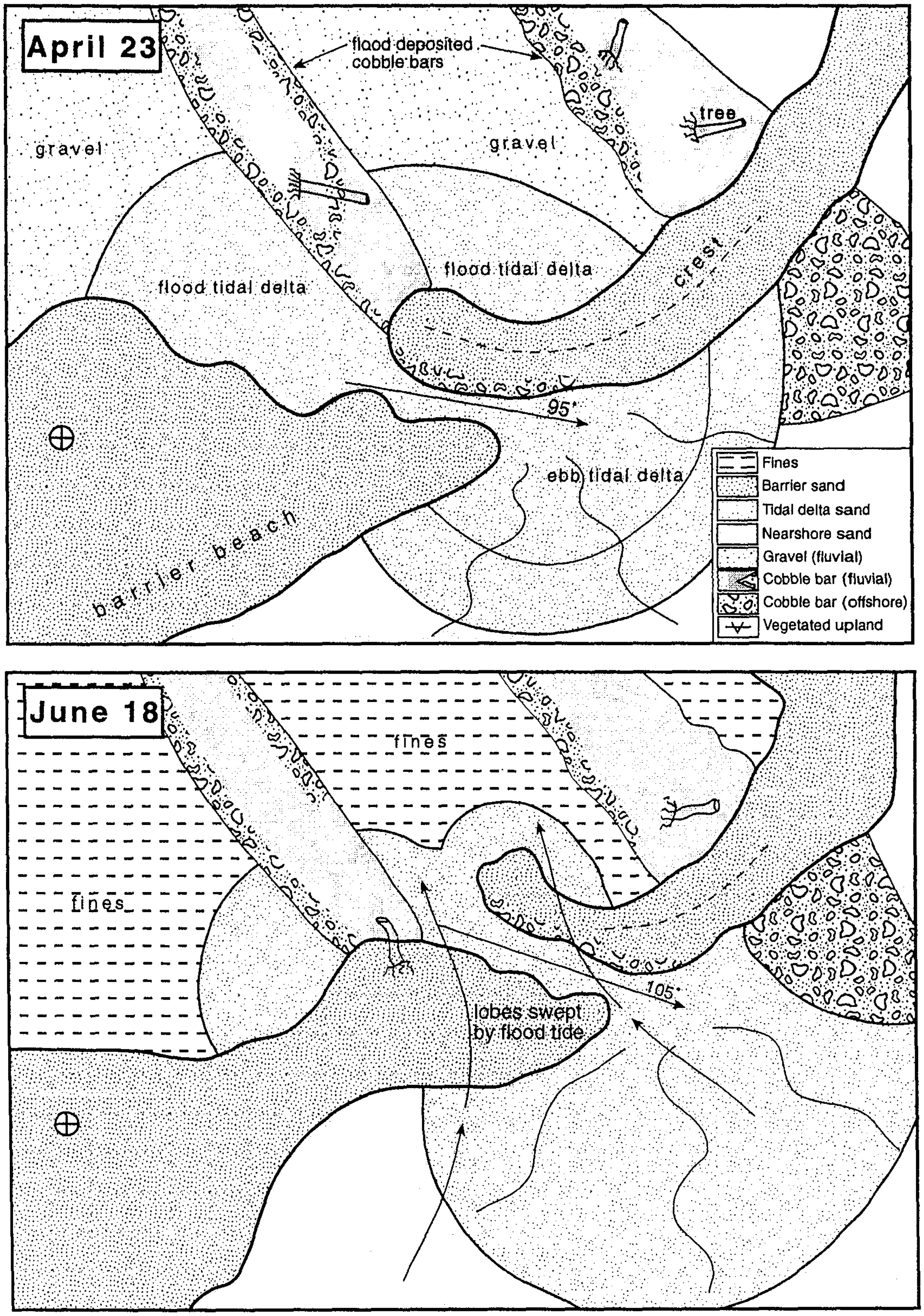


Figure 2-43 Geomorphic features at tidal channel, April and June 1998

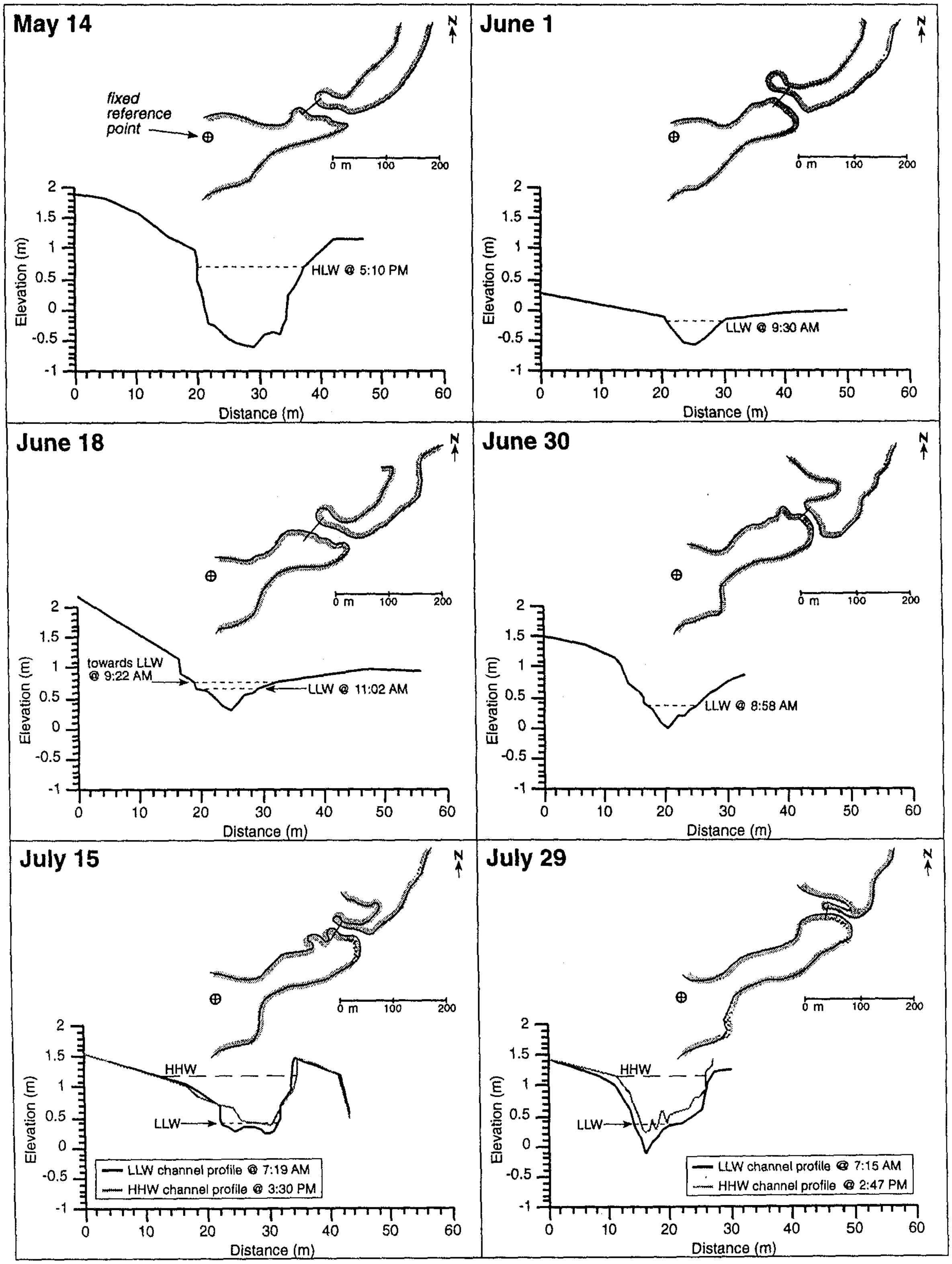


Figure 2-44 Tidal chanel profiles and locations, May 14 - July 29, 1998

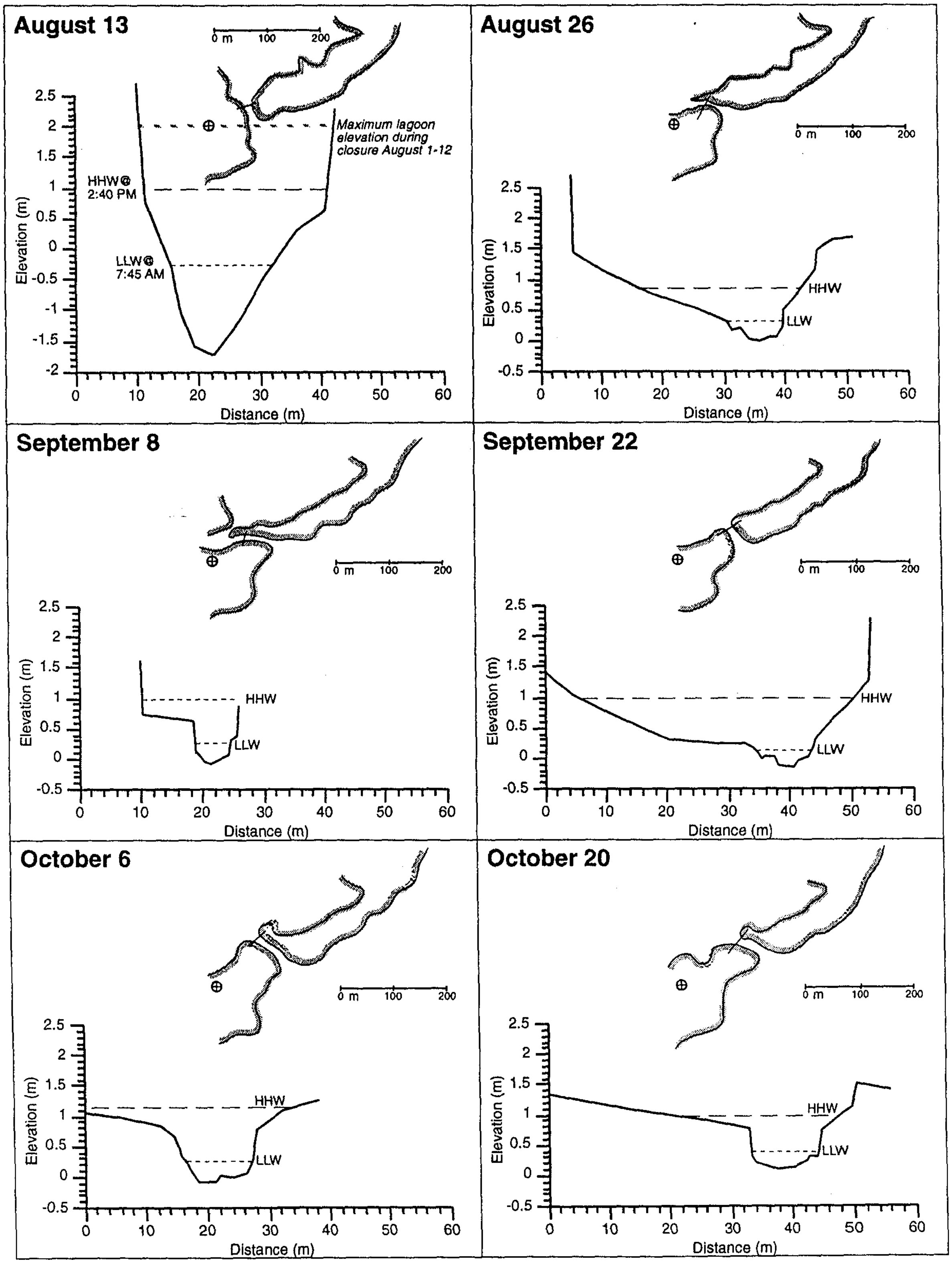


Figure 2-45 Tidal chanel profiles and locations, August 13 - October 20, 1998

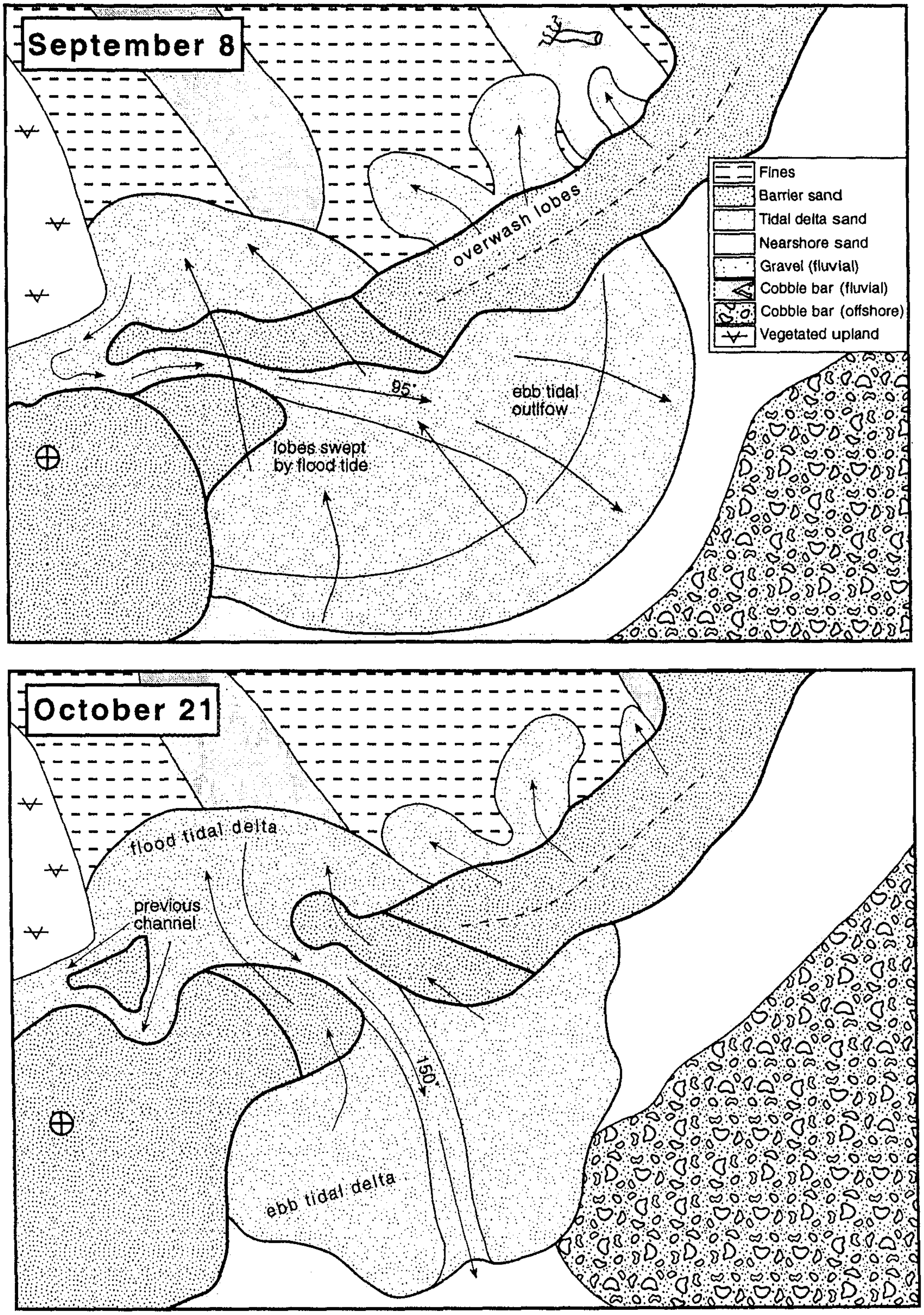


Figure 2-46 Geomorphic features at tidal channel, September and October 1998

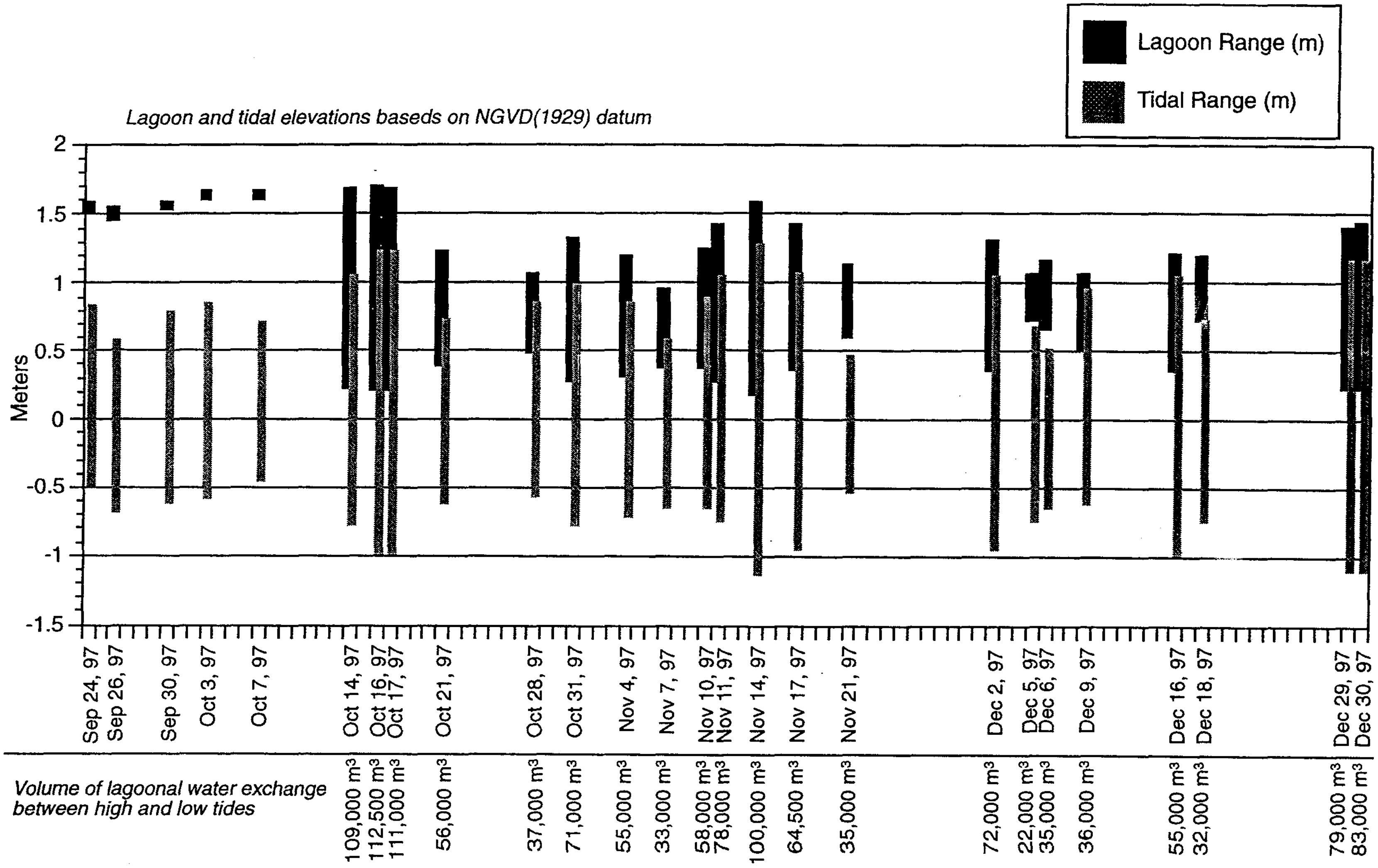


Figure 2-47 Malibu Lagoon-Estuary September 1997 - December 1997, tidal range, lagoon range, and volume of lagoonal water exchange

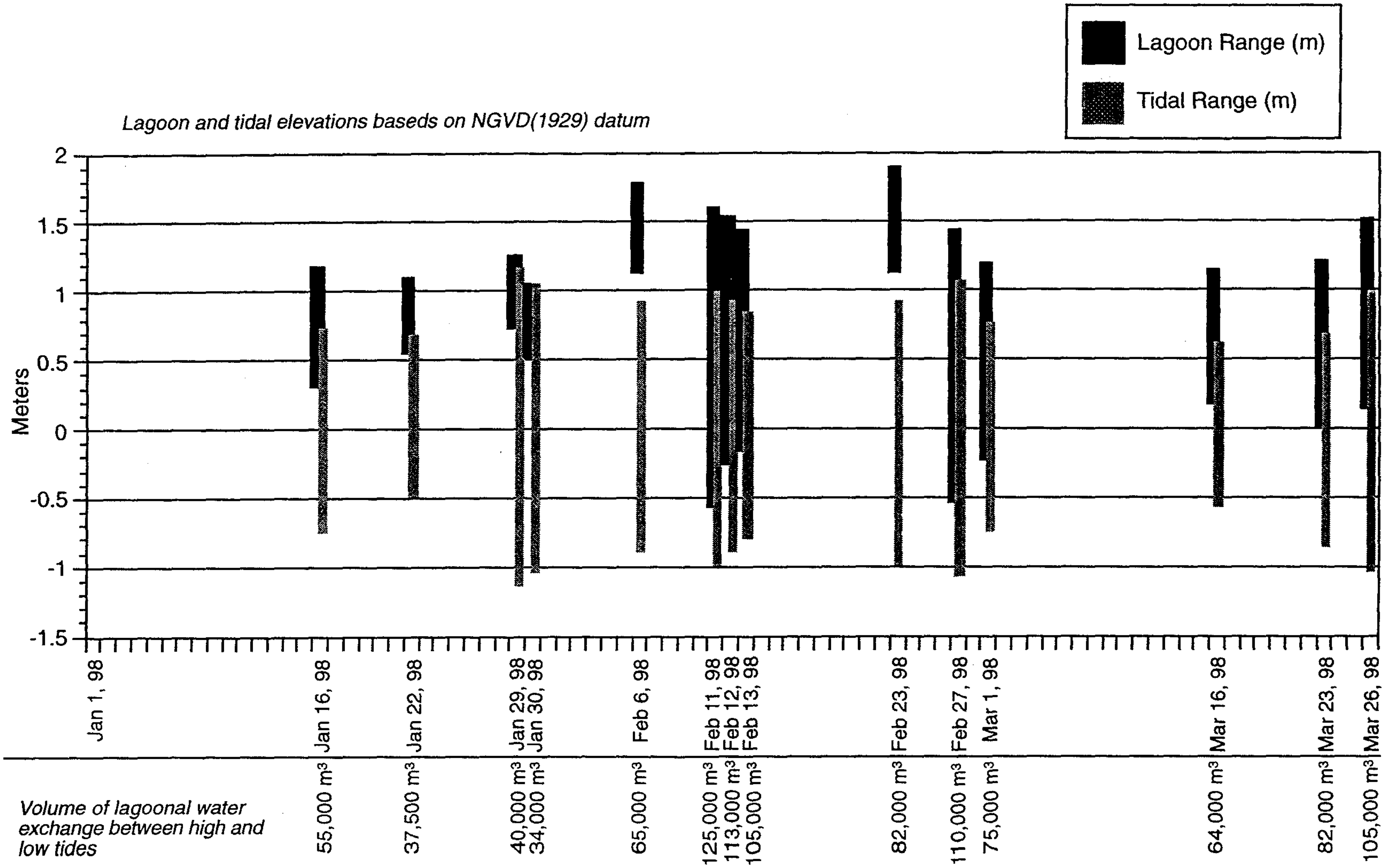


Figure 2-48 Malibu Lagoon-Estuary January 1998 - March 1998, tidal range, lagoon range, and volume of lagoonal water exchange

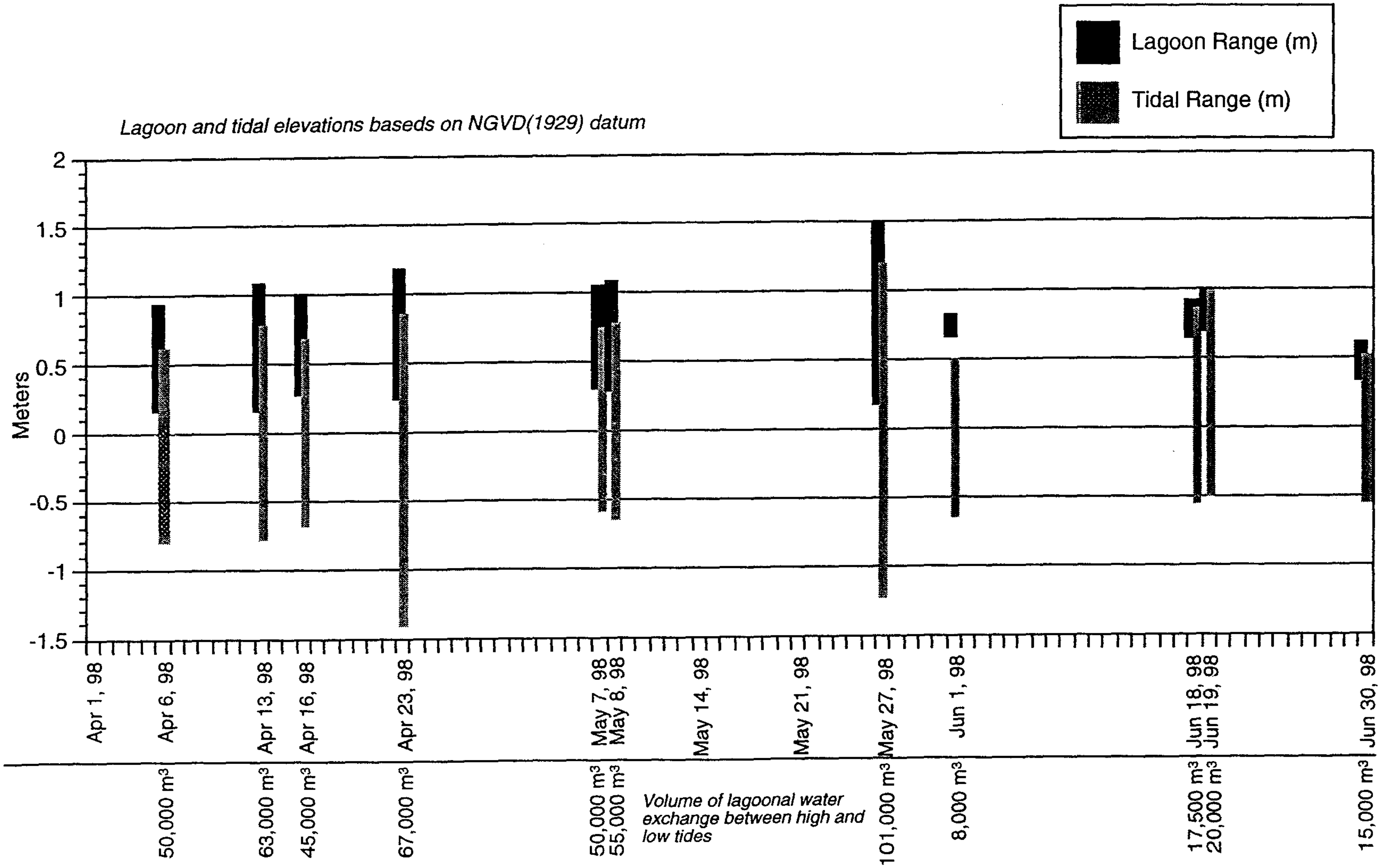


Figure 2-49 Malibu Lagoon-Estuary April 1998 - June 1998, tidal range, lagoon range, and volume of lagoonal water exchange

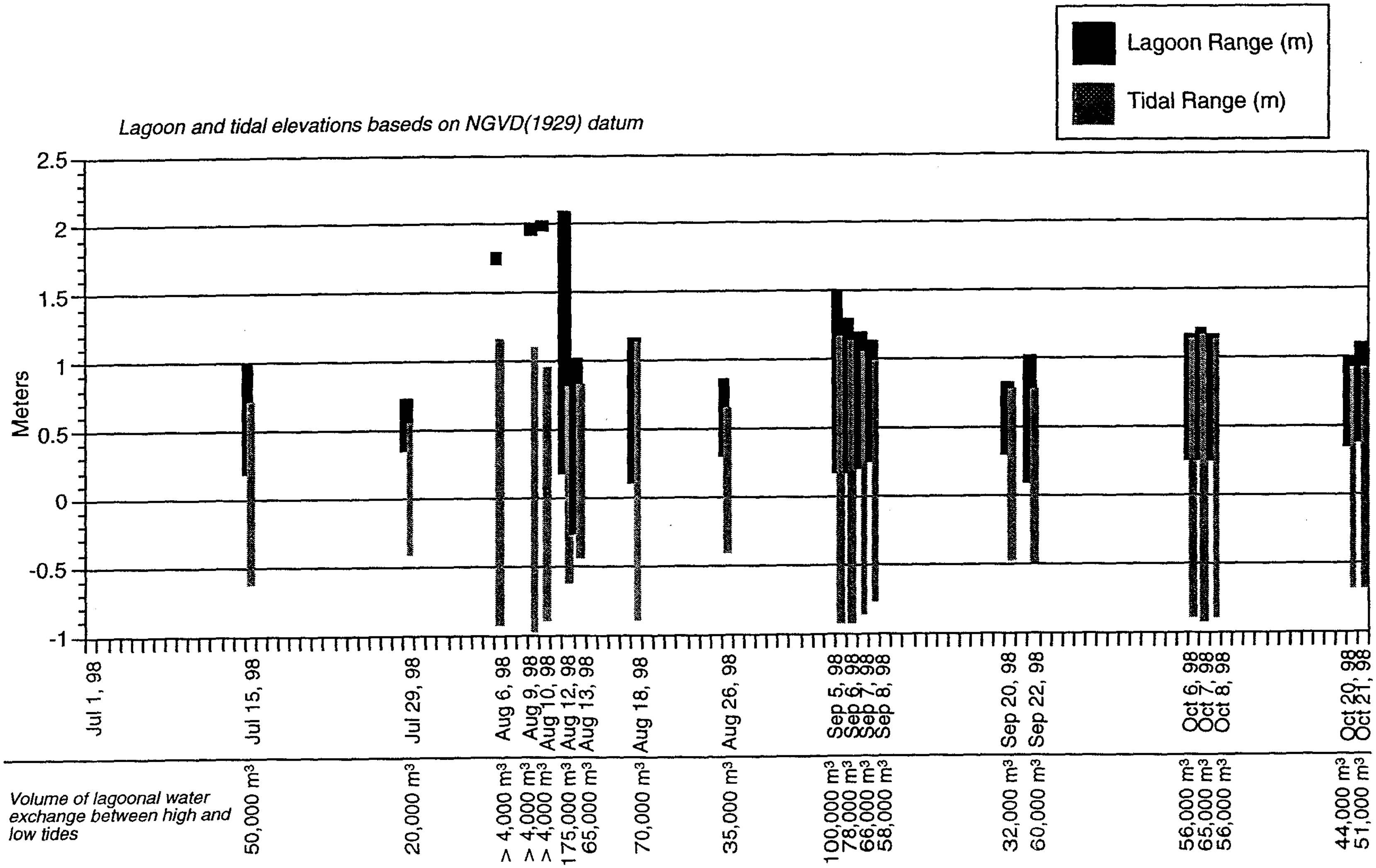


Figure 2-50 Malibu Lagoon-Estuary July 1998 - October 1998, tidal range, lagoon range, and volume of lagoonal water exchange

Chapter 2.6: Estimating future flows

Johannes Feddema

Contents

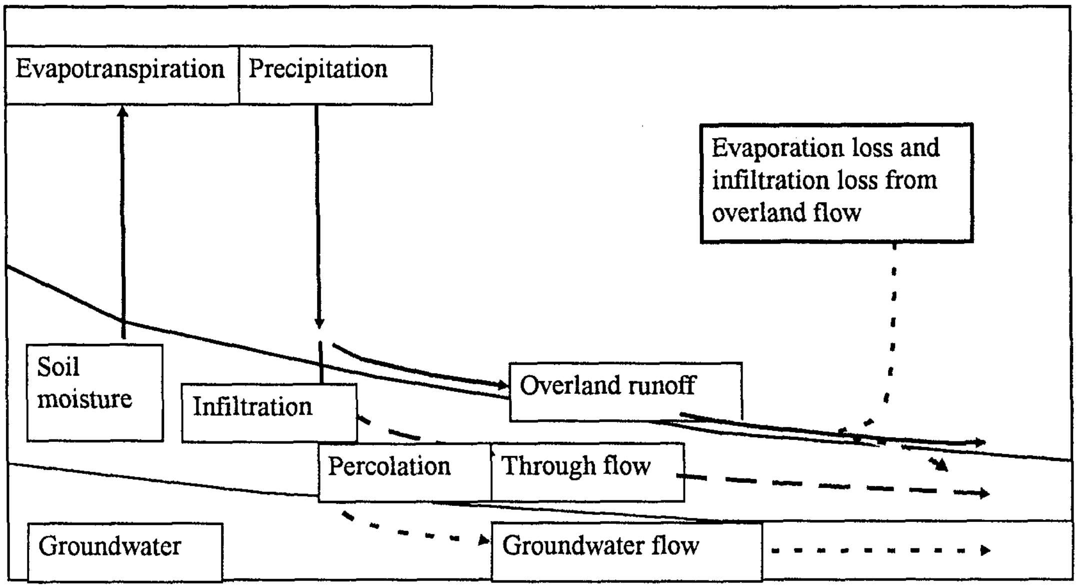
2.6.1 Overview of objectives

The objective of this section is to provide estimates of future water flows. In addition the model was developed to identify the source of runoff water. By linking the origin of the runoff to a specific land-use type we hope to provide an estimate of how water quality might change in future runoff. A combined runoff and water balance model was developed specifically for the Malibu watershed. Once the model was developed and calibrated using the Tapia gauging station, different scenarios were run to assess how water runoff might change in the near future. The current scenario of runoff uses a current land-use map and a number of data layers available as GIS files. The future scenario consists of similar data layers, but with a land-use scenario that assumes all city and county areas zoned for development are developed. This chapter will present: 1. an overview of the model and some of the assumptions made in the model; 2. results of the model calibration based on the 1995 water year (October 1, 1994 to September 30, 1995) weather records and daily stream flows measured at the Tapia stream gauge. Finally model runs for the 1995 water year will be presented for the entire watershed using a current land-use scenario and with the future land-use scenario. The current results are considered preliminary. The model is still being refined and a number of other scenarios are being developed to look at the impacts of burns, specific climate events (e.g. ENSO) and land-use change on Malibu water flows and water quality issues. These additional results will be published in a MA thesis and published journal articles.

2.6.2 Model Description

The model is a distributed watershed model based on two well established, existing, models. The model divides the watershed into 30 by 30 meter grid cells and assesses the water balance for each grid cell on a daily basis. Figure 2.6.1 provides a schematic representation of the model.

Figure 2.6.1: Schematic representation of the water balance model at each grid cell



For each grid cell the model estimates the water contained in the soil moisture layer. The main water input to the soil layer is from precipitation. However, before water can infiltrate into the soil moisture a portion is partitioned into overland runoff. The model partitions runoff by the SCS (SCS, 1972) method. Overland runoff is estimated based on the surface properties of the grid cell, including land-use, soil hydrologic properties, and five day antecedent rainfall condition. The remaining precipitation is considered to infiltrate into the soil moisture layer. The model then calculates potential evapotranspiration (PE) using the Thornthwaite method from temperature and latitude inputs (Thornthwaite and Mather, 1955; Willmott, 1977; Mather, 1978). Depending on the soil moisture content, moisture is then withdrawn for actual evapotransiration (AE). The rate of soil moisture withdrawal is 100% if the soil moisture content is more than 70% of total soil moisture holding capacity, once at 70% decreases linearly as the soil is emptied (soil moisture retention curve G in Mather, 1978). Finally, the water content of the soil is compared to the water holding capacity of the soil (gravitational water). If the infiltration amount is greater than the water holding capacity the excess is considered surplus moisture and can be used to recharge groundwater and may become throughflow (water flowing through the soil layer). Both throughflow and ground water are considered to flow into the stream with time lags.

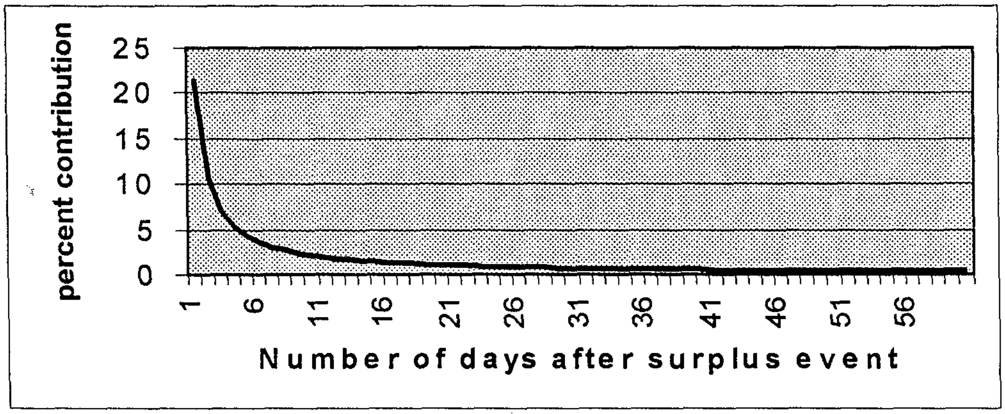
Total streamflow is calculated as the sum of overland runoff, lagged throughflow and lagged groundwater flows. Each is treated differently by the model. Overland flow is routed using an isochrone technique. The time needed for water to get from a grid cell to the mouth (or gauge) of the stream is estimated by the following equation (Linsley et al, 1982; Equation 9-24):

$$\mathbf{K}_m = \frac{0.015\mathbf{L}\sqrt{\mathbf{A}}}{\sqrt{\mathbf{s}}}$$

where K_m is the Muskingum storage coefficient measured in hours, L is the distance between the grid cell and the stream mouth/gauge, A is the area of the watershed and s is the streambed slope from the grid to stream mouth/gauge (see Linsley et al, 1982). This value is rounded to the nearest whole day, and overland flows generated by the grid cell are lagged by that number of days before they are included in streamflow estimates. For each day evaporation losses from the overland flow are subtracted (based on PE calculations for that day) and in addition 30 mm of water are considered to infiltrate each day during the passage from the grid cell to the stream mouth/gauge. The infiltrated water is then used to recharge soil moisture or may become throughflow and groundwater.

Throughflow is calculated as follows. For each day surplus moisture conditions are calculated (i.e. a condition where infiltration is sufficient to recharge soil moisture to the soil water holding capacity, and account for potential evapotranspiration for the day) 75 Percent of surplus is considered to become throughflow (this is based on some experimental model runs), the rest of the surplus is considered to percolate through to groundwater. Throughflow is gradually released to the stream over the next 60 days. An inverse relationship based on the number of days since the surplus event is used to determine the proportion of surplus that will be released for a given day (see figure 2.6.2). All the throughflow will be released in 60 days following the surplus event.

Figure 2.6.2: Percentage of throughflow contributed to runoff for the 60 days after a surplus event.



Groundwater contributions are treated similarly to the release of throughflow. Groundwater recharge is based on the assumption that 25% of surplus will percolate through to the groundwater. Average ground water releases are lagged by 5 months, but the actual calculation is based on an average water release over a 60 day. Specifically total groundwater contribution to stream flow is based on the total of 1/60th of the groundwater recharge value for each day over a 60 day period 4 to 6 prior to the flow event. Upon release, 20% of the combined groundwater and throughflow water is used for evapotranspiration, and the remainder contributes to stream flow. Although these calculations are processed at each grid cell these contributions would most likely occur along streambeds downstream of the grid cell location.

Total streamflow is calculated as the total contribution of overland runoff, throughflow and groundwater flow from each grid cell (about 250,000 cells). In addition to estimating the total water flow in the river the model also tracks the contribution of streamflow from each land-use listed. For example some land-uses contribute relatively greater proportions of runoff based on typical surface properties associated with that land-use. Specifically the non-natural land use types reduced soil water holding capacities as illustrated in table 1. These estimates are based on the proportion of land covered by impervious or low permeability materials. Open water was treated as a reservoir, and was generally not considered to contribute to overland runoff, but was considered for throughflow and groundwater flow simulation. Hence this land-use category has a disproportional contribution to dry season river flow estimates. Contributions to streamflow by the Tapia water treatment plant have not yet been included, but will be considered in future model runs (in part due to the extensive data collection efforts required). Table 2 shows the SCS curve numbers used depending on land-use, hydrologic soil type and soil condition (for antecedent condition II). In the current form of the model the good soil condition values are used for land-use categories 10-14 (natural lands and parks), and fair conditions are used for all other land-use categories. Antecedent condition I and III are calculated from regression equations, and CN numbers between conditions were linearly interpolated.

Table 2.6.1: Soil water holding reduction factors by landuse (15 mm = minimum used)

Land-use category	soil water holding treatment
1: Low density residential - 1- 5 dwelling unit (du) per acre	no change from normal
2: Medium density residential - 4/5 - 15/18 du per acre	80% of normal
3: High density residential - >15/18 du per acre	60% of normal
4: Commercial/Civic Centers	60% of normal
5: Industrial	60% of normal
6: Schools	60% of normal
7: Roads/freeways	40% of normal
8: Agricultural - crop	no change from normal
9: Agricultural - orchards	no change from normal
10: Open-space parks, groomed	no change from normal
11: Native vegetation - grasslands native and non-native	no change from normal
12: Native vegetation - shrublands & chaparral	no change from normal
13: Native vegetation - woodlands	no change from normal
14: Native vegetation - forest	no change from normal
15: Fallow/barren fields	no change from normal
16: Rural residential - <1 du per acre	no change from normal
17. Barren fields/vacant lots/ under-construction	60% of normal
18: Open water	treated separately
19. Rock outcrops	15 mm assigned

Table 2.6.2: SCS curve numbers by land-use category (see table 1 for explanation of categories), hydrologic soil type and soil condition. (Not all values are used so repeated values are used where value is of no consequence)

Hydrologic soil type	A	A	A	B	B	B	C	C	C	D	D	D
Soil condition	good	fair	poor	good	fair	poor	good	fair	poor	good	fair	poor
Land-use: 1	40	40	40	60	60	60	75	75	75	78	78	78
2	51	51	51	65	65	65	77	77	77	82	82	82
3	72	72	72	80	80	80	85	85	85	88	88	88
4	75	75	75	84	84	84	90	90	90	92	92	92
5	81	81	81	88	88	88	91	91	91	93	93	93
6	47	55	63	66	71	77	77	80	84	81	84	87
7	74	74	74	84	84	84	90	90	90	92	92	92
8	42	62	79	52	71	86	60	78	90	64	81	92
9	32	43	57	58	65	73	72	76	82	79	82	86
10	39	49	68	61	69	79	74	79	86	80	84	89
11	51	61	71	62	71	80	74	81	87	85	89	93
12	49	55	63	68	72	77	79	81	85	84	86	88
13	30	46	63	66	36	52	70	73	42	58	76	80
14	30	55	70	77	36	60	73	79	45	66	77	83
15	25	35	45	55	61	66	70	74	77	73	78	83
16	25	35	45	55	61	66	70	74	77	73	78	83
17	72	72	72	82	82	82	87	87	87	89	89	89
18	0	0	0	0	0	0	0	0	0	0	0	0

19	74	74	74	74	74	74	74	74	74	74	74	74

2.6.3 Data Organization.

A number of different data sources are required to run the model. These can be subdivided into three categories. First are the parameters defining surface characteristics based on soil and terrain properties. Second are surface properties related to human activities. Third are climate data used to establish water input and evapotranspiration losses. The variables used in the model are listed in table 3 with their respective data sources. Almost all the original data sources have been modified in a GIS for the purposes of running the model. In addition most of the original vector data sources have been converted to a 30 by 30 meter grid system.

Table 3: Data used in the model and sources, all are available as ArcView data layers

Data catagory	Data Source
Physical surface properties	
Soil type	NPS[a] from USGS soil survey maps
Soil hydrologic group	NPS: for mapping units, data added by project
Soil water holding capacity	NPS: for mapping units, data added by project
Soil depth	NPS: for mapping units, data added by project
Soil water holding capacity	Derived from soil data
Elevation	USGS[b] Digital elevation model (DEM[c] - 30m)
Slope	Derived from DEM
Aspect	Derived from DEM
Flowlength from grid cell	Derived from DEM
Infiltration rates[d]	NPS: for mapping units, data added by project
Human activity	
Current land-use	NPS: (vegetation); SCAG[e] (heavily modified)
Future land-use	NPS: (vegetation); SCAG and City Plans[f]
Fire extent[d]	NPS: used 1982 for ongoing project
Climate data	
Precipitation data	3 stations NCDC[g] (possibly LACPW[h] and VCPW[i])
Temperature data	One station from NCDC
Stream gauge data (daily flow)	One station from USGS

[a] = National Park Service, Santa Monica Mountains National Recreation Area

[b] = United States Geological Survey

[c] = Digital Elevation Model

[d] = Variables not used in the current model

[e] = Southern California Association of Governments

[f] = All entered manually from various paper sources

[g] = National Climate Data Center

[h] = Los Angeles County Department of Public Works (for future use)

Climate data are currently limited, but in the future additional data will probably be included from the Los Angeles and Ventura County Public Works agencies. However due to variable times of observation for these stations there are some problems to be resolved before it can be incorporated into the model. For the purpose of this report 1995 climate data was used to calibrate and run the model simulations. In the future other climate years or series of years will be used to simulate the impacts of future land-use impacts on ENSO year floods, and to evaluate the impact of fire on flow rates. In addition the model allows for a combination of these events to be simulated simultaneously to predict worst-case scenario conditions.

Model output provides watershed averaged values for a number of water balance and flow variables (table 4). Only a subset of the model output will be presented for this particular report. These include daily flow estimates and for the calibration section and flow and water source charts for the current and future land-use scenarios.

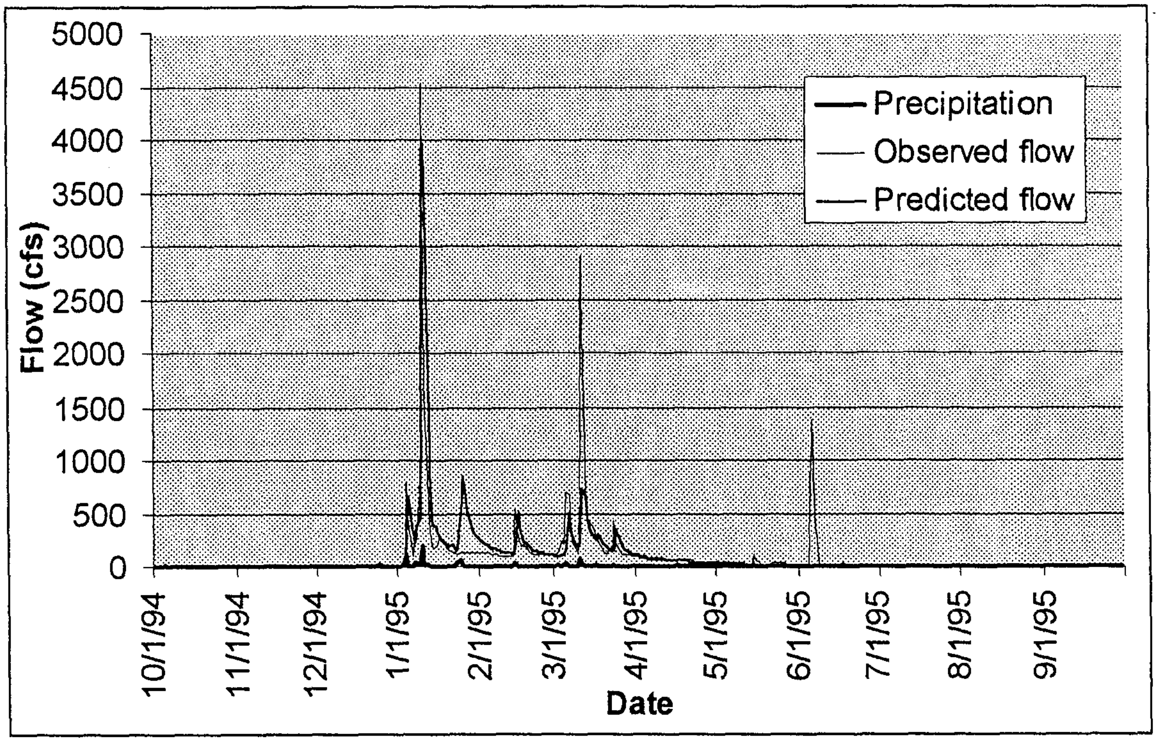
Table 4: Model output variables. All are averaged for the entire watershed.

Model output variables interpolated to and derived at gridcells
Interpolated temperature (inverse distance squared based)
Interpolated precipitation (inverse distance squared based)
Potential evapotranspiration
Actual evapotranspiration
Moisture deficit
Overland runoff
Infiltration
Moisture surplus
Groundwater recharge and contribution to streamflow
Throughflow contribution to stream flow
Soil moisture level
Total daily flow
Stream infiltration rates
Proportion of daily flow originating from specific land-use types

2.6.4 Model Validation

The model was validated using a subset of the Malibu watershed. Specifically the watershed above the stream gauge was used to estimate streamflow at the gauge. Input was based on a subset of the entire watershed database, and on the 1995 water year climate data for 3 precipitation stations and one temperature station. The model estimated daily streamflow was then compared to the observed daily stream flows. Results are graphically illustrated in figure 2.6.3.

Figure 2.6.3: Predicted and observed flow rates for the 1995 water year. Precipitation is also indicated at the bottom



Results show that the model predicts observed flows quite well. Most of the peak events are simulated very well with two exceptions. The exceptions illustrate some of the difficulties associated with the data input component of the model. The rain event of January 23-25 translates into a significant flow event based on model prediction. However, the observed values show very little response to the rainfall event. Most likely this is due to the lack of adequate data input from the three precipitation stations used to obtain rainfall estimates over the watershed. Only one of these stations is actually located in the watershed and their locations are biased to a eastern direction. Interpolation from these stations results in significant rainfall estimation errors on a daily time scale. In this case it is likely that while the eastern portion of the watershed received significant amounts of rainfall the rest of the watershed received relatively little rain. The result is a dramatic over-estimation of model predicted runoff for that event. A similar situation is observed on June 5-6 where none of the precipitation stations recorded any rainfall, but the observed flow records show a significant runoff event. In this case it is likely that there was significant rainfall over the western portion of the watershed that was not observed by any of the stations used in the study. Similarly the events of January 3-4 (140mm average basin wide precipitation from interpolation) and March 10-11 (120 mm average basin wide precipitation) result in similar predicted flows, but show significant variation in observed flow rates.

The geomorphology of this particular watershed makes this a particular difficult location to interpolate daily rainfall events accurately. The orographic effects on precipitation distribution, which can be significantly different depending on the storm direction, make accurate interpolation from a sparse data very difficult. This can only be improved with a better observation network. We are in the process of incorporating additional stations into our network from LA and Ventura County Public Works data sources. However there are difficulties in this approach because of time of observation issues and automation procedures.

The previous examples show the difficulty in obtaining truly accurate estimates of any given runoff event for any model. In terms of systematic errors the model has two potential problems. First is that peak flows tend to be smoothed compared to the observed values. In most cases this means that the model under-estimates the daily flow on the day of peak flow, but overestimates the flow for the next day or two days. When integrated over three or four days the total flows are similar, but the model tends to have a flatter hydrograph. It is likely that with further calibration this can be improved. The second systematic difference between the observed and predicted flow is in the dry-season flow rates. Near the end of April and early June, the model goes from a slight over-prediction of flow rates to under-predicting flow rates, and by the end of July the model predicts runoff values of less than 1 cfs, reaching zero flow by late August. Observed flows for this time period are consistently around the 5 cfs mark. This discrepancy can in part be explained by the water releases from the Tapia water treatment plant, which releases similar water quantities to the river system near the gauge. We can adjust for this water input in the future by including the Tapia water releases into the model. We have received the data to do this but have not yet had time to incorporate it in the model.

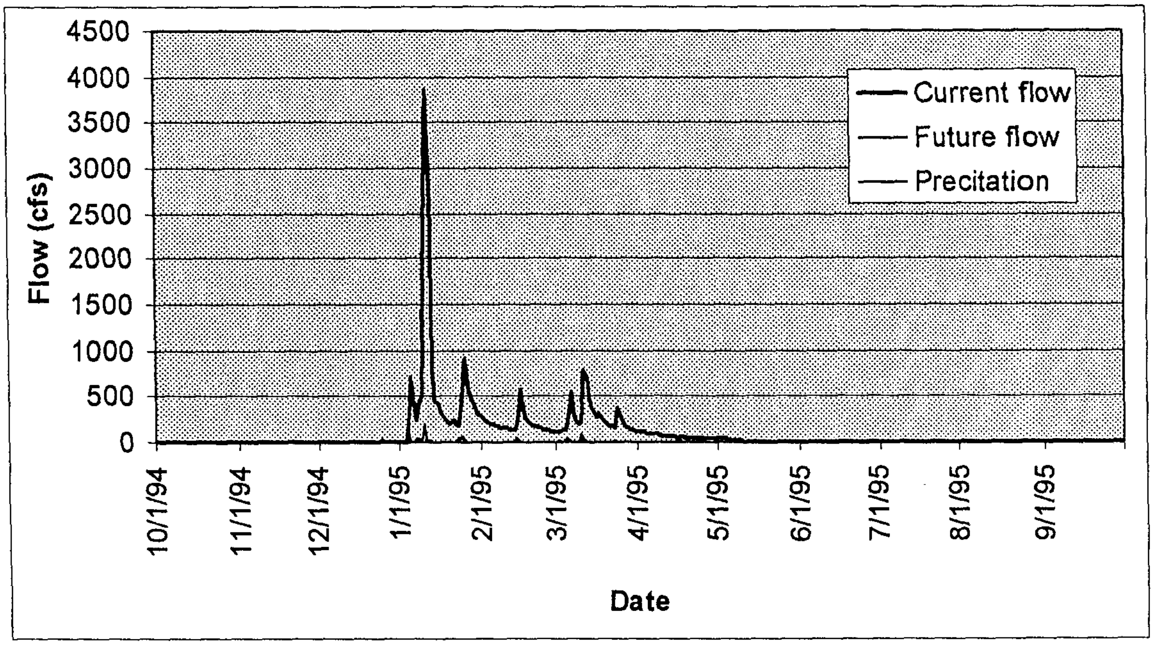
At this point, given the data input problems, it would be difficult to improve the model significantly. Any calibration would potentially be biased towards specific peak events and we need to build up a larger database of flow events. In addition the climate records are highly irregular, and there are many missing observations. We chose 1995 as a trial period because it had a number of interesting runoff events and a complete climate record for at least 3 precipitation stations. The model is capable of running for up to a 100 year time period, however on a 266 Pentium PC it takes roughly 5 hours per year to run the model (this could be dramatically reduced by reducing the grid resolution (e.g. to 90 meter DEM -- this should translate to a nine fold increase in runtime).

2.6.5 Comparison of current and future flow rates

To estimate the flow rates into Malibu Lagoon, we ran the model using the same climate data and slightly different surface characteristics to depict current and future conditions. For the current scenario, we used all the required data with the current land-use layer based on current vegetation and urban land-use maps (SMMC and SCAG -- heavily modified to fill in gaps etc.-- see the GIS database for the maps). The future scenario uses all the same basic soils and surface property inputs, but uses a land-use layer that represents a situation where all zoned areas in the watershed are completely built out. In other words any area zoned for residential land-use is assumed to have that land-use (in the current scenario many of these areas are still in a natural state). The future land-use map is based on the current land-use and zoning maps from various cities in the watershed. These were digitized and used to generate the future land-use changes over the current scenario.

Results for the two runoff scenarios (current and future) are shown in figure 2.6.4. Based on the graph it is impossible to distinguish the differences, but there are some during high flow events. Most of the watershed is regulated by runoff from naturally vegetated areas, so changes in land-use, especially in the upper watershed have relatively little influence on runoff volume. Water from these distant areas also has much more opportunity to infiltrate before it reaches the lagoon area. In most case the changes in flow are towards an increase for the future land-use scenario (up to 5 cfs). Results for the large January event depart from this trend with a slightly higher peak flow on the first day of a storm (almost 10 cfs), followed be a decline in flow rates the following few days (almost 20 cfs). These results vary because of the distribution of rainfall varies with each rainfall event.

Figure 2.6.4: Results of current and future runoff predictions based on changing land-use patterns in the Malibu watershed.

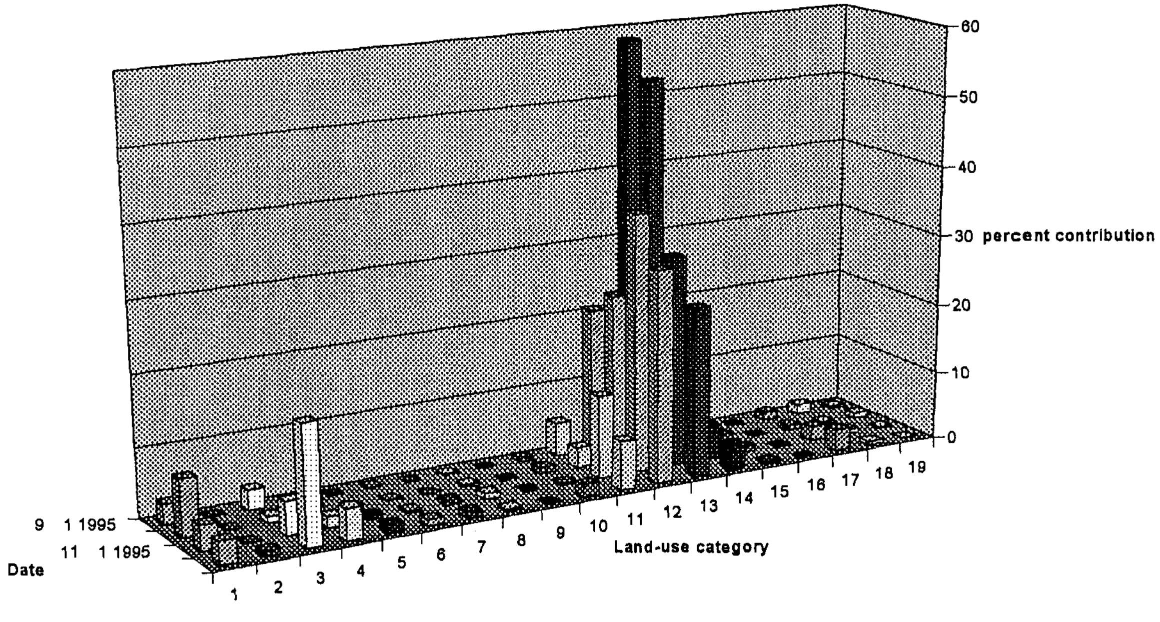


2.6.6 Comparison of runoff sources for current and future runoff events

For each day in the model runs, the model keeps track of the origin cell of all water that becomes runoff for that day. This includes all the water from a cell that contributes to overland runoff, throughflow and groundwater flow as incorporated in the model. Using this technique it is possible to breakdown the proportion of flow that originates from the 19 land-use categories used in the study. This is expressed in percentage terms for each daily flow. In this example we will comparative data for three events in the 1995 record, these include the extreme event of January 9-12, 1995 a medium flow event on February 13-14, 1995, and a low flow event on April 30, 1995.

Figure 2.6.5 shows the proportion of runoff from each land-use category for each day for the January event under the current land-use scenario. Note that there is a significant change in the contribution to flow by each land-use type over the 4 days. This is the result of the uneven geographic distribution of the land-use types and precipitation. Further locations from the river show a more significant contribution later in the flood event. It is evident that suburban water sources contribute later in the flow regime in part because they are located furthest away from the river outlet (e.g. Westlake Village etc.).

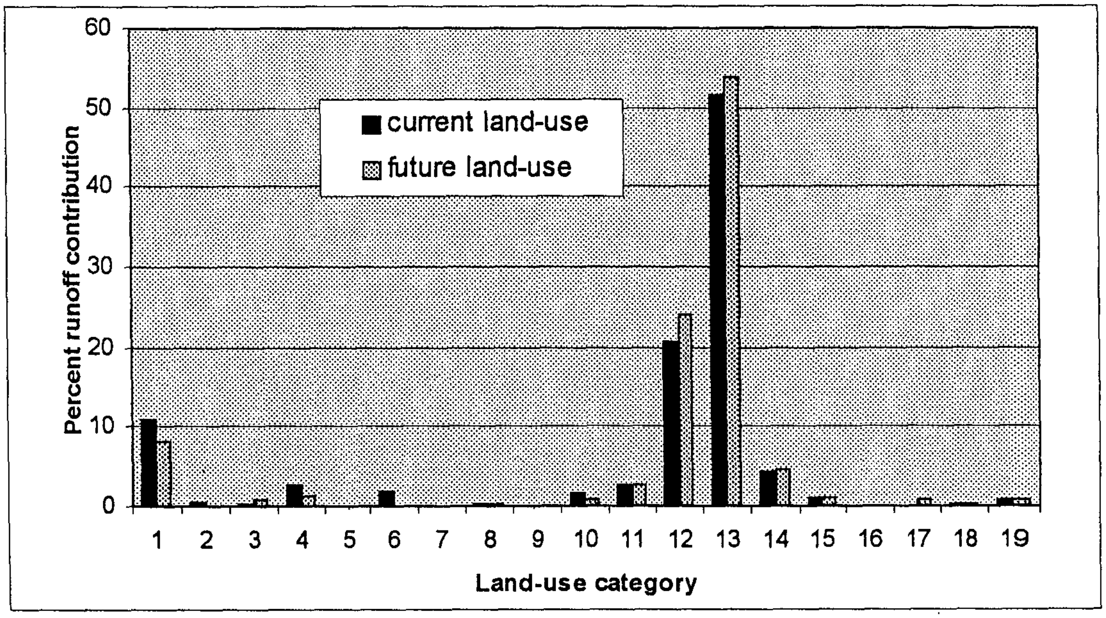
Figure 2.6.5: Predicted land-use sources for January 9-12, 1995 daily flow contributions under the current land-use scenario



Most of the runoff is generated from the natural land-use categories (10-14 -- see table 1), but urban residential contributes significantly to the later flows in the storm event as is expected given the distance of travel for much of this water, and can also be attributed to the distribution of rainfall for each storm day (Jan 10-12).

Although overall flow rates are not dramatically changed there are some interesting changes in water source between the current and future scenarios. On the first day of the storm (January 10 - figure 2.6.6) a greater proportion of the runoff is contributed in the future scenario compared to the current. However on the second day (January 11 - figure 2.6.7) there is a significantly greater contribution from urban runoff sources. This is expected since most of the early runoff will be from nearby sources, which are mostly natural vegetation classes. Most of the second day runoff will be from the more urban upper watershed. In the future it is the upper watershed that will see the most significant changes in land-use patterns. In addition the proportions also change because of different precipitation patterns associated with the two days.

Figure 2.6.6: Comparison land-use contributions to runoff for current and future scenarios on January 10.



For a less extreme event (February 13 and 14, 1995, figure 2.6.8) A similar trend is visible between current and future flow patterns, although there is less variability between the patterns for each day. Finally, figure 2.6.9 shows the change in runoff contribution between the current and future land-use scenarios for low flow conditions. This is probably the most significant change in that a significantly greater proportion of the creek flow will come from urban sources. However much of this will be from groundwater and throughflow sources.

Figure 2.6.7: Comparison land-use contributions to runoff for current and future scenarios on January 11.

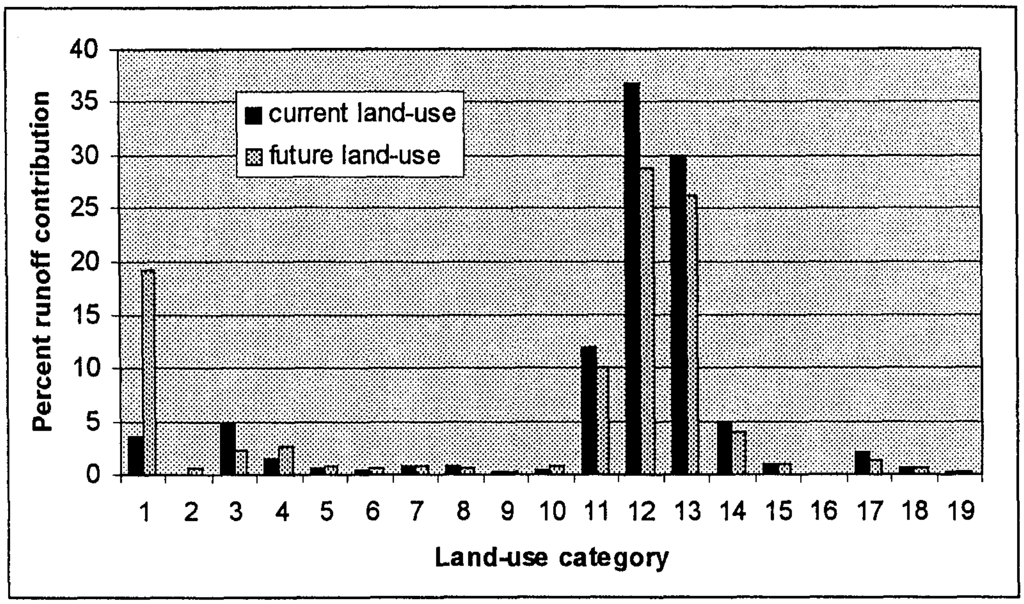


Figure 2.6.8 Current and future distributions of runoff by land-use category for a medium size storm (February 13-14), the first two dates are the current land-use scenario, and the second two dates are for the future land-use scenario.

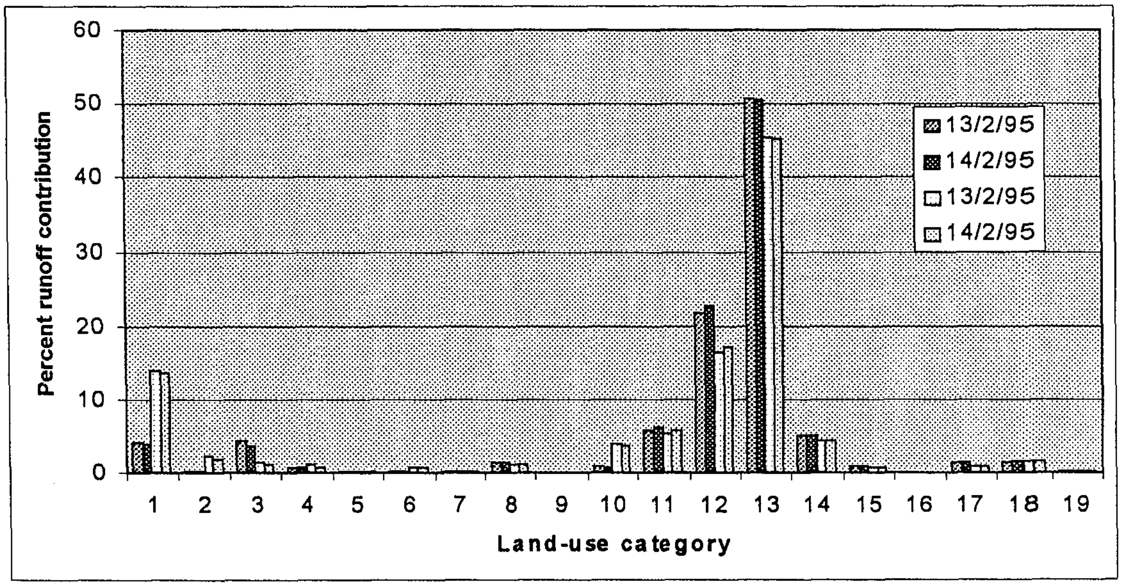
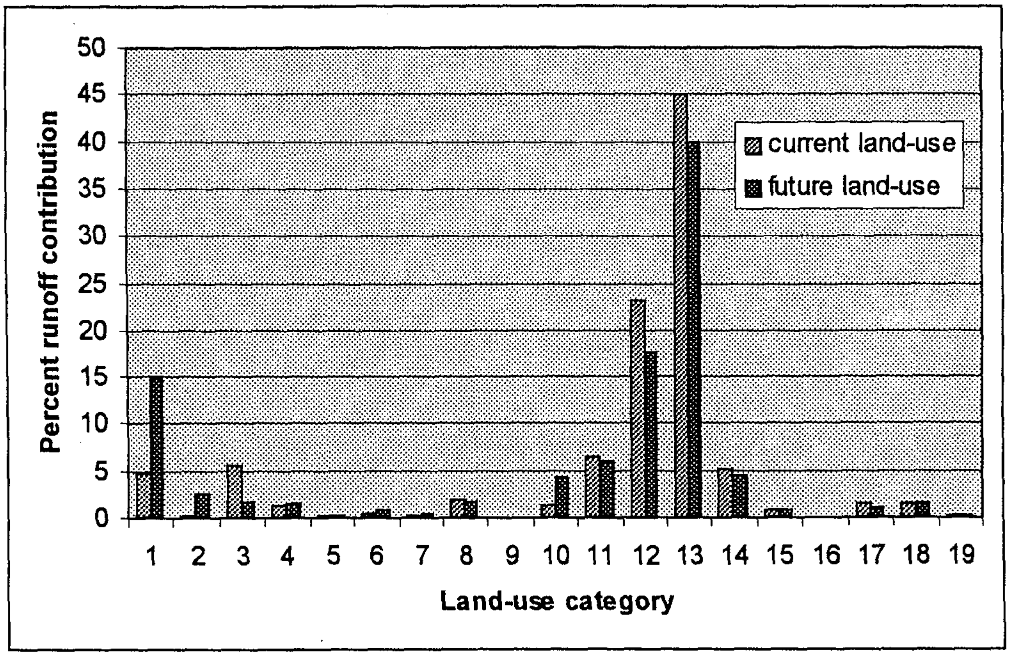


Figure 2.6.9 Low flow (April 30, 1995) land-use contributions under the current and future land-use scenarios.



2.6.7 Conclusions

Future flows in the Malibu basin will depend on a number of variables. Some of these variables are under direct political and human control while others are beyond our means of control. The former includes changes in land-use, channelization and creation of hydraulic structures (dams etc.). The latter includes such events as climate change, the frequency and severity of ENSO events, and changes in geomorphology of the basin (natural and human induced). For the purpose of this report we have focussed on one of these potential changes (land-use) to evaluate the efficacy using a hydrologic model to test future flow scenarios.

The model has shown reasonable agreement with observed water flows, given the quality of the input data that is readily available for such purposes. For the moment we elected to only run the model for a future land-use scenario to illustrate its applicability to predicting future flows for illustrative purposes. In the near future we expect to expand this work by evaluating changes associated with ENSO events (requires different climate input scenarios (historical or modeled), fire events (already incorporated through as part of land-use and SCS curve number selection), future climate changes based on GCM or regional scale models (create climate scenarios for input), and additional land-use scenarios. In addition it will be possible to consider these scenarios either separately or in combinations. The model was also developed in such a way as to be able to track the water source since much of the concern over the condition of the Malibu lagoon relates to water quality. By tracing the source of water in the flow we can make intelligent estimates of water quality in given flows. From this particular experiment it is evident that water quality and origin is dependent on a number of factors, the most important of which is the distribution of rainfall. However as the watershed is further low flows especially will have a greater contribution from urban water sources.

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Chapter 3: Biological and Water Quality Objectives and Habitat Associations

Richard F. Ambrose
Tonatiuh Trejo

3.1. Introduction

This chapter presents the results of our literature review of biological and habitat requirements of indicator species in lower Malibu Creek and Malibu Lagoon. This work was conducted as Task 3 of the Request for Proposals (RFP), which was "to gather and analyze current information on the biological requirements of identified sensitive species inhabiting Malibu Lagoon and lower Malibu Creek," and a portion of Task 4A, specifically a habitat association analysis and a summary of threats to the habitats most suitable for various animal species in Malibu Creek and Lagoon.

Although presented in the RFP as separate tasks, the development of water quality objectives and the summary of habitat requirements both focus on indicator species of lower Malibu Creek and Malibu Lagoon and both are concerned with how species respond to their physical environment. Accordingly, we have included both tasks in this chapter. Section 3.2 considers the information that could be used to generate biological and water quality objectives. Section 3.3 considers the critical habitat characteristics for the indicator species.

3.2. Biological and Water Quality Objectives

3.2.1. Introduction

One approach to protecting the ecological health of Malibu Lagoon is to develop water quality objectives based on the requirements of the species inhabiting the lagoon. In theory, maintaining the physical conditions of the Lagoon within the preferred (or at least tolerable) ranges of its inhabitants would help ensure a healthy lagoon ecosystem.

A difficulty with this approach is that there are hundreds of different species inhabiting the Lagoon, each with its own habitat requirements. Thus, a simplified approach is to identify indicator species that could serve as "representatives" of the entire community. We selected 15 indicator species (described below) for the lower Malibu Creek watershed and Malibu Lagoon.

In the following sections, we summarize the information we found on the tolerances of these indicator species to physical characteristics or chemicals in the water that could affect their biology. We focus most on the two endangered and, arguably, most important indicator species, the tidewater goby and steelhead. Following the sections covering these two species, we summarize the information available for the remaining positive indicators, and then the information on the negative indicators. As expected, there was no information available for most of the physical parameters for most of the species.

3.2.2. Methods

Many issues need to be considered when deciding on what indicator species to use. Indicator species could be chosen to be representative of the potentially impacted community, in that they would have an "average" response to changes in environmental conditions. On the other hand, one might want indicator species to be particularly sensitive to environmental changes, so they could serve as an "early warning system." Endangered species might be included because of particular concern about the status of their populations. In addition, one might want to include species that are not currently present in the habitat, but who might occur there if conditions were appropriate. For each of these reasons to include particular species as indicators, there are also reasons not to include them. For example, if an indicator species is too sensitive, then it is only useful for distinguishing between pristine and slightly degraded conditions. Also, if an indicator species does not occur at a site, it cannot be certain that its absence is due to environmental degradation rather than other reasons (such as lack of dispersal to the site).

The indicator species we considered are presented in Table 3-1. We have used two different categories of indicators. Most of the species are "positive" indicators, species whose presence or high abundance would suggest good environmental conditions and a healthy ecosystem. There are nine fish species. Two, the tidewater goby and steelhead trout, are federally listed endangered species. The tidewater goby is presently a common member of the Lagoon ichthyofauna, though it had been extirpated from the Lagoon and the current population is the result of a reintroduction. Although the tidewater goby has particular habitat and water quality requirements, they are likely to be generally reflective of the original lagoon ecosystem at Malibu, where there was a seasonal sand bar blocking the entrance to the ocean (Swift et al. 1989). Thus, tidewater gobies may be a good indicator of lagoon conditions. Steelhead trout traditionally run in Malibu Creek, but the run is greatly diminished and steelhead are currently uncommon in the system. Steelhead trout use the lagoon as well as the creek, but they are included primarily as indicators of creek conditions; they are the only creek indicator species evaluated. The seven other fish species are all common native species occuring in Malibu Lagoon, as well as being typical species of southern California estuarine systems. These species vary in the extent of their use of estuaries, some being completely restricted to estuaries for their entire life cycle, others using estuaries as nursery habitat, and others occuring freely in estuarine and marine waters. Finally, we include two invertebrate species, the jackknife clam and mud-flat crab. Both are currently common in Malibu Lagoon.

Four "negative" indicator species were also chosen. High abundances of these species would suggest a dysfunctional ecosystem. Three of these are introduced species. The mosquitofish is currently common in Malibu Lagoon and other estuarine systems with large freshwater inputs; it is generally not common in southern California estuaries that have not experienced augmented freshwater inflows. The yellowfin goby does not currently occur in Malibu Lagoon, but it has invaded other southern California estuaries. The oriental shrimp is currently common in Malibu Lagoon. The fourth negative indicator species, a polychaete worm, is a native species most likely to be abundant in degraded environments; it is currently common in Malibu Lagoon.

3.2.3. Species Accounts

In this section, we first discuss tidewater gobies and steelhead in detail, followed by summaries for the other indicator species. Information about the physical tolerances of the indicator species (along with appropriate literature citations) for salinity, temperature, ammonia, pH, dissolved oxygen, nitrate, nitrite, and sulfide are presented in the text and summarized in Table 3-2.

3.2.3.1. Tidewater Goby

3.2.3.1.1. Introduction

The tidewater goby, *Eucyclogobius newberryi*, is a small (≤ 50 mm), benthic fish endemic to California's coastal estuaries from the Agua Hedionda Lagoon, San Diego County, in the south to the Smith River, Del Norte County, in the north (Moyle et al. 1989). It is the only species in the genus *Eucyclogobius* (Moyle et al. 1989), but is closely related to several eastern Pacific species (bay goby, arrow goby *Clevlandia ios*, cheekspot goby *Ilypnus gilberti*, shadow goby *Quietula y-cauda*) (Swenson 1995). Most individuals complete their life cycle within one year (Capelli 1997), although laboratory specimens have survived up to three years (Swenson 1995). Habitat loss and degradation, and predation by exotic fishes have reduced the number of tidewater goby populations to fewer than 50, leading to its designation as a federally endangered species in 1994 (USFWS 1994). The tidewater goby is known to be a weak swimmer (Swenson 1995), and is therefore easily swept into the ocean during periods of heavy flow. For example, winter storms in 1972-73 caused the elimination of a tidewater goby population from Wadell Creek (Swenson 1995). Populations are considered to be genetically isolated (Crabtree 1985), as the goby lacks a marine phase in its life history and is therefore limited in its dispersal ability. However, tidewater gobies have been recorded at sites where they were reportedly eliminated by the 1987-92 drought (Capelli 1997). This suggests that recolonization and/or genetic exchange between neighboring populations may indeed occur. A short life span, narrow habitat requirements, and isolation of populations are all factors which, combined, increase the tidewater goby's susceptibility to natural and anthropogenic environmental change.

3.2.3.1.2. Life History

Although the tidewater goby may spawn at any time of year, spawning is most prevalent from spring to mid-summer (Capelli 1997). This period coincides with the time during which most California estuaries are naturally closed to the ocean and brackish water conditions prevail. Spawning activity may continue into fall and even winter if water temperatures remain warm and the berms found at the mouths of estuaries are not breached (Capelli 1997).

Of interest to behavioral ecologists, the breeding behavior of the tidewater goby is remarkable for the dominance and aggressiveness displayed by females. Unlike other gobies, females compete for access to burrows occupied by territorial males (Swenson 1995). Furthermore, females have highly developed black breeding coloration are reported to initiate courtship more frequently than males (Swenson 1995, Swift et al. 1989)

Males excavate 10-20 cm burrows in coarse sand and protect a clutch of 300-500 eggs (Lafferty et al. 1996) until they hatch 9-11 days later (Swenson 1995). Newly hatched fry measure 4-5 mm TL (Swenson 1995), lack distinct coloration, and begin a pelagic existence. At 15-18 mm SL juveniles assume a benthic lifestyle (Moyle et al. 1989).

Tidewater gobies are known to live in a variety of habitats, although adults seem to prefer vegetated areas, which provide both cover from predators and substrate for crustacean prey (Swenson 1995). The tidewater goby feeds primarily on small crustaceans (mysid shrimp, ostracods, amphipods, etc.), aquatic insects (chironomid and diptera larvae), and molluscs (Irwin and Soltz 1984, Moyle et al. 1989), with diet depending on season and habitat (Swenson 1995).

Other gobies native to California estuaries are not thought to compete with the tidewater goby for food, as they spend portions of their lives in the ocean. However, introduced species, particularly the yellowfin goby, *Acanthogobius flavimanus*, and shimofuri goby, *Tridentiger bifasciatus*, are trophic competitors of the tidewater goby. Furthermore, these fish also prey on tidewater gobies (Wang 1984, Saiki 1993, Swenson 1995). The diet overlap between the three gobies may increase their encounter rate, and is thought to enhance the predation risk for the tidewater goby (Swenson 1995).

Resulting extinctions of tidewater goby populations could have significant impacts upon estuarine trophic dynamics. The tidewater goby is often one of the most abundant small fish population in estuaries where it is present (Lafferty et al. 1996). As secondary consumers and a prey item for larger fish and piscivorous birds, tidewater gobies are an important part of estuarine food webs (Swenson 1995).

3.2.3.1.3. Reasons For Using The Tidewater Goby as an Indicator Species

The tidewater goby *Eucyclogobius newberryi* appears to be an ideal indicator organism. A comprehensive review of the scientific literature pertaining to this species has produced a substantial amount of information regarding its habitat requirements and life history. Similar data on other Malibu Creek and Malibu Lagoon fish species, with the exception of the steelhead trout (*Oncorhynchus mykiss*), was scarce.

Eucyclogobius newberryi is also important in that it holds a unique position among California fish. The tidewater goby is one of only seven species of gobies native to California estuaries (Capelli 1997), and also belongs to a group of just three fish species living along the Pacific coast dependent upon a low salinity habitat (Swift et al. 1989).

Also of interest for using the tidewater goby as an ecological indicator is its status as a federally endangered species. Since 1900, habitat loss and degradation have resulted in its disappearance from 74% of the coastal lagoons south of Morro Bay (Moyle et al. 1989). Competition with and predation by non-native fish such as the yellowfin goby

(*Acanthogobius flavimanus*), shimofuri goby (*Tridentiger bifasciatus*), stiped bass (*Morone saxatilis*), largemouth bass (*Micropterus salmoides*), white catfish (*Ameiurus catus*), tilapia (*Tilapia* spp.), and western mosquitofish (*Gambusia affinis*), may also be responsible for extinctions of tidewater goby populations (Saiki 1994, Lafferty and Page 1997, Wang 1984, Swenson 1995).

The native fish fauna of California is in serious decline, with 63% of its 155 taxa already extict or in danger of becoming extinct (Moyle 1995). Introduced fish species are at least partially responsible for this trend, the plight of the tidewater goby serving as a prime example. In the San Francisco Bay area, invasions by the predatory yellowfin goby *Acanthogobius flavimanus* (Brittan et al. 1970, McGinnis 1984) and the rainwater killifish *Lucania parva* (Lafferty and Page 1997) may have permanently eliminated local tidewater goby populations. In southern California, where the tidewater goby has disappeared from 74% of the coastal lagoons south of Morro Bay since 1900 (Moyle et al. 1989), over 100 non-native fish species have been reported, giving this region the distinction of exceeding all other areas of the state in numbers of successful invaders (Swift et al. 1993).

3.2.3.1.4. Habitat Requirements

Unlike virtually all other Malibu Creek and Malibu Lagoon fish, the tidewater goby has narrow habitat requirements. It is restricted to coastal brackish-water areas of coastal streams, marshes, lagoons, and estuaries in California (Swenson 1995, Swift et al. 1989, Lafferty and Page 1997).

3.2.3.1.5. Dissolved Oxygen

The EPA recommends dissolved oxygen levels ≥ 6.5 mg/L for early life stages of nonsalmonid fish. For all other life stages, the EPA recommends levels ≥ 6 mg/L (U.S. EPA 1986). The dissolved oxygen concentration range under which the tidewater goby is reported to live varies from 4-19 mg/L (Saiki 1994).

3.2.3.1.5.1. Recommendation

While early life stages of *Eucyclogobius newberryi* are present in Malibu Creek and Malibu Lagoon, dissolved oxygen levels should not fall below 6.5 mg/L. During all other times, the dissolved oxygen content should be ≥ 6 mg/L, and should never exceed 19 mg/L.

3.2.3.1.6. pH

For the maximum protection of freshwater aquatic life, the EPA recommends pH values in a range of 6.5-9.0. The recommendation for marine aquatic life is slightly narrower, at 6.5-8.5 (U.S. EPA 1986). *Eucyclogobius newberryi* is reportedly able to survive in waters with a pH range of 6.8-9.5 (Saiki 1994).

3.2.3.1.6.1. Recommendation

To best protect the tidewater goby, pH levels in Malibu Creek and Malibu Lagoon should always range from 6.8-9.0.

3.2.3.1.7. Salinity

The tidewater goby can survive in salinities from 0 to 53 ppt (Capelli 1997) and has been reported to spawn over a range of 2-27 ppt (Swenson 1995). However, most estuaries providing suitable habitat have salinities of 5-20 ppt, with the goby preferring a much narrower range of 10-15 ppt (Capelli 1997). For this reason, the tidewater goby is usually associated with estuaries that develop seasonal sand and cobble berms at their mouths, thus eliminating tidal action. Estuaries with a permanent connection to the ocean typically have higher salinities (20-33 ppt) and rarely support tidewater goby populations (Capelli 1997).

3.2.3.1.7.1. Recommendation

In areas of Malibu Creek and Malibu Lagoon where the tidewater goby is known to occur, water salinity should never fall below 2 ppt nor exceed 27 ppt, with an optimum range of 5-15 ppt.

3.2.3.1.8. Temperature

Water temperature is an important physical parameter affecting the metabolism, respiration, behavior, distribution, feeding rate, growth, and reproduction of aquatic organisms (U.S. EPA 1986).

The tidewater goby is capable of surviving in water having a temperature range of 8°C (Swift et al. 1989) to 25°C (Swenson 1995), and spawning may occur in temperatures of 9-25°C (Swenson 1995). Peak spawning reportedly occurs in 18-22°C water (Moyle et al. 1989).

3.2.3.1.8.1. Recommendation

Water temperature should be maintained between 8°C and 25°C, except during late spring through mid summer, when peak spawning occurs. During this period, temperatures should be 18-22°C, and should never fall below 9°C or exceed 25°C..

3.2.3.2. Steelhead

3.2.3.2.1. Introduction

The species *Oncorhynchus mykiss* includes both steelhead and rainbow trout native to the eastern Pacific Ocean and the coastal drainages of North America extending from the Santo Domingo River in northern Baja California (USDA 1995) to Alaska (Emmett et al. 1991). Since 1874, rainbow trout have been introduced in streams and lakes worldwide, and are currently found on every continent with the exception of

Antarctica (MacCrimmon 1971). Steelhead have a much narrower distribution, currently ranging from southern California to the Gulf of Alaska and interior British Columbia, from the coast to as far inland as Idaho (Di Silvestro 1997). Steelhead are also reportedly found in Kamchatka and Okhotsk Sea drainages in Siberia (McPhail and Lindsey 1970). Presently, Malibu Creek is the southern-most stream known to contain steelhead, with a population of up to 60 spawners (USDA 1995) and 145 juveniles (Keegan 1990). This population historically had about 1,000 adults (Nehlsen et al 1991).

Although this species was formerly known as *Salmo gairdneri*; the name was recently changed to *Oncorhynchus mykiss* due to its closer phylogenetic relationship to Pacific salmon (*Oncorhynchus*) than to Atlantic salmon (*Salmo*) (Thomas et al. 1986). *Salmo gairdneri* is the name typically encountered in the scientific literature.

Steelhead and rainbow trout frequently coexist and are distinguished not by their genetic composition, but by their life histories and behaviors. Steelhead are anadromous, meaning that they spend portions of their lives in both sea and freshwater. In contrast, rainbow trout spend their entire lives in freshwater. Interestingly, rainbow trout can give birth to anadromous fish and vice versa (Di Silvestro 1997). Why some fish go to sea and others do not is still unknown (Douglas 1995).

3.2.3.2.2. Life history

Steelhead begin life as eggs laid in the gravel of streams, where they incubate up to four months before hatching (Di Silvestro 1997). After hatching, juveniles spend one to three years in fresh water before migrating downstream, undergoing dramatic physiological changes, and entering the ocean (Carpanzano 1996). Steelhead from Oregon and Washington appear to head north to the Gulf of Alaska,while steelhead from southern Oregon and California tend to remain in offshore waters. Commercial fishing vessels have caught these steelhead as far as 3,000 miles out to sea (Di Silvestro 1997).

After spending one to five years in the ocean (Emmett et al. 1991), adult steelhead return to their natal streams to spawn. Unlike other Pacific salmonids which die immediately after spawning, approximately 20% of breeding steelhead return to the ocean and later spawn again, up to six times per individual (Carpanzano 1996). These repeat spawners are mostly female (Di Silvestro 1997).

Steelhead are known for their excellent homing abilities, a trait that has led to the development of unique stocks or races of steelhead in specific streams (Moyle 1976). At least two races are known to exist and are distinguished by when adult fish enter fresh water to spawn (Smith 1960). The summer run migrates during spring, summer, and early fall, while the winter run migrates during fall, winter, and early spring. In some large rivers with many tributaries, steelhead are presumed to migrate year-round. In California, some river mouths are closed during spring and summer, and steelhead may return only in fall after heavy rains (Fry 1973).

In freshwater and estuarine habitats, steelhead feed primarily on gammarid amphipods, small crustaceans, insects, and small fishes (Moyle 1976, Wydoski and

Whitney 1979). In the ocean, juveniles and adults feed on crustaceans, insects, squid, and fishes (LeBrasseur 1966, Wydoski and Whitney 1979).

In freshwater, steelhead are fed upon by coho salmon, char, mergansers, gulls, belted kingfisher, bears, marten, otter, and other steelhead. Its main predators in the ocean are the Pacific lamprey, seals, sea lions, and killer whales (Scott and Crossman 1973).

Mature steelhead are typically 45-70 cm in length and weigh 2-5 kg, but can reach up to 122 cm and 19.5 kg. Fish in the southern part of the range are typically smaller and spend less time in the ocean than those in the north. In a recent study, adult steelhead averaged 58.1 cm in length in California, 66.7 cm in Oregon, and 71.0 cm in British Columbia (Withler 1966).

Virtually all natural mortality (97%) occurs in the egg and larval stages, which are strongly affected by dissolved oxygen, water temperature, velocity, turbidity, depth, competition with other fishes, and pollution (Emmett et al. 1991, Shapovalov and Taft 1954).

The adult winter run of steelhead in Malibu Creek is from December to March, with the peak run in February and March (Fukushina and Lesh 1998).

3.2.3.2.3. Reasons For Using Steelhead Trout as an Indicator Species

An important reason for using the steelhead trout as an indicator species is the vast amount of information available in the scientific literature regarding its environmental requirements, a sharp contrast to virtually all other species inhabiting Lower Malibu Creek and Malibu Lagoon. For example, relevant information pertaining to both the mosquitofish, *Gambusia affinis*, and topsmelt *Atherinops affinis*, was limited to only salinity and temperature requirements. A review of the literature concerning the killifish, *Fundulus parvipinnis*, only yielded information on salinity, temperature, pH, and sulfide requirements. In comparison, relevant information concerning *Oncorhynchus mykiss* included over 100 references and information on the following water quality parameters: temperature, dissolved oxygen, ammonia, pH, salinity, nitrate, nitrite, and hydrogen sulfide. For each of these parameters, numerous studies exist.

Its narrow habitat requirements are yet another reason for choosing the steelhead trout. In Malibu Creek and Malibu Lagoon, almost all fish taxa are highly tolerant to environmental variability. For example, the killifish, *Fundulus parvipinnis*, can live in water ranging from completely fresh to that having salinities as high as 128 ppt (Moyle 1976), while the topsmelt, *Atherinops affinis*, tolerates water temperatures up to 33°C (91.4°F) (Carpelan 1955). Thus, it is difficult, if not impossible, to use these and other species as indicators of water quality in Malibu Creek and Malibu Lagoon.

Another reason for using the steelhead as an indicator species is the important role it presumably plays in southern California estuarine food chains. Research has demonstrated that salmon significantly enrich carbon and nutrient cycles near their spawning sites (Kline et al. 1990, Bilby et al. 1996). In fact, salmonids are regarded as keystone species in maintaining biodiversity, especially in areas where they are abundant (Allendorf et al. 1997).

The tremendous decline of natural populations of steelhead trout, particularly in southern California, is another important reason for choosing it as an indicator species. Despite lacking a predictable water supply, southern California's streams once sustained large runs of steelhead and resident rainbow trout. Recent estimates suggest that annual runs of 30-35,000 steelhead were found in the Santa Inez, Ventura, and Santa Clara rivers during the late 19th century (Douglas 1995). The combined effects of dam construction, stream chanelization, urbanization, and water development reduced these numbers to as few as 500 individuals by 1995 (Douglas 1995). Today, steelhead are rarely found south of the Ventura River (Emmett et al. 1991), with Malibu Creek representing the southernmost stream known to contain steelhead USDA 1995).

Since 1900, more than 23 endemic steelhead stocks have disappeared, and 43 other stocks face a moderate to high risk of extinction (Di Silvestro 1997). The Endangered Species Committee of the American Fisheries Society recently listed 214 native stocks of Pacific salmon (*Oncorhynchus* spp.), steelhead (*O. mykiss*), and coastal cutthroat trout (*O. clarki clarki*) as being at risk of extinction in California, Oregon, Idaho, and Washington (Nehlsen et al. 1991).

Due to declining natural populations, stocks have been augmented by hatchery production. In 1987, up to 17 million steelhead smolts were planted in the Columbia River Basin (Emmett et al 1991). However, the mass release of hatchery fish may have negative effects on wild populations. Studies have shown that hatchery fish have lower survival and reproduction rates than wild fish (Chilcote et al. 1986). Interbreeding with hatchery fish has led to reduced genetic diversity among wild populations and given rise to offspring with lower disease resistance (Reisenbichler and Phelps 1989).

Furthermore, anadromous salmonid species are composed of stocks that originate from specific watersheds and usually return to their natal streams to spawn, resulting in a large degree of reproductive isolation between populations. Because anadromous salmonid stocks are adapted to local environmental conditions, the loss of individual populations is likely to cause changes in genetic composition and loss of genetic diversity (Nehlsen et al. 1991).

Southern California steelhead populations frequently experience environmental conditions not encountered by northern populations. Rainfall and streamflow in southern California are highly variable and unpredictable, and long drought periods are not uncommon. Many streams dry up completely each year, and water temperatures periodically reach or exceed the upper lethal limit. These factors may in part explain recent data demonstrating significant genetic differences between populations of steelhead and rainbow trout in southern California and those north of San Simeon (Douglas 1995, Marx 1996).

3.2.3.2.4. Ammonia

The toxicity of ammonia to steelhead and rainbow trout has been studied extensively, as it is one of the two most significant water quality parameters limiting the production this species in aquaculture (Colt et al. 1980). The effects of ammonia on *Oncorhynchus mykiss* include decreased growth (Burkhalter and Kaya 1977, Rice and Stokes 1975), reduced nitrogen excretion (Fromm and Gillette 1968, Olson and Fromm 1971), increased incidence of disease (Burkhalter and Kaya 1977, Larmoyeux and Piper 1973), gill damage (Rice and Stokes 1974), and other sublethal physiological effects (Larmoyeax and Piper 1973, Mayer and Kramer 1973).

Ammonia is a naturally occurring product of biological metabolism, but high concentrations are often associated with human sources such as sewage treatment plants, agricultural and feedlot runoff, coal coking and gasification plants, and fertilizer manufacturing plants (Burkhalter and Kaya 1977).

Ammonia exists in both ionized (NH_4^+) and unionized (NH_3) forms, with its toxicity dependent on the concentration of the unionized ammonia (UIA) fraction (U.S. EPA 1986, Hofer et al. 1995). The proportion of ammonia present in the unionized form is largely determined by two other water quality parameters, pH and temperature (Alabaster and Lloyd 1982a, Trussel 1972).

Results indicate that the toxicity of ammonia, in terms of NH_3, increases at lower pH values (U.S. EPA 1984). Similarly, it has been shown that elevated water temperature increase the proportion of UIA present in an ammonia solution (Alabaster and Lloyd 1982a).

Other water quality parameters also affecting the lethal toxicity of ammonia to aquatic life include dissolved oxygen (Downing and Merkens 1955, Merkens and Downing 1957), salinity (Herbert and Shurben 1965), and carbon dioxide (Lloyd and Herbert 1960).

The toxicity of ammonia to rainbow trout has been widely studied, with 96-hr LC50 values ranging from 0.16 to 1.1 mg/L NH_3 (U.S. EPA 1984). Among numerous salmonid species tested by the EPA for ammonia toxicity, rainbow trout were the most sensitive, with lethal concentrations of ammonia as low as 0.32 mg/L (U.S. EPA 1984). The tolerance of rainbow trout to ammonia appears to increase as the fish develop through the larval stages, is greatest at the juvenile and yearling stages, and decreases thereafter (Thurston and Russo 1983).

Ammonia seems to have especially significant effects on developmental stages of *Oncorhynchus mykiss*. Growth and development of rainbow trout fry have been shown to be inhibited by long-term exposures to concentrations of ammonia as low as 0.05 mg/L (Burkhalter and Kaya 1977).

3.2.3.2.4.1. Recommendation

Following a comprehensive review of studies on *Oncorhynchus mykiss* and other salmonids, the EPA issued detailed guidelines in 1984 for ammonia in surface waters containing salmonids (U.S. EPA 1984). These criteria are based on both water temperature and pH, the two water quality parameters most strongly influencing ammonia concentration. Guidelines are listed for both 1-hour and 4-day exposure to ammonia. Criteria include both total ammonia concentration and the concentration of unionized ammonia, the portion responsible for adverse effects on aquatic life. Based upon our thorough literature review, we believe that adherence to these guidelines will be protective of steelhead trout in Malibu Creek and Malibu Lagoon.

3.2.3.2.5. Dissolved Oxygen

Dissolved oxygen (DO) is often a limiting factor in maintaining freshwater aquatic life. Low oxygen levels have a significant effect on many physiological, biochemical, and behavioral processes in fish. Depletion of oxygen levels is a common result of many forms of water pollution, and the effects on *Oncorhynchus mykiss* have been extensively studied (Alabaster and Lloyd 1982b, Barton and Taylor 1966, Davis 1975, Downing and Merkens 1955, Garside 1966, Jones 1971, Lloyd 1961, Matthews and Berg 1997, Nebeker and Brett 1976, Rombough 1988, Silver et al. 1963, Thurston et al. 1981).

Reduced dissolved oxygen concentrations are known to increase the toxicity of various poisons (e.g., ammonia, hydrogen sulfide, cadmium, cyanide, zinc, lead, copper, phenols) to freshwater aquatic life (Thurston et al 1981, Davis 1975). Studies have demonstrated low dissolved oxygen levels to increase the toxicity of ammonia (Downing and Merkens 1955, Merkens and Downing 1957), cyanide (Downing 1954), and zinc, lead, copper, and phenols (Lloyd 1961) to rainbow trout. Sublethal effects of low DO levels in steelhead trout include retarded development, reduced growth, and premature hatching and emergence of embryos (Rombough 1988).

Rainbow trout and steelhead reportedly require well-oxygenated (5-11 ppm) water (Douglas 1995). Another recent study found the optimal DO levels for rainbow trout to be ≥ 7 mg/L at temperatures ≤ 15°C, and ≥ 9 mg/L at temperatures >15°C (Barton and Taylor 1996). Spawning steelhead require at least 80% saturation, with temporary levels not lower than 5.0 mg/L (Moyle et al. 1989). The incipient lethal level for adult and juvenile rainbow trout is approximately 3 mg/L, depending on environmental conditions, especially temperature (Matthews and Berg 1997).

The extreme sensitivity of salmonids to low dissolved oxygen levels during early life is well-documented (Davis 1975, Alabaster and Lloyd 1982b, Rombough 1988). The lower threshold for the incubation of salmonid embryos is reported to be 5.0 mg/L (Reiser & Bjornn 1979), with 100% mortality of embryos occurring at 1.6 mg/L (Garside 1966, MacCrimmon 1971, Shumway et al. 1964).

A comprehensive review of the minimum oxygen requirements of Canadian aquatic life (Davis 1975) recommends DO levels ≥ 9.74 mg/L to provide the maximum level of protection for salmonid larvae and mature eggs. Symptoms of oxygen distress in larvae and eggs were reportedly noticeable at levels below 8.09 mg/L (Davis 1975). In a more recent review, the EPA recommends DO levels ≥ 11 mg/L to protect salmonid embryo and larval stages (U.S. EPA 1986).

With regards to juvenile and adult life stages, the EPA has designated levels ≥ 8 mg/L as sufficiently protective (U.S. EPA 1986), while Davis proposes DO levels ≥ 7.84 mg/L (Davis 1975).

Streams with oxygen-supersaturated water may also adversely affect steelhead trout, but such conditions are rarely encountered in nature. Elevated oxygen levels can lead to gas-bubble disease in fish, especially when accompanied by high pH values (Alabaster and Lloyd 1982b). One study found the 96-hr LC50 value for steelhead to be 116% saturation, while the 30-day LC50 was 114% (Nebeker and Brett 1976).

3.2.3.2.5.1. Recommendation

Dissolved oxygen criteria in Malibu Creek and Malibu Lagoon for *Oncorhynchus mykiss* should depend upon the life stages present, since young fish are especially sensitive to low oxygen levels. Therefore, we recommend DO concentrations ≥ 9 mg/L while embryo and larval stages are present, with levels never lower than 7 mg/L. For all other life stages, we recommend DO levels ≥ 6 mg/L, with temporary levels never to fall below 4 mg/L.

3.2.3.2.6. Hydrogen Sulfide

Hydrogen sulfide is an anaerobic degradation product of both organic sulfur compounds and inorganic sulfates, including those in sewage, algae, and other naturally deposited organic material (U.S. EPA 1986). It is a soluble, highly poisonous gas having a characteristic rotten egg odor, and can be detected in the air by humans at a concentration as low as 0.002 ppm (U.S. EPA 1986).

Data concerning the effects of hydrogen sulfide on *Oncorhynchus mykiss* was scarce. One study reported the 96-hr LC50 for rainbow trout to be 0.4μM (Bagarinao 1991). Another researcher reports rainbow trout survival in hydrogen sulfide concentrations as high as 0.45 mg/L (Ortiz et al. 1993), but this study was based on short-term (8-hour) exposure. Recent long-term field and laboratory studies demonstrate hydrogen sulfide toxicity at much lower concentrations (U.S. EPA 1986). Accordingly, the EPA recommends levels no higher than 2 μg/L of hydrogen sulfide for the protection of fish and other aquatic life (U.S. EPA 1986).

3.2.3.2.6.1. Recommendation

The scarcity of data concerning the toxicity of hydrogen sulfide to *Oncorhynchus mykiss* precludes us from drawing any definite conclusions. We recommend following the EPA criteria (≤ 2 µg/L) as long as no contradictory data causes a revision of this limit.

3.2.3.2.7. Nitrate

Nitrate is formed by the complete oxidation of ammonium ions by water microorganisms (U.S. EPA 1986). It is reportedly of little concern to aquatic life (Colt et al. 1980). There was a scarcity of data regarding the effects of nitrate on steelhead and rainbow trout. The only reference found reported the upper lethal tolerance of rainbow trout to be 1300 mg/L NO_3-N (Westin 1974). In its only recommendation regarding water nitrate levels, the EPA concluded that levels at or below 90 mg/L would have no adverse effects on warmwater fish (U.S. EPA 1986). No mention is made of any criteria for coldwater fish or salmonids.

3.2.3.2.7.1. Recommendation

At a minimum, 1300 mg/L should be set as the upper limit of nitrate in Malibu Creek and Malibu Lagoon. However, this limit should flexible and subject to change, as conclusive data concerning this water quality variable is lacking. Low nitrate levels are not a concern, as only elevated levels are potentially harmful to aquatic life.

3.2.3.2.8. Nitrite

Nitrite is a naturally occurring anion, and is produced by the bacterial oxidation of ammonia (Colt et al. 1980). Its concentration is typically less than 0.005 mg/L (Lewis and Morris 1986). Nitrite is toxic to aquatic organisms in that it alters hemoglobin, thereby reducing the total oxygen-carrying capacity of the blood (Colt et al. 1980). The toxicity of nitrite can therefore be increased by a reduction in the dissolved oxygen concentration. Temperature, which has a direct relationship with dissolved oxygen availability, could also be expected to increase nitrite toxicity (Lewis and Morris 1986). The lethal toxicity of nitrite is also dependent upon the pH (Wedemeyer and Yasutake 1978, Lewis and Morris 1986), calcium concentration (Russo et al. 1974, Wedemeyer and Yasutake 1978), and the chloride level (Eddy et al. 1983, Perrone and Meade 1977, Wedemeyer and Yasutake 1978).

Salmonids are among the most sensitive taxa studied, with little difference in tolerance among species (Lewis and Morris 1986). In a study on rainbow trout, the 96-hr LC50 of nitrite ranged from 0.19 to 0.39 mg/L NO_2-N for 2-235g fish. The incipient lethal level was reported to be 0.14-0.15 mg/L NO_2-N (Russo et al. 1974).

In another study, young steelhead were tested for 6 months and it was found that 0.015-0.060 mg/L of nitrite had no significant effect on growth (Hermanutz et al. 1987).

3.2.3.2.8.1. Recommendation

After reviewing various studies, the EPA concluded that nitrite nitrogen levels at or below 0.06 mg/L should be protective of salmonid fishes (U.S. EPA 1986). Nothing we have found in our literature review would contradict this criterion, so we propose setting this limit in Malibu Creek and Malibu Lagoon.

3.2.3.2.9. pH

Water pH levels have long been known to significantly affect freshwater communities. Most research examining the effects of pH on fish and other aquatic life has focused on low pH levels, since acidic streams and lakes are a greater problem than alkaline waters. These studies have demonstrated that salmonids, and in particular *Oncorhynchus mykiss*, are extremely sensitive to water pH values. Of four salmonid species tested in a Norwegian study (Grande et al. 1978), rainbow trout were found to be the least resistant to low pH levels. Although a laboratory study placed the lower limit of rainbow trout at pH 4.0 (Audet and Wood 1988), the lower tolerance may be as high as pH 5.5-6.0 in some natural waters (Grande et al. 1978).

Steelhead appear to grow best in slightly alkaline (pH = 7.0-8.0) water, but can survive in water ranging in pH from 5.8 to 9.6 (Moyle 1976).

Hatching and developmental stages of *Oncorhynchus mykiss* are especially sensitive to acidity (Marcus et al. 1990). Below pH 4.5, complete mortality of rainbow trout embryos has been reported (Kwain 1975), regardless of test temperatures. Other data suggests that the reproductive capacity of rainbow trout will be significantly reduced in waters of pH 5.5 or lower (Weiner et al. 1986).

Water temperature is known to play a role in determining the sensitivity of *Oncorhynchus mykiss* to acid solution. For example, the median lethal pH was 4.75 for 50% hatching success of newly fertilized rainbow trout eggs at 10°C. However, at 5°C, the median lethal pH value for 50% hatching success rose to 5.52 (Kwain 1975.

Research concerning the response of *Oncorhynchus mykiss* to alkaline water is limited, but appears to provide accurate information. Despite reports of salmonid mortality at pH 9.0 or greater (Jordan and Lloyd 1964, Yesaki and Iwama 1992), a recent study demonstrated that free-swimming rainbow trout were capable of long-term survival (28 days) at pH 9.5 (Wilkie et al. 1996). It is unknown what effects, if any, this pH level would have on developmental stages of *Oncorhynchus mykiss.*

3.2.3.2.9.1. Recommendation

The EPA recommends a pH range of 6.5-9.0 as providing the maximum level of protection for freshwater fish (U.S. EPA 1986). A thorough literature search has provided no information pertaining to *Oncorhynchus mykiss* contradictory to this recommendation. Therefore, this range appears to be reliable and is expected to protect steelhead trout in Malibu Creek and Malibu Lagoon.

3.2.3.2.10. Salinity

This section refers to the salinity found in the freshwater habitats which steelhead use for development and reproduction. Obviously, the salinity range encountered by the marine phase is small (roughly 30-36 ppt).

In a study conducted on rainbow trout, growth rates were highest in freshwater, and declined with increasing salinity (Morgan and Iwama 1991). This study also reports that metabolic rates increased with salinity and were inversely correlated with growth rates. Research conducted on other salmonid species also demonstrate that growth rates are highest in freshwater (Clarke et al. 1981, McKay and Gjerde 1985, and McCormick et al. 1989).

Several studies report 20 ppt salinity to be the upper limit for survival of juvenile (10-30 g) rainbow trout (Landless 1976, Eddy and Bath 1979, Johnsson and Clarke 1988).

3.2.3.2.10.1. Recommendation

Because steelhead smolts and adults reportedly spend little time in estuaries (Emmett et al. 1991), this recommendation will apply primarily to Malibu Creek and not Malibu Lagoon. The maximum salinity shall not exceed 20 ppt at any time, and levels should almost always approximate 0 ppt.

3.2.3.2.11. Temperature

Water temperature is a significant factor restricting the distribution of *Oncorhychus mykiss*. Consequently, numerous studies have examined the effects of temperature on steelhead and rainbow trout (Adams et al. 1973, Baltz et al. 1987, Cherry et al. 1975, Cherry et al. 1977, Coutant 1977, Garside and Tait 1958, Garside 1966, Hokanson et al. 1977, Javaid and Anderson 1967, Jobling 1981, Kwain 1975, Lee and Rinne 1980, Matthews and Berg 1997, McCauley and Pond 1971, McCauley et al. 1977, Nielsen and Lisle 1994, Peterson et al. 1979, Wichert and Lin 1996, Zaugg et al. 1972). Considerably more data exists for upper than for lower temperature limits.

Studies on northern populations report 26-27°C as the upper lethal limit for *Oncorhynchus mykiss* (Jobling 1981). Steelhead in southern California are known to inhabit streams with water temperatures as high as 28°C (Carpanzano 1996), but only when the water is saturated with dissolved oxygen (Emmett et al. 1991).

The optimum temperature for the growth of juvenile and adult rainbow trout reportedly lies between 15.7 and 17.2°C (Hokanson et al. 1977), although another researcher extends this range to 13-21°C (Moyle 1976).

This species is known to tolerate 0°C seawater (Colt et al. 1980, Saunders et al 1975), with the lower lethal limit reported to be approximately -0.7°C (Saunders et al. 1975).

During spawning, steelhead appear to be especially sensitive to water temperature. One study recommends a temperature range of 3.9-9.4°C while spawning is taking place (Reiser and Bjornn 1979), while the EPA lists 9°C as the maximum average weekly temperature for spawning in rainbow trout (U.S. EPA 1986). However, a more recent publication reports that spawning in steelhead may occur in temperatures ranging from 8-15.5°C (Emmett et al. 1991).

Steelhead embryos are also sensitive to elevated temperatures. The EPA lists 13°C as the short-term maxima for embryo survival of rainbow trout (U.S. EPA 1986), while another study recommends temperatures of 3.9-9.4°C during the incubation of embryos (Reiser and Bjornn 1979).

Another developmental stage affected by water temperatures is the parr-smolt transformation, in which freshwater-dwelling juvenile steelhead undergo dramatic physiological changes in preparation for an ocean existence. These changes are reportedly inhibited by temperatures above 15°C (Adams et al. 1973).

Research suggests that shading from streamside vegetation may play an important role in controlling stream temperatures and providing suitable habitat for *Oncorhynchus mykiss* populations . A recent study concluded that decreases in canopy cover along the banks of a desert stream resulted in significant declines in densities of trout and increases in densities of warm water cyprinids (Tait et al. 1994). Densities of northern rainbow trout populations have been shown to be correlated with stream temperature (Hawkins et al. 1983, Murphy et al. 1981). Vegetation cover may play an even more important role in southern California, where higher stream temperatures are common (Carpanzano 1996). Therefore, removal of streamside vegetation along Malibu Creek and Malibu Lagoon may negatively affect steelhead trout, and should be avoided.

3.2.3.2.11.1. Recommendation

Low water temperatures are not a concern, as this species is known to tolerate 0°C seawater (Colt et al. 1980, Saunders et al 1975), and temperatures in Malibu Lagoon reportedly do not fall below 10.5°C (Dillingham and Manion 1989). Therefore, it is probably of no practical value to set a lower temperature limit in Malibu Creek and Malibu Lagoon with regards to this species.

The upper temperature limit for steelhead trout should depend upon time of year and developmental stages present. When spawning activity and incubation of embryos is taking place, we recommend that temperatures not exceed 15°C. During the rest of the year, the upper limit in both Malibu Creek and Malibu Lagoon should be set at 28°C, as long as dissolved oxygen levels remain high. However, when the lagoon mouth is closed from tidal flushing, dissolved oxygen levels may fall and a slightly more conservative limit of 26°C in Malibu Lagoon would be appropriate. In addition, removal of streamside vegetation along Malibu Creek and Malibu Lagoon should be banned, or at least severely restricted.

3.2.3.3. Other indicators of good ecosystem health

The species in this section are native southern California estuarine species (although some of them only occur in estuaries during a limited part of their life cycle). All of these have been found in Malibu Lagoon and are characteristic of southern California estuaries. The presence of these species can be viewed as an indication of good ecosystem condition.

In this section, we first present information about fish species, followed by information about two invertebrate species.

3.2.3.3.1. Fundulus parvipinnis (California killifish)

California killifish are very abundant in Malibu Lagoon. During the Baseline Ecological Study (Manion and Dillingham 1989), this species was found in the lagoon in all samples except February's. Similarly, Ambrose et al. (1995) found killifish throughout the year. California killifish are year-round residents of the Lagoon, and during the winter and early spring the population consists of mainly adults.

California killifish are found in shallow coastal waters, occasionally found in freshwater streams or brackish lagoons of southern California (Moyle 1976). They are probably omnivorous, taking advantage of the most abundant invertebrates and algae in their environment. Allen (1982, p. 784) considers them a low-level carnivore, feeding on small crustaceans and insects. Fritz (1975, p. 101) reports that their food consists mainly of arthropods with annelids, gastropods, fish ova and algae making up a minor part of the diet. Amphipods, copepods, ostracods, and dipteran insects appear to be the most abundant food items. Breeding takes place mostly from May-June but continuing through July and into August if water temperatures are low early in the year, according to Moyle (1976) or April through September (Fritz 1975). Much suitable freshwater habitat has been eliminated, but they are still abundant in salt water.

California killifish are most abundant in saltwater lagoons and estuaries but can tolerate a wide range of salinities so populations have become established in a number of freshwater streams (Moyle 1976). According to Moyle, they can live in water ranging from completely fresh to that having salinities up to 128 ppt. Carpelan (1961, p. 36) reported that killifish can survive in salinities at least as high as 55 ppt, but the maximum tolerance was not observed. Small fish are more resistant to sudden changes in salinity than are larger fish but the larger fish can withstand lower oxygen levels.

Cairns (1982, p. 273) reports that the family Cyprinodontidae has an overall temperature range of 21-40°C, the general mean is 28-36°C. Hubbs (1965, p. 113) reported that larvae of *Fundulus* hatched at temperatures between 16.6 and 28.5°C.

Gonzales et al. (1989) studied the effects of pH on the east-coast congener, *Fundulus heteroclitus*. With an incipient lethal pH between 3.75 and 4.0, it appears that *F.heteroclitus* is much more tolerant of low pH than many freshwater species in similarly hard water (p 171).

Bagarinao and Vetter (1993) have noted that sulfide can affect fish performance. They report (p 730) that mass fish kills are often attributed to hypoxia/anoxia, salinity and temperature fluctuations, or low pH, but it is quite likely that sulfide is responsible for some fish kills. They also note that earlier studies have shown that the killifish is more tolerant to sulfide than several other species of shallow water marine fish. For example, Bagarinao (1991) reported the 96-hr 50% lethal concentration of sulfide to *Fundulus* is 700 μM, and the 8-hr tolerance limit is 5mM of sulfide, the 20-hr tolerance limit is 1.5 mM sulfide (p 61), and the acute tolerance limit is about 300 μM H_2S in seawater pH 8.3 at 16-20°C, higher than has been observed for any animal (p 138).

3.2.3.3.2. Antherinops affinis (topsmelt)

Topsmelt are one of the most common fish in Malibu Lagoon. They are opportunistic feeders, characterized as both a herbivore/detritivore and a low-level carnivore (Allen 1982, p. 784). Emmett et al. (1991, p. 188) report they are omnivorous, feeding primarily during the day. They are important prey for many piscivorous birds and fishes, including yellowtail and other large fishes. Five subspecies are currently recognized, with *A. affinis littoralis* ranging from Monterey down to San Diego (Emmett et al. 1991, p.186). Juveniles and adults are pelagic, but are found over a wide range of habitats depending on the time of year.

Topsmelt can spend their entire life cycle in marine waters. They are tolerant of higher salinities. Somewhere in the range between 80 and 90 ppt, conditions become intolerable for *Antherinops* (Carpelan 1955, p. 281). Carpelan (1955) also noted that topsmelt live throughout the year in ponds with salinity 150% that of sea water (51 ppt) (p 284). Gravid females were observed to spawn in water which had a salinity of 72 ppt (p281). Carpelan (1961, p. 39) report that as salinity increased during summer and early fall in the Los Peñasquitos Lagoon (in San Diego County), *Antherinops* thrived at the maximum salinity of 63 ppt. Middaugh and Shenker (date?, p. 235) report a tolerance to lower salinity, also, at least in juvenile *Antherinops* from Estero Americano (near Bodega Bay), who can tolerate salinities ranging from 2 ppt to approximately 80 ppt. In addition, Anderson et al. (1990, p. 11-12) report that recent laboratory studies of salinity tolerance in young *A.affinis* demonstrated that they are able to tolerate low salinities as well. Young fish, 24-days-old were acclimated from 10 ppt to 2 ppt in 2 ppt/day increments. All fish survived the period of acclimation to 2 ppt and for 29 days at the low salinity. In a second experiment, 24-day-old *A.affinis*, initially held at 30 ppt, were subjected to a 2 ppt/day increase salinity. No mortalities occurred until 60 ppt salinity. Incremental mortality occurred as salinity increased to 80 ppt where the cumulative mortality was 48%. An increase to 82 ppt salinity caused cumulative mortality to rise to 80%. Anderson et al. (1990) further note that adult A.affinis are reproductively active during May-August. This period generally coincides with low coastal rainfall and high salinities in California estuaries and coastal lagoons. While they observed optimal larval growth at 20 and 30 ppt and collected reproductively adults from Estero Americano at 34 ppt salinity, other field observations indicate that *A.affinis* adults may spawn at salinities up to 72 ppt in the Alviso Salt Ponds of San Francisco Bay (Carpelan 1957). Moreover, Carpelan (1955) reported that waters of the Alviso Salt Ponds only became intolerable for young *A.affinis* between 80 and 90 ppt.

Carpelan (1955, p. 283) reports a remarkable tolerance to temperature changes. For example, the extreme diurnal range observed in the ponds was 12°C, from a morning low of 21°C (69.8F) to an afternoon high of 33°C (91.4°F). *Antherinops* must also withstand an annual range of 25°C, from a low of 8°C (46.4°F) to as high as 33°C (91.4°F). Coutant (1977, p. 740) report an *Atherinops* sp. upper avoidance temperature of 28°C, a final preferendum of 25.2°C, and a lower avoidanceof 22°C, according to Doudoroff (1938). Cairns (1982) reports that *Atherinops* sp. preferred 25.2°C water, and the family Atherinidae has an overall temperature range of 25.2-32°C. Hubbs (1965) report that larvae of *Atherinops* hatched at temperatures between 12.8 and 26.8°C (p. 113), with the maximum developmental temperature tolerance is probably between 27 and 28.5°C. Hubbs also noted that the lower developmental temperature tolerance has not been ascertained; however, it must be not far below 12.8°C because death closely follows hatching at that temperature (p 119). Emmett et al. (1991, p. 187) found the upper and lower lethal temps for juvenile fish to be 31.7°C and 10.4°C, respectively.

3.2.3.3.3. Clevlandia ios (arrow goby)

Arrow gobies are small, benthic fish. The benthic life stages are strictly estuarine, but the larvae are found in nearshore coastal waters. It can reach extremely high abundances. One factor that may allow *Clevlandia ios* to dominate disturbed areas is its life history strategy (Nordy and Zedler 1991, p. 91). It matures within one year and spawns from September through June. The arrow goby is a low-level carnivore, feeding mainly on insects, benthic microinvertebrates, and zooplankton (Allen 1982, p. 784). Macdonald (1975, p. 119) report that harpacticoids, ostracods, nematodes, oligochaetes, and cyclopoids are most important food items, with amphipods, caprellids, and larger oligochaetes important only to larger fish. It is preyed upon by *Paralichtys californicus, Hysopsetta guttulata, Leptocottus armatus*, and *Fundulus parvipinnis* (Nordby and Zedler 1991, p. 91). California halibut is also probably a major predator of arrow gobies (Macdonald 1975).

3.2.3.3.4. Leptocottus armatus (staghorn sculpin)

Staghorn sculpin feed heavily on decapod crustaceans, such as *Hemigrapsus oregonensis* (Armstrong et al. 1995, p. 456). Haaker (1975, p. 130) reports a wide variety of food items eaten with a concentration on decapod crustaceans (*Hemigrapsus oregonensis*, ghost shrimp *Callianassa* sp., and pea crabs *Pinnixia* sp.; it also feeds on fish, mainly *Clevlandia ios* and the shadow goby, and occasionally the killifish *Fundulus parvipinnis*. Jones (1962, p. 359) reports that the diet of adults and the diet of juveniles differ most markedly in the smaller number of fish present in the juvenile diet. Where stomachs of adults contained 13.5% fish, those of juveniles contained only 0.3% fish. Juvenile staghorn sculpins undoubtedly are restricted to an invertebrate diet largely because of their small size. Few fishes in the estuary are smaller than the young staghorn sculpins to serve as prey, and intraspecific predation of juvenile staghorn sculpins, which has been observed in aquaria, is probably infrequent in nature.

Young sculpin inhabit brackish water streams and channels and move down into the estuary as they grow larger during their first year (Armstrong et al. 1995, p. 456).

Moyle (1976, p. 366) reports that staghorn sculpin are truly euryhaline, not only are they found in water that ranges in salinity from fresh to salt (34 ppt and probablyhigher), but they often move freely between waters of varying salinities. Carpelan (1961, p. 38) reports an upper limit of salt tolerance of *Leptocottus* in the vicinity of 51-53 ppt. Adults are limited to marine waters during the breeding season and are less tolerant of low salinity than are younger age groups (Jones 1962, p. 361). It spawns in winter, the young are present in the estuary only in summer when salinities are high and, therefore, require no adaptation to low salinity.

Jones (1962, p. 334) reports the eggs of the staghorn sculpin did not hatch at salinities of less than 10.2 ppt. Eggs of the staghorn hatched successfully in the salinity range from 10.2 to 34.3 ppt. In each experiment, the percentage of eggs which hatched was highest in salinities of 10.2 ppt, lowest in salinities of 34.3 ppt, and intermediate in salinities of 17.6 and 26.4 ppt. Some of the larvae of the staghorn sculpin hatched successfully at salinities from 10.2 to 34.3 ppt (p 336), appeared normal, and swam actively about the container; but others either could not swim off the bottom of the container or, because their tails were curved to one side, could swim only in circles. The hatch of normal larvae was lower in salinities of 10.2 and 34.3 ppt and higher in the intermediate salinities of 17.6 and 26.4. Two of the experiments indicated that 26.4 is closer to the optimum salinity than is 17.6. The hatch of abnormal larvae was highest in 10.2 ppt and decreased with increasing salinity (p. 337). Newly hatched staghorn sculpin larvae are more tolerant of low salinity than are embryonic stages. The maximum hatch of normal larvae occurred in water at a salinity of 26.4 ppt. However, normal larvae survived longest in the lower salinities of 10.2 and 17.6 ppt. All larvae hatched at high salinities and then transferred to 10.2 ppt survived longer than larvae retained in high salinities. At salinities of 5.1 ppt and less, the survival time of larvae was quite short, and environments with such low salinities obviously are unsuitable for newly hatched larvae (p 339). Juvenile staghorn sculpins can withstand a wide range of salinity and are more tolerant of low salinity than are either the eggs or the larvae. Survival time was shortest in stream water or tap water, both of 0.1 ppt salinity. At higher salinities, specimens survived longer, and the survival indices indicate that the optimum salinity for survival is 10.2 ppt (p 339). Small juveniles, which are present only during the spring months, are more tolerant of low salinity than are the larger juveniles present in summer and autumn.

3.2.3.3.5. Hypsopsetta guttulata (diamond turbot)

Diamond turbot, a flatfish, feed on mollusca, polychaetes, and crustaceans (Haaker 1975, p. 167).

No information on the physical tolerances of diamond turbots was found.

3.2.3.3.6. Gillichthys mirabilis (longjaw mudsucker)

Longjaw mudsuckers are strictly estuarine species.

Cairns (1982, p. 277) reports that longjaw mudsuckers prefer 22°C.

3.2.3.3.7. Girella nigricans (opaleye)

Opaleye are primarily marine, but juveniles use estuaries as a nursery.

Cairns (1982, p. 279) reports that 55-60mm fish preferred 26-28.2°C water. Jobline (1981, p. 447) reports the optimum growth temperature from several studies as 24, 23 °C, the final preference from several studies) as 23.5, 26°C, and the lethal temperature as 31.4°C. The family Kyphosidae has a temperature range of 26-31.2°C (Cairns 1982, p. 273).

3.2.3.3.8. Tagelus californicus (jacknife clam)

The jacknife clam is a suspension feeder although it belongs to the primarily deposit-feeding Superfamily Tellinacea (Page et al. 1992, p. 259). It is the only common clam species in Malibu Lagoon.

Jacknife clams are judged by laboratory tests to be intolerant of low salinities (Peterson 1975, p. 962). Nordby and Zedler (1991, p. 90) report that *Tagelus* was intolerant of the lowest salinities, 3-10% seawater, and that this species was strongly affected by lowered salinity; it was least abundant at the site nearest the source of wastewater flow. Manion and Dillingham (1989, p. 91) report that die-offs of jacknife clams in Malibu Lagoon seem directly related to continued exposure to fresh water and possibly also to pollution (August 1987 Pepperdine spill)

3.2.3.3.9. Hemigrapsus oregonensis (yellow shore crab or mud-flat crab)

The mud-flat crab can survive in salinities as high as 175% seawater (~62 ppt) (Gross 1961). No living *Hemigrapsus* were found in the lagoon studied by Gross (1961) when the salinities had exceeded 180% seawater (p. 300). Williason (1980) reports that *H. oregonensis* of size 9-12 mm survived up to 80 hours in water of salinity 2ppt, and that ~55% of *H. oregonensis* of size 14-24.1 mm survived 100+ hours in 2 ppt salinity. Manion and Dillingham (1989, p. 102) report that bottom salinities, where crabs are active, ranged from 2ppt to 37 ppt, which is within the range tolerated by his species. The mud crab is a species that endures moderately polluted conditions in Los Angeles Harbor, and has the ability to tolerate wide ranges of salinities, including prolonged periods of both freshwater and hypersaline conditions (Garth and Abbott 1980, cited in Manion and Dillingham 1989).

Although we found no studies specifically focusing on temperature tolerances of mud-flat crabs, in Malibu Lagoon bottom temperatures when crabs are active ranged from 10-27.5°C. Highest numbers were recorded when water temperatures were warmest (Manion and Dillingham 1989, .p 102).

Manion and Dillingham (1989, p. 108) concluded that mud crabs at Malibu Lagoon show the resiliency needed of a species which can survive there under constantly fluctuating physical conditions. In particular, these crabs seem to be able to adapt to very wide ranges of salinities where other species cannot (Zedler and Nordby 1986), and to survive during extended periods where salinity levels remain low. Since mud crabs are highly tolerant of polluted conditions, present water quality in the lagoon probably is not limiting.

3.2.3.4. Indicators of poor ecosystem health

In this section, we present information about species that do not represent desirable conditions in Malibu Lagoon. Three of these indicators are introduced species. Their presence does not necessarily indicate poor water quality, since there are a wide variety of conditions that could allow them to invade a particular habitat. We also include one native species, a polychaete, because it is common in degraded habitats, and it is often common where there is poor water quality.

3.2.3.4.1. Gambusia affinis (western mosquitofish)

The mosquitofish is a very tolerant species introduced to streams throughout southern California (and elsewhere) to control mosquito populations. The mosquitofish is a low-level carnivore, feeding mainly on insects, benthic microinvertebrates, and zooplankton (Allen 1982, p. 784). Haynes and Cashner (1995, p.1039) note that the ability of *G. affinis* to adapt to different, often harsh habitats by modifying its life history has allowed it to become one of the most successful vertebrate species on Earth. Although the species is generally tolerant of a wide range of conditions, males succumb more quickly than females to environmental stressors, suffering higher mortality when exposed to temperature extremes, overcrowding, starvation, and hypoxia (Haynes and Cashner 1995, p.1036). Leidy (1984) noted that it preferred warm, turbid, heavily silted pools, often containing rubble with moderate amounts of floating and rooted aquatic vegetation. These highly disturbed intermittent stream habitats usually contained few additional species (Leidy 1984, p. 19).

Although *G. affinis* is a freshwater species, it is tolerant of a wide range of salinities. Al-Daham and Bhatti (1977) noted that *G. affinis* was resistant to salinities of 50% seawater (20-50 ppt). Nonetheless, in southern California estuaries with a distinct salinity gradient, its highest densities are often found at the stations with the lowest salinities or greatest freshwater influence (Nordby and Zedler 1991, Ambrose et al. 1995).

Mosquitofish prefer relatively warm temperatures. Cairns (1982, p. 281) reports that adults preferred 27°C water, and 25-35mm fish preferred 34.7-35.3°C water. Winkler (1979, p. 62-63) reports field populations chose the 31°C chamber of the temperature gradient within the first 10-15 min and remained there for several days (p 62); Arkansas populations of *G.affinis* also chose preferred temperatures of 28-31°C. Coutant (1977, p 741), summarizing the results from several studies, reports a adult final preferendum of 31°C (Winkler 1973), an adult upper avoidance of 29.5°C and a final preferendum of 27°C (Bacon et al. 1967), an adult (15-19mm) upper avoidance of 32°C (Bacon et al. 1967), and an adult (<15mm) upper avoidance of 35°C (Bacon et al. 1967). Jobling (1981, p. 445) reports the optimum growth temperature from several studies (°C): 28.6, 30.9, the final preference from several studies (°C): 28, 31, and the lethal temperature as 37.3°C. The incipient lethal temperature to *Gambusia* is 37-38C°

(Wurtsbaugh and Cech 1983). The family Poeciliidae has an overall temperature range of 27-35.3°C; the general mean is 29-34°C (Cairns 1982, p. 273).

3.2.3.4.2. Acanthogobius flavimanus (yellowfin goby)

The yellowfin goby is an introduced species in California, where they are found in shallow, muddy littoral areas in fresh, brackish, and salt water. They are naturally common in shallow coastal waters of Japan, Korea, and China. Yellowfin gobies were first collected in Sacramento-San Joaquin Delta in 1963, and are now common in the Delta and are spreading rapidly (Moyle 1976, p. 348). They are well adapted for estuarine living because they are capable of withstanding abrupt changes between fresh and salt water, and can survive water temperatures greater than 28°C. They feed on a wide variety of crustaceans and small fishes associated with the bottom, as well as algae. Yellowfin gobies are strong predators and competitors and have the potential to seriously alter the communities they invade. For example, populations of the tidewater goby may be in some danger of being eliminated through competition, and in at least one area, they have partially displaced staghorn sculpins (Moyle 1976). Leidy (1984, p. 26) reported that native species of fish were extremely uncommon where *A. flavimanus* was abundant.

As noted above, yellowfin gobies have a wide salinity tolerance. They can probably complete their entire life cycle in fresh water (Moyle 1976).

3.2.3.4.3. Palaemon macrodactylus (oriental shrimp)

Oriental shrimp are an introduced species that is relatively common in Malibu Lagoon.

According to Newman (1963, p. 127), it is adapted to wide variations in salinity and temperature, adults can be maintained in normal or dilute sea water at temperatures ranging from 14-26°Celsius for indefinite periods of time.

In the laboratory, these shrimp survive well at temperatures between 14-26°C, and tolerate wide ranges of salinities (Chance and Abbott 1980, in Manion and Dillingham 1989, p. 109). At Malibu Lagoon, there appears to be no correlation between water temperature and the presence of shrimp. Shrimp appeared on surveys where temperatures extended well beyond this range, with temperatures varying from 10.5-27.5°C (p 109)

3.2.3.4.4. Polydora nuchalis (polychaete worm)

Polydora nuchalis is an appropriate indicator of negative conditions because it is an opportunistic polychaete. Opportunistic polychaetes including *Polydora ligni*, *Capitella* spp., and *Streblospio benedicti* are known to rapidly colonize and dominate benthic communities during or following disturbances such as discharge of sewage or industrial waters, nutrient additions and subsequent eutrophication, oil spills, and even severe storms and hurricanes. This response has been documented in shallow bays, estuaries, mudflats, and salt marshes throughout the world, including the Wadden Sea (Beukema 1991, Beukema and Cadée 1997) and the Venice Lagoon (Sordino et al. 1989), the coast of Japan (Tsutsumi et al. 1987), Scotland (Bagheri and McLusky 1982), Norway (Holte and Oug 1996), Portugal (Pardal et al. 1993), Holland (Reish1979), the Netherlands (Lambeck and Valentijn 1987), Massachusetts (Grassle and Grassle 1974), Connecticut (Zajac and Whitlatch 1982), Mission Bay in San Diego (Levin 1986), and the Los Angeles Harbor (Nordby and Zedler 1991). These population explosions are often are followed by equally dramatic population declines (Levin et al. 1996).

Estuarine polychaetes have a profound influence on the properties of sediments such as grain size distribution, interstitial water, and dissolved gases (Heip 1995). According to the U.S. EPA (1980), polychaetes play an important role in the movement of sediments in much the same manner as earthworms do on land. When polychaetes disappear, as during anoxic events, the physical and chemical characteristics of the top sediment layers are greatly affected (Heip 1995). Polychaetes also play an important role in providing food for birds and fish (U.S. EPA 1980).

Reish and Fauchald's (1977) review of studies of benthic soft-bottom communities in terms of density (no./m^2) showed polychaete densities to be high, averaging 44.3%, and exceeding 50% in over half of the studies reviewed. As a percentage of the total number of species in a community, polychaetes ranked high, averaging over 40% in all studies considered. Since they are such a large component of benthic communities, this group should be included in assessments of benthic communities, as many researchers including Pearson and Rosenberg (1978), Reish (1979), and Levin et al. (1996), have concurred. *Capitella capitata* is probably the most commonly used marine organism as an indicator of marine pollution (Reish 1979), while *Polydora ligni* and *Streblospio benedicti* have also been used as indicators of organically polluted sediments (Pearson and Rosenberg 1978, Levin 1984, Sordino et al. 1989). Nordby and Zedler (1991, p. 91) suggest that high densities of capitellids and *Polydora* spp. may have been encouraged by sewage spills, since both taxa are associated with pollution. In LA Harbor, *Capitella* sp. and *Polydora cornuta* were most abundant in polluted to very polluted areas (Nordby and Zedler 1991). Furthermore, the structure of benthic communities reflects the environmental conditions of the water prior to the time of sampling, whereas water samples only reflect the conditions at the time of sampling (Reish 1979, Metcalfe 1989).

Polydora nuchalis is the only species of polychaete consistently identified in the sediments of Malibu Lagoon (Manion and Dillingham 1989, Ambrose et al. 1995). It is usually found in mudflats of estuaries and bays (Woodwick 1953; *see* Manion and Dillingham 1989 p. 77 for ref). An extensive survey at Malibu Lagoon revealed that *P. nuchalis* represented 72% of all infauna collected (Ambrose et al. 1995) and was also the most frequently collected infaunal organism at every sampling location. Ambrose et al. (1995) conclude that the invertebrate fauna at Malibu Lagoon exhibits very low species richness, especially when compared to other southern California

According to Pearson and Rosenberg (1978), stable communities are characterized by high species numbers and biomass but only moderate abundances. Furthermore, high densities of polychaetes are typical of organically enriched estuaries (Bagheri and McLusky 1982). For example, polychaetes represented 63% of the individuals sampled a highly enriched estuary in Portugal (Pardal et al. 1993). It is not difficult to conclude, therefore, that Malibu Lagoon is a highly unstable environment and is probably affected by relatively high organic enrichment

Little information exists on the life history characteristics and response to organic enrichment of *Polydora nuchalis*. However, a significant amount of information exists for *P. ligni* (also referred to as *P. ciliata* in the literature). Therefore, this summary focuses mainly on *P. ligni*. Relevant data on *Capitella capitata* and *Streblospio benedicti* is also presented. This is done because they share similar characteristics, abundant information is available for them, and because both *C. capitata* and *S. benedicti* frequently co-occur with *Polydora* (Levin et al. 1987). All 3 species are of similar size (10-20 mm) and rapidly colonize disturbed areas (Levin et al. 1987). From a range of studies, Reish and Fauchald (1977) ranked the most opportunistic polychaetes as *C. capitata*, first, followed by *P. ligni* or *Streblospio benedicti* in North America and *Scolelepis fuliginosa* in Europe. According to Reish and Fauchald (1977), opportunistic species are found in greater numbers among polychaetes than in any other taxonomic group.

Polydora is one of the largest polychaete genera, with species common in coastal waters worldwide and known for their ecological plasticity (Manchenko and Radashevsky 1993). *P. ligni* is a common estuarine and near shore species (Zajac 1986) and is found in all oceans and at all latitudes (Grassle and Grassle 1974, U. S. EPA 1980). According to Dauer et al. (1981), *P. ligni* prefers sediment composed of at least 90% silt-clay and is generally found in mud or sand tubes in the upper few cm of sediment. *P. ligni* exhibits wide salinity tolerance, so may be found anywhere from the open coast to estuaries (U.S. EPA 1980). In southern California, *P. ligni* is a commonly encountered species under marine or estuarine conditions, both as a bottom-dwelling adult and as a planktonic larva (Rice 1975, U.S. EPA 1980). Sexes are separate, although some hermaphroditism has been noted (Rice 1975). Females have the potential to produce up to 8 broods, and life span in the field is estimated to be 6-8 months by Zajac (1986) and 1-2 years by Anger et al. (1986). The average life span of laboratory specimens was 13 months (Zajac 1991).

The population dynamics of *P. ligni* exhibit distinct seasonal phases in response to disturbance (Zajac 1991). The spring and early summer growth period is followed by a late summer and early fall transition period and, finally, a late fall and winter maintenance period. While the mid-summer population increase of *P. ligni* appears to be predictable, the magnitude of density changes can vary. Zajac (1991) reports that peak abundance in 1982 was almost 3 times higher than in 1983.

When high rates of organic enrichment are maintained over time, polychaetes tend to persist, and are often dominant both with respect to biomass and numbers of individuals (Grassle and Grassle 1974, Reish and Fauchald 1977, Reish 1979). A preference for high concentrations of organic matter, rather than tolerance to hypoxia/anoxia and hydrogen sulfide is thought to explain this. Tsutsumi (1990) suggests that the association of *Capitella* spp. with organically enriched areas in Japan indicates a 'physiological requirement' for highly organic food. He reached this conclusion by demonstrating that a very high sedimentary protein content was required for the presence of reproductively functional females.

Studies by Levin (1986), Grémare et al. (1988) and Sardá et al. (1996) indicate that food quality, particularly the elevated nitrogen content found in areas undergoing eutrophication, may regulate polychaete growth and reproduction. Food nitrogen content was highly correlated with both fecundities and reproductive output in *Capitella* (Grémare et al. 1988). *Polydora ligni* and *Streblospio benedicti* populations responded to nutrient and sewage enrichment by increasing dramatically (Levin 1986). Finally, experimental nitrogen fertilization stimulated high densities of *C. capitata*, *P. ligni*, and *S. benedicti* in a New England salt marsh (Sardá et al. 1996).

Numerous studies report a correlation between opportunistic polychaete abundance and mass blooms of macroalgae of the genera *Ulva*, *Enteromorpha*, *Chaetomorpha*, *Cladophora*, and *Gracilaria* (Nicholls et al. 1981, Soulsby et al. 1982, Reise 1983, Thrush 1986, Reise et al. 1989, Tsutsumi 1990, Raffaelli et al. 1991, Desprez et al. 1992, Pardal et al. 1993, Bridges et al. 1994, Everett 1994, Ahern et al. 1995, Flindt et al. 1997). Algal decomposition frequently leads to anoxia and high levels of hydrogen sulfide in the sediments below, and these polychaetes are among the few invertebrates that thrive under such harsh conditions. They are also able to take advantage of the increased food available in and under macroalgal mats (Hull 1987). *Capitella capitata* reportedly feeds on *Ulva* detritus and is capable of deriving a major portion of its nitrogen intake directly from the macroalgae (Everett 1994).

Previous researchers commonly assumed tolerance to be the most widely adopted strategy to pollution stress by macrobenthic communities (*see* Grassle and Grassle 1974 for refs). However, recent work indicates that mere tolerance to severe environmental conditions is a relatively uncommon adaptive strategy; the species that respond rapidly to organic enrichment are not unusually tolerant of hypoxia/anoxia or hydrogen sulfide (Gray 1979, Forbes et al. 1994). Rather, life history characteristics of these opportunists are probably more important than the range of tolerance of the average individual.

Reduced oxygen supply is perhaps the most serious consequence of organic pollution on aquatic life (Pearson and Rosenberg 1978). Most species of the marine macrobenthic infauna belong to the taxonomic groups polychaetes, molluscs, echinoderms, and crustaceans. Studies show that these groups exhibit different levels of tolerance to hypoxia. According to Diaz and Rosenberg (1995), polychaetes are the most tolerant taxa, followed by bivalves and crustaceans. However, Hagerman et al. (1996) report that bivalves generally have the highest tolerances to low dissolved oxygen levels, followed by polychaetes and crustaceans.

Whatever the case, polychaetes are certainly affected by low oxygen levels. Despite being tolerant of hypoxia for 14 days under experimental laboratory conditions, short periods of anoxia are known to eliminate entire populations of *Streblospio benedicti* (Llansó 1991). Additionally, no species of polychaetes were found in water having levels less than 0.3 mg/L by Crippen and Reish (1969), and a suppression of the number of polychaete species was noted when the dissolved oxygen content fell below 1.0 mg/L conclusion by demonstrating that a very high sedimentary protein content was required for the presence of reproductively functional females.

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Adaptations used by opportunistic polychaetes to survive under hypoxia/anoxia include a reduction in activity to decrease oxygen consumption (Llansó 1991), and switching from aerobic to anaerobic metabolism (Warren 1984, Diaz and Rosenberg 1995).

In organically enriched communities, relatively high levels of toxic hydrogen sulfide (H_2S) accumulate in the sediment as a result of the activities of certain anaerobic bacteria (Tsutsumi 1990). Hydrogen sulfide is lethal to most invertebrates and fish when present at levels of the order of parts per million (U.S. EPA 1980). However, Cuomo (1985) showed that sulfides promote the larval settlement of *Capitella*, and that settlement is enhanced both in organically enriched sediment containing sulfides and sediment-free habitats containing sulfides. These results suggest that this species may prefer the environment that sulfides provide rather than simply favoring organically enriched sediment. Cuomo (1985) also demonstrated that *Capitella* are able to successfully reproduce in the presence of H_2S. This is advantageous because H_2S is usually indicative of anaerobic organic matter decomposition, reflecting the presence of available detritus for polychaetes. According to Jørgensen (1980), polychaetes living in H_2S-rich areas resist sulfide poisoning by pumping oxic respiratory water into their tubes. When the oxygen becomes depleted, they usually creep out of their tubes and are found lying on the mud surface, limp and motionless but often still alive. High resistance to H_2S often parallels that to hypoxia/anoxia (Shumway and Scott 1983). This is not surprising as the two conditions frequently occur simultaneously (Hagerman et al. 1996).

Low salinities appear to limit the distribution of opportunistic polychaetes in coastal estuaries. In San Diego, polychaetes of the genera *Polydora* and *Capitella* in Los Penasquitos Lagoon reportedly disappeared when salinities were under 10 ppt (Greenwald and Hurlbert 1993). In a Dutch estuary, heavy rainfall over a long period of time completely eliminated *C. capitata*, *Streblospio benedicti*, and *P. muchalis* populations (Reish 1979).

Studies also show opportunistic polychaetes to be sensitive of elevated salinities. In Los Penasquitos Lagoon, *Polydora* and *Capitella* disappeared when salinities were over 40 ppt (Greenwald and Hurlbert 1993), while Pearson and Rosenberg (1978) showed *P. ciliata* was only dominant in salinities ≤ 33 ppt.

P. nuchalis is apparently able to tolerate a wide range of salinity (Woodwick 1953; *see* Manion and Dillingham 1989 for ref), while the preferred range for *P. ciliata* is reported to be 13-24 ppt (Pearson and Rosenberg 1978).

Wible (1984) found that *P. nuchalis*, which has lecithotrophic development, produced larger eggs at colder temperatures. He also found that increasing temperature (from 15°C to 25°C) significantly increased survivorship, growth rates and percentage reproduction of *P. nuchalis*.

Effects of temperature can by confounded in field studies by simultaneous changes in several parameters. For example, Greenwald and Hurlbert (1993, p. 307) report that temperature increased with increasing salinity, pH and dissoved oxygen decreased with increasing salinity.

3.2.4. Biological Water Quality Objectives

The principal goal behind the summary of physical tolerances of the target species is to establish biological water quality objectives that are protective of the Malibu Lagoon community. The physical tolerances are summarized in Table 3-2, and potential water quality objectives can be derived by scanning the values in this table. This task is complicated by the fact that different species, even desirable species, have quite different tolerances. More importantly, there is little information about the tolerances of most of the target species to the physical conditions of concern. Nonetheless, we have made some initial suggestions, organized by the major physical categories.

3.2.4.1. Salinity

Virtually all of the estuarine species tolerate very low salinities, since the normal seasonal cycle of souther California estuaries includes periods of very low salinity during periods of high rainfall runoff.

Where upper limits to salinity have been determined, they are typically higher than usually occur in Malibu Lagoon, greater than 40 or 50 ppt. However, a number of the species, such as tidewater gobies, prefer much lower salinities, 10-15 ppt. To protect these species, at least some low-salinity habitats must be available. With the tidewater goby, this typically occurs at the upper end of the lagoon, where freshwater enters the estuary.

3.2.4.2. Temperature

Malibu Lagoon's temperature does not differ from normal ambient temperatures, and so is within the tolerable range of most of the target species.

Temperature is a particular concern for steelhead trout. During spawning and incubation, temperatures should not exceed 15°C. At other times, temperatures should not exceed 26-28°C.

3.2.4.3. Ammonia

There is little information about the tolerated limits to ammonia in the target species. The recommended upper limit for steelhead is 0.45 mg/L of unionized ammonia.

3.2.4.4. pH

There is little information about the tolerated limits to pH in the target species. The best range for steelhead in 7-8, although they can tolerate pH as low as 4 and as high as 9.5. The range for tidewater gobies is 6.8-9.5.

3.2.4.5. Dissolved Oxygen

The minimal value of dissolved oxygen for most target species is 4 mg/L. Steelhead require a higher level, >7 mg/L.

3.2.4.6. Nitrate

There is little information about the tolerance of the target species to nitrate. Steelhead are reported to tolerate up to 1300 mg/L.

A recent report by Marco et al. (1999) indicates that amphibians can be susceptible to quite low levels of nitrate and nitrite (see below).

3.2.4.7. Nitrite

There is little information about the tolerance of the target species to nitrite. Steelhead can tolerate up to 0.39 mg/L, although <0.15 mg/L is best.

A recent report by Marco et al. (1999) indicates that amphibians are susceptible to quite low levels of nitrate and nitrite. Levels of nitrite below the drinking water standard killed over half of the Oregon spotted frog tadpoles after 15 days of exposure. Four other species tolerated higher levels, but still experienced 50% mortality at nitrite levels well below those that the US EPA considers safe for warmwater fishes.

The Marco et al. (1999) study was conducted with amphibians, which are not indicators we chose for Malibu Creek. However, the fact that very little information was available for nitrate and nitrite tolerances suggests that nitrates and nitrites might be more critical water quality factors than previously appreciated.

3.2.4.8. Sulfide

There is little information about the tolerance of the target species to sulfide. Steelhead may be able to tolerate up to 0.4 μg/L, although the EPA recommended limit of ≤ 2 μg/L would be more protective.

3.3. Habitat Association Analysis

3.3.1. Introduction

This analysis was conducted to identify the habitat associations of critical or "indicator species" in the lower Malibu Creek watershed (Table 3-4). Critical habitat characteristics, such as influences of season, diel and tidal cycles, and substrate type, are summarized for each indicator species in Table 3-5. Finally, associated threats to these species and their habitats are outlined in Table 3-6.

Although the summary of habitat associations for indicator species provided in this chapter could be useful for assessing the appropriateness of existing habitat or for planning habitat restoration projects, it is important to recognize the limited focus of this approach. Although some species can be considered "umbrella" species because their habitat needs coincide with the needs of many other species, this is often not the case, and none of the indicator species included here should be viewed as umbrella species. Information on the habitat associations of these indicator species should be considered in planning assessment or restoration activities, but they should not be given undue weight. In particular, habitat restoration should focus on overall system function rather than the presence of a particular species.

3.3.2. Methods

The issues surrounding the choice of indicator species have been discussed in Section 3.2.2. For this analysis, we included the two invertebrate species and nine fish species selected as "positive indicators" in that Section. However, for this analysis we expanded the list of indicator species beyond the aquatic species discussed in Section 3.2 to include non-aquatic species, specifically sensitive reptiles (2 species), birds (5 species) and plants (2 species). Not all of these species currently occur in the Malibu Creek watershed or Malibu Lagoon (and we did not attempt to survey the habitat for them). If species are not known to currently occur in this system, they were included because they were thought to have occurred there historically, or could potentially occur there. Categories of protected species included: Federally endangered and threatened species; Federally proposed critical habitat; Federal candidates for listing by the U.S. Fish and Wildlife Service; State endangered and threatened species; and State species of special concern (Table 3-4). In addition to the nine fish species discussed previously, the Santa Ana sucker (*Catostomus santaanae*) and the unarmed threespine stickleback (*Gasterosteus aculeatus williamsoni*) were included in this inventory because they may have once been found in Malibu Creek. In 1975, an unsuccessful attempt was made to transplant the threespine stickleback to Malibu Creek (Swift et al. 1993).

Habitats in which indicator species are found included lagoon/subtidal, intertidal mudflat, salt marsh, stream, riparian, and sandy beach and islands. Many of the indicator species inhabit several of these habitat types.

3.3.3. Results

Besides the general information provided in Tables 3-4, 3-5 and 3-6, relevant habitat association information was found only for the following species:

3.3.3.1. Eucyclogobius newberryi

Compared to the invertebrates, relatively abundant data on habitat association is available for the tidewater goby *Eucyclogobius newberryi*. According to Swenson (1995), tidewater gobies are found in a variety of habitats, including sandy lagoons, mud or gravel sections of streams, and muddy marsh pools and channels. Adults seem to prefer vegetated areas, which provide both cover from predators and habitat for crustacean prey. During the time gobies are reproductively active, they may require the presence of coarse sand, in which males excavate burrows (Lafferty et al. 1996).

Tidewater goby populations may be negatively affected by the artificial breaching of the sand and cobble berms found at the mouths of California lagoons (Capelli 1997). Artificial breaching can carry gobies into the ocean or strand them in shallow pools, increasing their vulnerability to predation. Stranding of tidewater gobies has been observed at Malibu Lagoon after an artificial breach (Manion and Ambrose, unpublished data). Artificial breaching may also adversely affect reproduction and rearing, reduce dissolved oxygen concentrations to lethal levels, and decrease the abundance of non-marine invertebrates which provide the primary food source for tidewater gobies.

3.3.3.2. Oncorhynchus mykiss

With regard to the steelhead trout *Oncorhynchus mykiss*, research suggests that plant canopy cover may play an important role in maintaining stream temperatures favorable to this species. A recent study concluded that decreases in canopy cover along the banks of a desert stream resulted in significant declines in densities of native trout (Tait et al. 1994). Densities of northern rainbow trout populations have been positively correlated with stream temperature (Hawkins et al. 1983, Murphy et al. 1981). Vegetation cover may play an even more important role in streams at the southern end of the species range, where higher streams temperatures are common (Carpanzano 1996). Removal of streamside vegetation may negatively affect steelhead trout populations in Malibu Creek and Malibu Lagoon, and should therefore be avoided.

Other steam characteristics also favor steelhead. Instream cover such as logs, rocks, and aquatic vegetation provides protection from predators and areas of decreased flow where steelhead can rest (Carpanzano 1996). Moyle and Baltz (1985) report that juveniles and adults favored deeper parts of streams, while shallower parts were favored by young-of-year rainbow trout. They also found that preferences for higher mean water column velocities increased with size of rainbow trout. In areas where stream temperatures reach lethal levels (> 28°C), thermally stratified pools provide refuge habitat for many young-of year, yearling, and adult steelhead in Northern California (Nielsen et al. 1994). Finally, juvenile steelhead are usually found in microhabitats such as pools, gravel riffles and runs, rocky turbulent stretches and plunge pools in white water torrent areas (Hartman and Gill 1968).

3.3.3.3. Palaemon macrodactylus

The oriental shrimp *Palaemon macrodactylus* is commonly found in Malibu Lagoon. In this literature search, no references were found regarding the habitat preferences of this species. However, two studies provide data for *P. adspersus*, a European species (Isaksson and Pihl 1992, Pihl et al. 1995). They show that this species is favored by a moderate increase in opportunistic filamentous macroalgae, but negatively affected by a further cover of algae. *Palaemon adspersus* probably favors this habitat because food items eaten by this species, including amphipods and copepods, live there.

3.3.3.4. Polydora nuchalis

No habitat association information is available for the polychaete worm *Polydora nuchalis* either. Again, data on a related species, *P. ligni*, will have to suffice. According to Dauer et al. (1981), *P. ligni* prefers sediment composed of at least 90% silt-clay and is generally found in mud or sand tubes in the upper few cm of sediment.

3.4. Discussion

The most common threats to indicator species in the lower Malibu Creek watershed are loss and degradation of habitat, hydrological alterations, invasion by competitors and predators, eutrophication, and erosion. Losses of habitat due to development cause species abundance to decline, leading to an associated decrease in reproductive success for many species. Hydrologic alterations, such as lagoon breaching and artificial bank stabilization, may affect critical habitat characteristics of tidal cycle and breeding habitat availability for selected species (discussed in Chapter 7). In addition, timing of lagoon breaching may be crucial to reproduction or survival of many juvenile fish. Invasion of critical habitat by humans and animal predators threatens survival and reproduction of many animal indicator species (Table 3-6). Erosion in the watershed impacts critical spawning ground habitat for several of the fish species. Causes of erosion in the lower Malibu watershed include development, loss of native, stabilizing riparian vegetation, large animal use of riparian zone, and road construction/improvements.

An initial goal of this task was to try to develop water quality objectives that would support indicator species in Malibu Creek and Malibu Lagoon. If such water quality objectives could be developed, the objectives could be compared to local enviromental conditions to determine whether the local conditions are suitable or need to be improved to support viable populations of indicator species. The development of comprehensive water quality objectives is not possible at this time, however, because the physical tolerances of the indicator species have not been evaluated for most parameters of interest. For example, except for steelhead, no information could be found on tolerances of the indicator species to ammonia, nitrate or nitrite, so it is not possible to establish a limit for these substances to protect living resources in the Lagoon or Creek.

Some general observations can be made, however. Because estuaries naturally experience extreme variations in salinity as salt water mixes with fresh water, the estuarine species generally tolerate a wide range of salinities. However, the tidewater goby prefers lower salinity, 10-15 ppt, and so provision of at least some areas of lower salinity (such as the upper end of the estuary, where the Creek empties into the Lagoon) is important for managing this species. Because Malibu Lagoon currently has a higher freshwater inflow than occurred in the pristine system, salinity conditions are very suitable for the tidewater goby. On the other hand, some estuarine invertebrates (exemplified by the jackknife clam) cannot tolerate extended periods of low salinity. The lowered salinity (or, more likely, the alterred temporal pattern of low salinity) may limit jackknife clam and other invertebrate species in Malibu Lagoon. Low salinity also favors mosquitofish, a negative indicator that is very abundant at Malibu Lagoon.

Probably the most important water quality limitation in Malibu Lagoon is the dissolved oxygen (DO) concentration. Species such as topsmelt have been shown to be intolerant of low DO, but a DO level of >4 mg/L is generally recognized as necessary for most species. Some species, such as the negative indicator *Polydora nuchalis*, tolerate low DO, but the positive indicator species apparently cannot. There is no extensive monitoring record of DO in Malibu Lagoon. However, Ambrose et al. (1995) report periods of low DO in association with algal mats in the Lagoon. Heavy algal cover and the consequent low DO have been associated with fish kills in some systems. However, we have no well-documented records of extensive fish kills in Malibu Lagoon. During the Ambrose et al. (1995) study, fish in traps on the bottom of the Lagoon were killed during low-DO episodes, but widespread fish kills were not observed.

As noted above, there is no information about the tolerances of the Lagoon indicator species to ammonia, nitrate or nitrite, so no water quality objectives can be determined on the basis of direct impacts to the indicator species. However, the recent study by Marco et al. (1999) suggests that nitrate and nitrite may have direct effects on aquatic organisms at fairly low levels. Furthermore, these nitrogenous compounds may have an important indirect effect through their enhancement of algal growth. Excessive algal growth indicative of eutrophication can result in low DO conditions that are known to impact the indicator species. The conditions leading to eutrophication are complex, however (see Chapter 5).

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Table 3-1. Indicator species for Malibu Creek watershed and Malibu Lagoon.

Common name	Scientific name	Comments
Positive indicators		
Tidewater goby	*Eucyclogobius newberryi*	Federally listed endangered species Common native estuarine species
Steelhead	*Oncorhynchus mykiss*	Federally listed endangered species
California killifish	*Fundulus parvipinnis*	Very common, native estuarine species
Topsmelt	*Antherinops affinis*	Common estuarine and marine species
Arrow goby	*Clevlandia ios*	Benthic estuarine species with marine larvae
Staghorn sculpin	*Leptocottus armatus*	Benthic estuarine/marine species
Diamond turbot	*Hypsopsetta guttulata*	Benthic species using estuaries as a nursery
Longjaw mudsucker	*Gillichthys mirabilis*	Benthic estuarine species
Opaleye	*Girella nigricans*	Marine species using estuaries as a nursery
Jacknife clam	*Tagelus californicus*	Only common clam in Malibu Lagoon
Mud-flat crab	*Hemigrapsus oregonensis*	Native estuarine species
Negative indicators		
Western Mosquitofish	*Gambusia affinis*	Very common; introduced for mosquito control
Yellowfin goby	*Acanthogobius flavimanus*	Introduced species with potentially serious impact on native species; not currently found in Malibu Lagoon
Oriental shrimp	*Palaemon macrodactylus*	Introduced species
Polycheate worm	*Polydora nuchalis*	Native opportunistic species

Table 3-2. Physical tolerances of indicator species.

Species	Salinity	Temperature	Ammonia	pH	Dissolved Oxygen	Nitrate	Nitrite	Sulfide	# References
Positive indicators									
Eucyclogobius newberryi (tidewater goby)	0-53 ppt prefers 10-15 ppt	8-25°C prefers 18-22°C		6.8-9.5	4-19 mg/L				**13**
Oncorhynchus mykiss (steelhead trout)	0-20 ppt in streams	0-28°C prefers 13-21°C	upper limit is UIA concentration of 0.45 mg/L	4-9.5 best is 7-8	>7mg/L at temps ≤ 15°C >9mg/L at temps >15°C as low as 3.75	up to 1300mg/L	up to 0.39mg/L <0.15mg/L is best	up to 0.4 microM at 20°C	**71**
Fundulus parvipinnis (killifish)	0-128ppt	16.6-40°C prefers 16.6-28.5°C						up to 300 microM	**10**
Antherinops affinis (topsmelt)	2-82 ppt	8-33°C prefers 25°C			intolerant of low DO				**9**
Clevlandia ios (arrow goby)									**3**
Leptocottus armatus (staghorn sculpin)	0-53 ppt								**7**
Girella nigricans (opaleye)		up to 31.4°C prefers 26-28.2°C							**2**

Table 3-2. Physical tolerances of indicator species (cont.)

Species	Salinity	Temperature	Ammonia	pH	Dissolved Oxygen	Nitrate	Nitrite	Sulfide	# References
Gillichthys mirabilis (longjaw mudsucker)		prefers 22°C							**2**
Tagelus californicus (jacknife clam)	lower limit is 3-10% seawater								**4**
Hemigrapsus oregonensis (yellow shore crab)	2-62 ppt	10-27.5°C prefers warm water							**3**
Negative indicators									
Gambusia affinis (mosquitofish)	0-50 ppt	38°C is upper limit prefers 28-31°C							**10**
Acanthogobius flavimanus (yellowfin goby)	0 ppt to >35 ppt	upper limit ~28°C							**2**
Palaemon macrodactylus (oriental shrimp)	normal to dilute seawater	10.5-27.5°C							**2**
Polydora nuchalis (polychaete)	10-40 ppt	wide range tolerated			needs > 0.3 mg/L				**3**

Table 3-3. Tolerance of key invertebrate species.

Species	**Tolerant**	**Intolerant**	**Salinity**	**Temperature**	**pH**	**Dissolved Oxygen**	**Feeding Ecology**
Tagelus californianus (jacknife clam)		X	intolerant of low salinities (3-10% seawater)				
Palaemon macrodactylus (oriental shrimp)	X		can tolerate normal or dilute seawater	14-26 C			
Hemigrapsus oregonensis (yellow shore crab)	X		up to 175% seawater (60-62 ppt)				
Polydora nuchalis	X		10-40 ppt				

Table 3-4. Presence of indicator species and their status in habitat types of the lower Malibu Creek watershed.

Indicator Species	Status	Lagoon/ Subtidal	Intertidal Mudflat	Salt Marsh	Stream	Riparian	Sandy Beach & Islands
<u>Invertebrates</u>							
California jacknife clam (*Tagelus californicus*)			X				
yellow shore or mud-flat crab (*Hemigrapsus oregonensis*)			X	X			
<u>Fish</u>							
arrow goby (*Clevlandia ios*)		X	X				
California killifish (*Fundulus parvipinnis*)		X	X	X			
diamond turbot (*Hypsopsetta guttulata*)		X	X				
longjaw mudsucker (*Gillichthys mirabilis*)		X	X				
opaleye (*Girella nigricans*)		X	X				
Santa Ana sucker (*Catostomus santaanae*)	C2, CSC				X		

Table 3-4. Presence of indicator species and their status in habitat types of the lower Malibu Creek watershed.

Indicator Species	Status	Lagoon/ Subtidal	Intertidal Mudflat	Salt Marsh	Stream	Riparian	Sandy Beach & Islands
staghorn sculpin (*Leptocottus armatus*)		X	X				
southern steelhead (*Oncorhynchus mykiss*)	FT	X			X		
tidewater goby (*Eucyclogobius newberryis*)	FE	X	X		X		
topsmelt (*Antherinops affinis*)		X	X				
unarmored threespine stickleback (*Gasterosteus aculeatus williamsoni*)	FE, PCH, SE				X		
<u>Reptiles</u>							
San Diego mount. king snake (*Lampropeltis zonata pulchra*)	C2, CSC					X	
Southwestern pond turtle (*Clemmys marmorata pallida*)	C1, CSC				X	X	X

Table 3-4. Presence of indicator species and their status in habitat types of the lower Malibu Creek watershed.

Indicator Species	Status	Lagoon/ Subtidal	Intertidal Mudflat	Salt Marsh	Stream	Riparian	Sandy Beach & Islands
Birds							
Brown pelican **(*Pelecanus occidentalis*)**	**FE**	**X**					**X**
California least tern **(*Sterna antillarum browni*)**	**FE**	**X**	**X**				**X**
Least Bell's vireo **(*Vireo bellii pusillus*)**	**FE**				**X**	**X**	
Light-footed clapper rail **(*Rallus longirostris levipes*)**	**FE**		**X**	**X**			
Western snowy plover **(*Charadrius alexandrinus nivosus*)**	**FT, PCH**			**X** **(occasional nesting on salt flats)**			**X**
Plants							
Gambel's water cress **(*Rorippa gambelii*)**	**FE, ST**			**freshwater and brackish marshes**		**X**	
Salt marsh bird's-beak **(*Cordylanthus maritimus* ssp. *maritimus*)**	**FE, SE**			**X**			

Table 3-4. Presence of indicator species and their status in habitat types of the lower Malibu Creek watershed (continued).

Legend:

FE = Federally endangered
FT = Federally threatened
PCH = Federally proposed critical habitat
C1 = Category 1 candidate for listing by the U.S. Fish and Wildlife Service
C2 = Category 2 candidate for listing by the U.S. Fish and Wildlife Service
CSC = California Department of Fish and Game "species of special concern"
SE = State Endangered
ST = State Threatened

Table 3-5. Critical habitat characteristics for indicator species.

Indicator Species	Seasonal	Diel Cycle	Tidal Cycle	Substrate Type
<u>Invertebrates</u>				
California jacknife clam (*Tagelus californicus*)	- recruitment			- sandy
yellow shore or mud-flat crab (*Hemigrapsus oregonensis*)	- recruitment (May through August)	- feeds mainly at night	X	
<u>Fish</u>				
arrow goby (*Clevlandia ios*)	- annual species		- forage at high tide	- muddy and disturbance
California killifish (*Fundulus parvipinnis*)	- habitat/area shifts		- forage at high tide	
diamond turbot (*Hypsopsetta guttulata*)	- recruitment/ emigration (use lagoon as nursery)			
longjaw mudsucker (*Gillichthys mirabilis*)	- habitat/area shifts		- forage at high tide	- muddy
opaleye (*Girella nigricans*)	- recruitment/ emigration (used only as a nursery)			
Santa Ana sucker (*Catostomus santaanae*)				

Table 3-5. Critical habitat characteristics for indicator species (continued).

Indicator Species	Seasonal	Diel Cycle	Tidal Cycle	Substrate Type
Fish continued				
staghorn sculpin (*Leptocottus armatus*)	- recruit./ontogenetic habitat shift			
southern steelhead (*Oncorhynchus mykiss*)	- immigration/ development			
tidewater goby (*Eucyclogobius newberryis*)	- annual species - reproduction/ recruitment - seasonal breeding peaks			- gravel - sand or mud
topsmelt (*Antherinops affinis*)	- recruitment/ emigration (nursery and residents) - spawn in lower salinties in spring			
unarmored threespine stickleback (*Gasterosteus aculeatus williamsoni*)	- annual species			
Reptiles				
San Diego mount. king snake (*Lampropeltis zonata pulchra*)				
Southwestern pond turtle (*Clemmys marmorata pallida*)				- sandy shore required for laying eggs

Table 3-5. Critical habitat characteristics for indicator species (continued).

Indicator Species	Seasonal	Diel Cycle	Tidal Cycle	Substrate Type
Birds				
Brown pelican (*Pelecanus occidentalis*)	- lay eggs between December and July	- return to nesting colonies at night	- roosting	
California least tern (*Sterna antillarum browni*)	- only present during breeding season (April – September)		- foraging area	- light-colored sand or shells/small gravel for nesting
Least Bell's vireo (*Vireo bellii pusillus*)	- only present between mid-March and August			
Light-footed clapper rail (*Rallus longirostris levipes*)	- reproduction (mid-March to mid-August)		- influences habitat availability	
Western snowy plover (*Charadrius alexandrinus nivosus*)	- breeding from mi-March to September		- influences habitat availability	- sand for nesting
Plants				
Gambel's water cress (*Rorippa gambelii*)	- perennial species			
Salt marsh bird's-beak (*Cordylanthus maritimus* ssp. *maritimus*)	- annual species		- inundation only at high tides	

Table 3-6. Threats to habitats of indicator species. X = known and potential threats to indicator species

Indicator Species	Eutrophication	Invasion	Hydrological Alterations	Other
<u>Invertebrates</u>				
California jacknife clam (*Tagelus californicus*)	**- low oxygen**		**- low salinity**	
yellow shore or mud-flat crab (*Hemigrapsus oregonensis*)		**- Green crab**		**- juveniles used for fishing bait**
<u>Fish</u>				
arrow goby (*Clevlandia ios*)	**- low oxygen**			
California killifish (*Fundulus parvipinnis*)				**- previously sold for bait**
diamond turbot (*Hypsopsetta guttulata*)	**- low oxygen**			
longjaw mudsucker (*Gillichthys mirabilis*)	**- low oxygen**			**- used as bait in fresh and salt water**
opaleye (*Girella nigricans*)				

Table 3-6. Threats to habitats of indicator species (continued).

Indicator Species	Eutrophication	Invasion	Hydrological Alterations	Other
<u>Fish continued</u>				
Santa Ana sucker (*Catostomus santaanae*)				- drought
staghorn sculpin (*Leptocottus armatus*)	- low oxygen			
southern steelhead (*Oncorhynchus mykiss*)	- low oxygen		X	- Siltation of streambed spawning grounds - coastal development (i.e., dams and water diversion)
tidewater goby (*Eucyclogobius newberryis*)	- low oxygen	yellowfin goby African clawed frog	X	- Siltation of spawning grounds - Barrier breaching
topsmelt (*Antherinops affinis*)				
unarmored threespine stickleback (*Gasterosteus aculeatus williamsoni*)				- reengineering of urban creeks for flood control - increased stream velocity - reduc. in streambed vegetation - occurrence of large oil seeps - interbreeding -

Table 3-6. Threats to habitats of indicator species (continued).

Indicator Species	Eutrophication	Invasion	Hydrological Alterations	Other
Reptiles				
San Diego mountain king snake (*Lampropeltis zonata pulchra*)				
Southwestern pond turtle (*Clemmys marmorata pallida*)				- loss of habitat (especially sandy shore for reproduction)
Birds				
Brown pelican (*Pelecanus occidentalis*)				- high DDT and pesticide concentrations (resulting in eggshell thinning) - human and predatory animal disturbance of breeding colonies - decline in northern anchovy populations for chicks
California least tern (*Sterna antillarum browni*)		- vulnerable to predation	- fluctuating water levels flood the nesting sites	- development of beach nesting areas (expansive stretches of shoreline needed) - declines in food supply (i.e., during El Nino)

Table 3-6. Threats to habitats of indicator species (continued).

Indicator Species	Eutrophication	Invasion	Hydrological Alterations	Other
<u>Birds continued</u>				
Least Bell's vireo (*Vireo bellii pusillus*)		- *Arundo donax*		- parasitism by brown-headed cowbird - loss of riparian habitat (especially vegetation removal and flood control levee construction)
Light-footed clapper rail (*Rallus longirostris levipes*)		- non-native red fox predation	- *Spartina* needs tidal flushing	- loss and degradation of salt marsh habitat (especially *Spartina foliosa* used for nesting)
Western snowy plover (*Charadrius alexandrinus nivosus*)				- development and human disturbance of beach nesting sites
<u>Plants</u>				
Gambel's water cress (*Rorippa gambelii*)		- *Arrundo donax*	- requires a permanent water source (fluctuating water levels from adjacent agricultural activities)	- loss of suitable wetland habitat - encroachement of unsecure sand (caused by off-road vehicle use)

Table 3-6. Threats to habitats of indicator species (continued).

Indicator Species	Eutrophication	Invasion	Hydrological Alterations	Other
<u>Plants continued</u>				
Salt marsh bird's-beak (*Cordylanthus maritimus* ssp. *maritimus*)			**X**	**- development and alteration of salt marsh habitat**

Chapter 4 - Vegetation

Philip W. Rundel

4.1. Riparian Community Structure – Lower Malibu Creek

Riparian corridors are habitats of keystone significance in the mountains of southern California as they form the interface between terrestrial and aquatic ecosystems. In this position, riparian corridors provide critical ecosystem services well beyond the small spatial area that they cover. At the ecosystem level, riparian systems regulate the exchange of nutrients and organic matter between upland chaparral and woodlands and stream systems, contribute large woody debris to stream channels thus influencing sediment transport and deposition, and contribute root mats which help maintain stream bank integrity. At the biological level, riparian systems regulate stream temperature and light regimes, thereby influencing a stream's capacity to sustain viable populations of aquatic organisms, and form distinct biological communities that support high levels of biodiversity. These functions are of particular important in Southern California mountain ranges such as the Santa Monica Mountains where irregular cycles of fire and flood provide unusually dynamic landscape disturbances. These areas are subject to impacts of fluvial disturbances from heavy rainfall events, with associated sediment deposition and/or erosion. Nonfluvial impacts from adjacent upland areas to riparian corridors occur in the form of fire, landslides, and other alterations to their physical structure.

Riparian communities and associated wetland habitats make up less than 1% of the land area of the Santa Monica Mountains of Southern California, but surprisingly are the primary habitat for 20% of the native flora. This remarkable biodiversity is consistent with the high biodiversity found in other riparian communities in the western United States.

Adaptations for survival in dynamic riparian communities appear to result from generalist strategies that work well in riparian zones across broad mesoclimatic gradients. Patterns of biogeographic distribution for the riparian-specialist flora of the Santa Monica Mountains clearly indicate that these species are commonly widespread in distribution. This is not surprising given that the relatively high availability of water in riparian habitats decouples many plant species from regional rainfall regimes. None of the specialist riparian flora of either lower Malibu Creek or of the entire Santa Monica Mountains is included as rare or endangered for the California flora (Skinner and Pavlik 1994).

Given the dynamic changes of fire and flood cycles that alter the physical environment of riparian ecosystems in Southern California, it is not surprising that riparian plant communities are highly irregular in structural and compositional diversity. Riparian communities reflect not only the effects of both individual and cumulative disturbance regimes along their stream channels, but also the impacts of landscape processes affecting adjacent chaparral and woodland communities. Structural and compositional complexity presents problems in developing workable classification systems based on species dominance for riparian plant communities in California (Holland 1986, Sawyer and Keeler-Wolf 1995). In deference to the impacts of such irregular disturbance regimes, geomorphic history and structure are now being considered in developing new classification systems for riparian communities in the coastal mountains of Southern California (Ferrin et al. 1996b).

4.2. Classification of Riparian Community Types

The history of habitat classification in California, including riparian ecosystems, has been presented in some detail by Ferren et al. (1996a). The most widely used system of classification for terrestrial habitats in the state has been a semi-published contribution for the California Department of Fish and Game, *Preliminary Descriptions of the Terrestrial Natural Communities of California* (Holland 1986). This project provided a reorganization of previous systems of classification into a new format with a hierarchical numerical classification with element codes, names, descriptions, and characteristic species for each community. This system included approximately 68 wetland community types, with four of these being present along lower Malibu Creek, as described below. The California Native Plant Society, together with the Department of Fish and Game, has sponsored a new synthesis of California terrestrial communities in a volume entitled, *A Manual of California Vegetation* (Sawyer and Keeler-Wolf 1995). This synthesis described a large number of wetland community types, and further attempted to bridge the gap between previous superficial classification of California wetland communities and national efforts to classify wetlands more formally. Nevertheless, there are a number of criticisms that have been raised for this classification system in its poor separation of riparian and adjacent upland communities, its somewhat arbitrary designation of community types, and the workability of its keys to community identification. Attempts are also being made to develop a system of classification for riparian habitats and the wetlands in California using a more hydro-geomorphic definition of community units (Ferrin et al. 1996b).

Lower Malibu Creek presents a mosaic of relative natural riparian communities and other areas with highly degraded riparian community structure. While we have attempted to apply both the Holland system and Sawyer and Keeler-Wolf system of classification to these communities, neither system of classification provides units that can be mapped on aan appropriate scale. Often, it is possible to identify three differing community types along less than 50 m of riparian habitat. For this reason a simple mapping of riparian habitats was not possible.

There are six keystone woody species, identified here because of the frequency and abundance, which form the major part of the riparian communities along lower Malibu Creek. These species are as follows:

Platanus racemosa (California or western sycamore)

Populus fremontii (Fremont cottonwood)

Quercus agrifolia (coast live oak)

Salix laevigata (red willow)

Salix lasiolepis (arroyo willow)

Umbellularia californica (California bay)

In addition, five other native woody species may also be locally significant in riparian communities along lower Malibu Creek:

Alnus rhombifolia (white alder)

Fraxinus velutina (velvet ash)

Juglans californica (California walnut)

Populus trichocarpa (black cottonwood)

Salix exigua (sandbar willow)

Three Holland community types and a number of community subdivisions are present along the study area of lower Malibu Creek. These types are as follows, with their index numbers shown:

- **Riparian forests** (61000)
  - Southern riparian forest (61300)
    - Southern coast live oak forest (61310)
    - Southern arroyo willow riparian forest (61320)
    - Southern cottonwood-willow riparian forest (61330)
- **Riparian woodlands** (62000)
  - Southern sycamore-alder riparian woodland (62400)
- **Riparian scrubs** (63000)
  - Southern riparian scrub (63300)
    - Southern willow scrub (63320)
    - Mulefat scrub (63310)

This system in its primary focus on the height and density of the dominant vegetation becomes clearly artificial in attempting to separate the gradient from forest to woodland to scrub/shrubland communities. Many or even most riparian communities along lower Malibu Creek exhibit mosaics, at varying scales, for all three structural types. Human impacts in opening natural communities further complicate this designation.

The plant communities along riparian and adjacent woodland areas of the lower Malibu Creek corridor would fall into seven vegetation series within the classification system of Sawyer and Keeler-Wolf (1995). As with the Holland system, these units occur in mosaics of varying sizes and are not readily mappable.

- **Arroyo willow series** – arroyo willow sole or dominant shrub or tree in canopy; other willows, California sycamore, Fremont cottonwood, and mulefat may be present; shrubland with emergent trees to 10 m; canopy continuous; ground layer sparse to abundant.

- **California sycamore series** – California sycamore sole or dominant in canopy as widely spaced trees; arroyo willow, red willow, coast live oak, California bay, and Fremont cottonwood may be present; trees to 35 m; canopy open; shrubs infrequent to common; ground layer variable.

- **Coast live oak series** – coast live oak as sole or dominant tree in canopy; California bay and laurel sumac as common associates; trees to 30 m; canopy continuous, shrubs occasional to common; ground layer variable.

- **Mixed willow series** – more than one willow species shares dominance as shrubs and/or trees in canopy; arroyo willow, Pacific willow, red willow, and California sycamore may be present; usually shrubland with emergent trees to 10 m; canopy continuous; ground layer sparse.

- **Mulefat series** – mulefat the sole or dominant shrub in the canopy; arroyo willow and/or narrowleaf willow may be present; shrubs < 4 m in height; canopy continuous, ground layer sparse.

- **Pacific willow series** – Pacific willow as sole or dominant tree in canopy; California sycamore, Fremont cottonwood, and other willows may be present; if shrubland, emergent trees to 15 m or more may be present; canopy continuous; shrubs sparse under tree canopy; ground layer variable.

- **Giant reed series** – giant reed as the sole or dominant cover; emergent shrubs and trees may be present between clumps of giant reed, but community diversity is low; giant reed cover becoming dense and continuous to 8 m.

4.3. Human Impacts on the Riparian Corridor of Lower Malibu Creek

Riparian communities, despite their significance, have been widely altered and eradicated in recent decades, with estimates given that less than one third of the original riparian corridors in the United States remain. Expanded urban development, agricultural activities, livestock grazing, and dam construction have been major factors in the elimination of riparian communities. Even in protected areas of the Santa Monica Mountains, riparian communities are not immune from threat.

Despite generalist adaptations to disturbance regimes, riparian zone plants are highly sensitive to human impacts. Vegetation clearance, trampling, stream channel modifications, altered fire regimes, grazing, and recreational activities have all had significant impacts on the structure and diversity of riparian communities in the Santa Monica Mountains. These impacts come about through physical changes in the environment as well as secondarily by the introduction of alien species that choke out the growth of natives. We have noted that riparian plant species diversity is commonly inversely correlated with levels of disturbance, while frequency of alien plant occurrences is directly related to disturbance. Very little is known, however, about the relationship between biodiversity and ecological functional in riparian ecosystems. Alien species appear to be increasing in diversity and abundance in riparian habitats in the Santa Monica Mountains. Some of these species have the potential to profoundly impact the structure and function of these ecosystems.

4.3.1. Alien Species Invasions

Alien species invasions represent a highly significant threat to the ecological structure of riparian communities throughout the Santa Monica Mountains, including those habitats along lower Malibu Creek. More than fifty species of aliens occur in riparian corridors of the Santa Monica Mountains, nearly half of all naturalized alien species in the region. These species include some strongly aggressive invaders that have the potential to dramatically impact the structure and biodiversity of riparian ecosystems.

The alien species of greatest concern in lower Malibu Creek, as well as in many riparian habitats in the Santa Monica Mountains and throughout Southern California, is the giant reed, *Arundo donax* (Poaceae). This tall woody grass forms dense clumps reaching up to 9 m in height. *Arundo donax* was originally introduced to California from the Mediterranean Basin for landscaping and erosion control. With its ability to rapidly colonize denuded flood zones, extraordinary rates of growth, and hardiness of established clumps, *Arundo donax* has rapidly spread through riparian habitats in Southern California. Highly disturbed riparian habitats such as the Santa Ana River in Orange County contain *Arundo donax* thickets covering 70% or more of its stream banks over extensive areas.

Viable seed production appears to be absent in California, and thus *Arundo donax* spreads through vegetative means. Physical disturbance of riparian corridors seems to aid this spread by opening available sites and fragmenting rhizomes. Once established, *Arundo donax* roots deeply and broadly, making it highly drought resistant. While the culms of this cane are themselves highly flammable, and thus allow wildfires to penetrate into riparian corridors and damage native species, this species resprouts rapidly from its rhizomes and expands its dominance following such disturbance.

There are two primary ways in which the spread of *Arundo donax* can affect the structure and diversity of riparian communities. Thick stands of *Arundo donax* crowd out and shade native riparian species, particularly keystone woody species such as sycamores, willows, and alders. Such *Arundo donax* stands also provide a large biomass of highly flammable plant material. Under these conditions, chaparral fires which commonly jump over or stop along riparian corridors will burn intensely through these areas, seriously weakening or killing native species. *Arundo donax*, however, readily resprouts after fire to regain and expand its previous dominance.

Several other woody plant species have also become locally abundant invaders in riparian habitats in lower Malibu Creek. *Ricinus communis* (Euphorbiaceae), the castor bean, forms dense thickets along both small runoff channels and larger streams such as Malibu Creek. These thickets often crowd out competing native species, but seem to be associated primarily with areas of heavy site disturbance. *Nicotiana glauca* (Solanaceae), wild tree tobacco, is locally abundant in riparian habitats where disturbance has occurred. This species forms dense monospecific stands in disturbed flood plains in other areas of riparian habitat in southern California and northwestern Baja California, suggesting that it may become increasingly invasive along lower Malibu Creek. Although not currently a problem along lower Malibu Creek, *Ailanthus altissima* (tree of heaven) is becoming widely established in riparian habitats of the Santa Monica Mountains, and has the potential to become much more aggressive as an invader.

Several herbaceous species among the large number of aliens present along lower Malibu Creek are potential subjects of concern. The most significant of these is fennel, *Foeniculum vulgare*, which may become dense in open disturbed sites. Two thistle species, the milk thistle, *Silybum marianum,* and the bull thistle, *Cirsium vulgare,* have become widely established in a number of riparian habitats in the Santa Monica Mountains including lower Malibu Creek. These thistles form dense stands and may become aggressive weedy invaders with strongly negative impacts on native species.

4.4. Field Sampling Methods

Riparian vegetation along Malibu Creek from the Salvation Army Camp downstream to the bridge at Pacific Coast Highway was surveyed to determine major plant communities and the presence and extent of invasion by exotic species.

4.4.1. Sample Sites

From the Salvation Army Camp to the downstream end of the Tapia Water Treatment Facility, riparian community sampling was carried out approximately every 500 meters to develop preliminary data on the scale of woody plant community variation along Malibu Creek (Figure 4-1). From this point downstream to the Pacific Coast Highway bridge, samples were taken where a change in plant community composition was observed. Depending upon accessibility to the stream, samples were either taken from a vantage point in the stream itself or at a viewpoint along Malibu Canyon Road. A sample site included the length of stream visible both upstream and downstream from the vantage point chosen by the surveyors.

4.4.2. Data Collected

Two types of samples were taken: those from vantage points in the stream, and those from the roadside. For samples taken in the stream (designated below as sections with the prefix "C", observations were made for the following attributes of the site:

- Plant Community: plant communities as described by Holland were determined. In many cases more than a single community was present.
- Dominant Species: dominant trees and shrubs were identified and described with respect to percent coverage for the given segment of stream, approximate range of heights, and approximate distances from the stream.
- General Weediness: the understory and stream channel were each ranked on a scale of 0-5, with 0 being few to no weeds and 5 being extremely weedy.
- Disturbance: disturbance at a site, if present, was categorized as either anthropogenic or natural, and briefly described.
- Bank Slope: the slope of each bank was estimated to be in one of the following categories: 0-14°, 15-29°, 30-44°, 45-59°, 60-89°, 90°.
- Stream Width: the width of the stream was estimated.
- Stream Botttom: the stream bottom was briefly described.
- Algae: percernt cover by algae was estimated.
- General Observations: general observations were noted for some sites.

For samples taken from the road using field glasses (designated as sections with the prefix "R"), the following attributes of a site were described.

- Plant Community: plant communities as described by Holland were determined. In many cases more than a single community was present.
- Domnant Species: dominant trees and shrubs were identified.
- General Weediness: the understory was ranked on a scale of 0-5, with 0 being few to no weeds and 5 being extremely weedy.
- General Observations: general observations were noted when appropriate.

4.5. Field Sampling Results

4.5.1. Status of Riparian Communities

In all but a few highly disturbed areas, the riparian plant communities along lower Malibu Creek appear to be thriving. Three communities as described by Holland (1986) dominated most of the riparian areas: Southern Sycamore-alder Riparian Woodland, Southern Cottonwood-Willow Riparian Forest, and Southern Willow Scrub. Active anthropogenic disturbance appears to be surprisingly limited along lower Malibu Creek with the exception of riparian areas where construction activities have taken place, as at Rindge Dam, Cross Creek Shopping Center and the Tapia Water Treatment Facility.

Arundo donax is the exotic invader that poses the greatest threat to these communities. In highly disturbed areas, impressively large thickets dominate the riparian zone, and clumps of varying size were observed in every section of stream surveyed. Other non-native species were observed, but none were as abundant or approached the level of impact shown by *Arundo donax.*

4.5.2. Riparian Community Structure

These species, in general, form a continuous corridor along both banks of the study area of lower Malibu Creek. Willows (predominantly *Salix lasiolepis* and *Salix laevigata*) are a major component of the riparian communities present. These willows occur either as an understory in Southern Cottonwood-Sycamore and Southern Cottonwood-Willow Riparian Forests, or as the dominant overstory plant in Southern Willow Scrub. Dense willow thickets are common and observed in all three communities. In the Southern Cottonwood-Willow Riparian Forest seen in Section C5, willows play a characteristically less important role than in the other two communities; however *Populus fremontii* fills in to contribute to continuous woody coverage. It is only in the few highly disturbed areas that willow coverage is reduced to small amounts, leaving areas in the riparian zone without coverage by keystone woody species. These areas are:

- Section C1, where the Cross Creek Shopping Center on the west bank and a housing development on the east bank are major disturbance factors that are immediately adjacent to the stream banks;
- Sections R2, R3 and R4, the Rindge Dam, the area immediately downstream of it and the highly sedimented floodplain immediately upstream of it; and
- Section C9, the Salvation Army Camp and Tapia Water Treatment Facility.

In these areas, the continuous corridor of woody riparian species is interrupted. This is most evident in Sections R3 and R4, adjacent to and upstream of Rindge Dam, where there are so few woody individuals present that it is impossible to classify these stands as to community type. It is notable that riparian areas that were apparently disturbed during the construction of the dam and area above the dam where siltation has occurred continue to offer very poor coverage by native riparian species. Revegetation efforts would clearly be valuable in these areas. Sample Section C4, just upstream of the R4 floodplain area, shows approximately 75% woody riparian coverage at the downstream end of the section, as it transitions to the Southern Cottonwood-Willow Riparian Forest in Section C5. The area apparently impacted by the dam covers a much greater length of stream than the areas impacted by the shopping center and water treatment facilities, where disturbance is far more localized around the point of disturbance. Local areas with high disturbance near the Cross Creek Shopping Center could be classified as Mulefat Scrub.

Aside from the major structures mentioned above, anthropogenic disturbance to the riparian zone can be characterized as minor. Small fire rings and campsites were observed, usually with litter in the form of beer cans and food wrappers along the banks. There are footpaths along the banks in a few places, and occasional paths from Malibu Canyon Road to the stream. Fishing line was observed in the creek in several places. It was rare to encounter other people on the stream banks or in the stream during the frequent surveys made over the summers and falls of 1997 and 1998.

4.5.3. Establishment of **Arundo donax**

A major threat to the continuous woody riparian corridors along Malibu Creek is invasion by *Arundo donax*. There was no section of the stream where this species was absent. In the floodplain areas at Sections C1 and C2, and C7 and C8, large thickets, up to more than 10m high and 50m wide, dominate the riparian zone at the expense of willows and other native woody species. Bank slopes in these areas are shallow. Large thickets also dominate the riparian zone, forming a virtual monoculture in the absence of all but a few woody individuals in the area at Rindge Dam and above in Sections R3 and R4. Although the stream is at the bottom of a valley with steep slopes here, the stream banks are highly sedimented above the dam, forming a gently sloped plain on both sides of the stream. This is where the *A. donax* has become established. The large thickets that seem to characterize floodplain areas were not observed in Section C3. However, several well-established clumps as well as smaller younger clumps were observed here. Bank slopes in this section are increasingly steep when compared with those downstream. In Sections R1 and R2, with steeper bank slopes, *A. donax* is present in smaller clumps, some well-established and others short and clearly recent in origin. From Section C4 upstream to Section C6, where the stream is in a valley between steep slopes on both banks, *A. donax* is present only in small clumps, most of which are young and thin. Section C9, which is contained within Tapia Park, has very little *A. donax*. Clumps that were observed in this section were thin, and none was observed on Salvation Army Camp grounds.

Exotic species observed other than *Arundo donax* were mostly herbs, with the exception of the shrubby invader *Ricinus communis,* castor bean. This species is present with its greatest abundance and most impressive plant size in highly disturbed areas, most notably in Sections C1 and C9. In Section C1, for example, cover was estimated at 20-30% with individuals 2-3m high. However, it is also present along most of the stream banks surveyed, in some areas represented only by scattered seedlings. These populations will almost certainly increase in size and density unless treated.

One final observation was notable. This was the extent of green algal cover on the stream bottom, and in some sections through the water column, all along lower Malibu Creek. Although algae cover was observed to be as light at 10% in one area, overall, it was moderate to heavy, and reached an estimated 80% cover in Section C5. Thick mats were present not only on the stream bottom, but dried on boulders presently above water level as well.

4.6. Field Sample Data

4.6.1. SECTION C1.

General Observations

Highly disturbed with anthropogenic activity continual throughout,development on both banks. Sizeable established thickets, as well as newer clumps of Arundo donax. Array of domesticated fruit, nut and other trees, shrubs and herbs that appear to be intrusions from streamside housing developments. Waterfowl present.

Plant Community (Holland) - Southern Willow Scrub

Dominant Species

Salix lasiolepis, Salix laevigata - together representing approximately 30% coverage, individuals approx. 4 -5 m high, immediately at stream bank

Arundo donax - represents 30-50% cover; clumps >10 m high, 50 m wide, at stream bank

Ricinus communis - 20-30% cover; 2-3 m high,at stream bank

Other species:

Platanus racemosa, Quercus agrifolia, Juglans californica, Fraxinus velutina, Foeniculum vulgare, Baccharis salicifolia, Artemesia douglasiana, assorted domesticated fruit, nut and other trees, shrubs and herbs

General Weediness - Understory extremely weedy, stream very few weeds

Bank Slope - Both banks 0-15°

Stream Width – 20 m

Stream Bottom - Rocky, boulders up to 1.5m diameter

Algae - 30-50% cover on stream bottom and through water column

Disturbance - Severe, both anthropogenic and flooding; homesteads on banks; shopping center, housing as close as 50-75 m from stream on both banks.

4.6.2. SECTION C2.

General Observations

Minor to no anthropogenic disturbance observed here. *Arundo donax* well established throughout, heavy at upstream end of section. Sizeable sandbar here was included in survey. Waterfowl present.

Plant Community (Holland) - Southern Sycamore-Alder Riparian Woodland

Dominant Species

Platanus racemosa dominates sandbar 60% coverage, individuals 15-20 m tall; elsewhere approx. 25% coverage thinning to only scattered individuals at upstream end of section, individuals 10-25m tall, at streambank throughout.

Quercus agrifolia not observed on sandbar, approx. 15% coverage elsewhere thinning to only scattered individuals at upstream end of section, individuals 10-25 m tall, at streambank throughout.

Salix lasiolepus, Salix laevigata, Salix exigua together representing 20-40% coverage, 3-5 m tall with occasional 10-15 m individuals, at streambank throughout.

Arundo donax present in dense clumps 3-10 m tall, up to 70% coverage at upstream end of section.

Other Species:

Ricinus communis scattered seedlings present. *Foeniculum vulgare, Baccharis salicifolia, Artemesia douglasiana, Rubus ursinus, Scirpus acutus,* 2 palms observed.

General Weediness - ranged from little to none on sandbar to moderate with high diversity of grasses,herbs and shrubs, to 70% coverage by *A. donax*, but very few other weeds at upstream end of section.

Bank Slope - At downstream end of section, east bank 0-15°, 60-90° elsewhere.

Stream Width - >50m at downstream end of section, 10-20m at upstream end of section.

Stream Bottom - sandy with boulders 1-2m diameter.

Algae - little to moderate coverage throughout.

Disturbance - Minor (footpath on east bank of stream) to no anthropogenic disturbance observed here. Flooding is major natural disturbance risk.

4.6.3. SECTION C3.

General Observations

Minor to no anthropogenic disturbance observed here. Arundo donax well established throughout,heavy at upstream end of section. Densely covered sandbar here was included in survey.

Plant Community (Holland) - Southern Willow Scrub

Dominant Species

Salix lasiolepus, Salix laevigata - together representing 70-100% coverage, 7-10m at downstream end of section,1-2m at upstream end of section, at streambank throughout.

Salix exigua - scattered individuals, 2-4m, at streambank throughout.

Platanus racemosa - 10-15% coverage at downstream end of section, individuals 15m, scattered individuals at upstream end of section, at streambank throughout.

Quercus agrifolia - scattered individuals, approx. 15m tall, ≥10m away from stream.

Populus fremontii - scattered individuals, approx. 15m tall, ≥5m away from stream.

Arundo donax - scattered young clumps with thin stems up to 10m tall at downstream end of section, series of major clumps 5-6m tall, 5-10m wide at upstream end of section.

Ricinus communis 1-2m tall individuals at downstream end of section, seedlings in open areas along banks at upstream end of section.

Other Species:

Two palms, *Baccharis salicifolia, Artemesia douglasiana, Scirpus acutus.*

General Weediness - ranged from moderate with low diversity, mostly young stands of A. donax, at downstream end of section to little to none at upstream end of section.

Bank Slope - At downstream end of section, east bank 30-45°, west bank 15-30°, increasing in steepness toward upstream end of section.

Stream Width - varies from 5m-50m throughout section.

Stream Bottom - rocky with boulders up to 3m diameter.

Algae - covers stream bottom.

Disturbance - little to no anthropogenic disturbance observed.

4.6.4. SECTION R1.

General Observations

Thickets of mixed *Salix* species with sparse young, thin clumps of *Arundo donax*. Stream has some boulders, but mostly smaller rocks, and appears to be flowing at a rapid pace.

Plant Community (Holland) - Southern Willow Scrub in transition to Southern Sycamore-Alder Riparian Woodland

Dominant Species

Salix spp. (Most likely *S. lasiolepus* and *S. laevigata*) 80% coverage

Platanus racemosa - 40% coverage

Quercus agrifolia - 5-10% coverage

Other species:

Arundo donax present in sparse, thin, young clumps

Scirpus sp., Typha sp.

General Weediness - 1

4.6.5. SECTION R2.

General Observations

Stream narrower than Section R1, with larger boulders, and apparently slower flow. Riparian dominant species thinning out (relative to Section R1) with *Arundo donax* present in several well-established clumps.

Plant Community (Holland) - Southern Sycamore Alder Riparian Woodland

Dominant Species:

Salix spp. (Most likely *S.lasiolepus* and *S.laevigata*) - sparse coverage

Platanus racemosa - 30% coverage

Quercus agrifolia - 30% coverage

Other Species:

Arundo donax - several well-established clumps

One palm tree observed

General Weediness - 3 (low diversity, reflects *Arundo donax)*

4.6.6. SECTION R3.

General Observations

Area immediately above dam. Highly disturbed, sediment deposition behind dam, very sparse dominant riparian vegetation, and large, well-established thickets of *Arundo donax.*

Plant Community (Holland) - Vegetation too sparse to classify.

Dominant Species:

Arundo donax dominates riparian zone with many well-established, large clumps

Salix sp. (Appears to be *S. exigua*) sparse

Other Species:

Typha sp. sparse

General Weediness - 4-5 (low diversity, reflects *Arundo donax)*

4.6.7. SECTION R4.

General Observations

Floodplain upstream of dam. Highly disturbed with light keystone riparian vegetation, and large, well-established thickets of *Arundo donax.*

Plant Community (Holland) - Appears to be highly disturbed Southern Willow Scrub.

Dominant Species:

Arundo donax - dominates riparian zone with many well-established, extremely large clumps

Salix spp. (Most likely *S.lasiolepus, S.laevigata and S.exigua*) - ≤ 10% coverage

Platanus racemosa - a few individuals

General Weediness - 4-5(low diversity, reflects *Arundo donax)*

4.6.8. SECTION C4.

General Observations

Minor anthropogenic disturbance observed in riparian zone. However, road is as close as approx. 75m to west bank in some places, and fishing line observed in stream indicates recreational use here. Overall keystone woody riparian coverage approx. 75%, much light reaches floor. Waterfowl present. Stream slope relatively steep here with several cascades over boulders. Stream flow relatively rapid. Little to no *Arundo donax* observed.

Plant Community (Holland) - Southern Sycamore-Alder Riparian Woodland

Dominant Species

Salix lasiolepus, Salix laevigata - together representing 20% coverage, approx. 3 m tall, at streambank to approx. 10 m away

Salix exigua - rare single individual

Platanus racemosa - 10-20%, individuals 15-20 m, at stream bank to 50 m away

Quercus agrifolia - 20-25% coverage on east bank, 10% coverage on west bank, individuals 10-20 m tall, east bank at stream bank to 100 m away from stream, west bank 25m-100m away from stream.

Populus fremontii - scattered individuals

Umbellularia californica - single individual, 15 m tall, 15 m from stream bank

Other Species

Arundo donax - rare young, thin clumps

Artemesia douglasiana, Malosma laurina, Foeniculum vulgare, Rubus ursinus

General Weediness - Moderate, many herbs, grasses in understory

Bank Slope - 30-45° at upstream end of section, decreasing to floodplain area at downstream end of section

Stream Width -10-20m

Stream Bottom - large boulders up to 10m diameter, also small rocks <1m diameter, some sandy patches

Algae - 60-75% coverage on stream bottom.

Disturbance - major disturbance appears to be from flooding, some small campfire sites on west bank, road as close as 75m in some places on west bank, fishing line in stream, footpath from road to stream at downstream end of section

4.6.9. SECTION C5.

General Observations

Minor anthropogenic disturbance observed here. Evidence of recent flooding. Woody riparian keystone species relatively diverse. Many vines on east bank. *Arundo donax* sparse. Crustaceans thriving in stream.

Plant Community (Holland) - Southern Cottonwood-Willow Riparian Forest

Dominant Species

Populus fremontii - 30-40% coverage on east bank, 50% coverage on west bank, 3-20 m tall, at stream bank throughout

Salix lasiolepus, Salix laevigata - together representing 1-10% coverage on east bank, 20-30% on west bank, 2-7 m, at stream bank throughout.

Platanus racemosa 0-10% coverage on east bank, 10-20% on west, 4-10 m tall

Quercus agrifolia - 10-20% coverage both banks, 15-20 m tall, at stream bank to 50 m away from stream

Alnus rhombifolia - single individual, approx. 25 m tall, at stream bank

Fraxinus velutina - 0-10% coverage, 8-10 m tall

Other Species:

Arundo donax patches 3-4 m tall, 4-5 m from stream bank

Rubus ursinus

General Weediness - high herbaceous diversity, many vines, grasses growing around boulders in stream

Bank Slope - 60-90° east bank, 30-45° west bank

Stream Width - 5-7 m

Stream Bottom - sandy with boulders up to 3 m diameter.

Algae - 80%, dried on boulders, and stream bottom covered with thick mats

Disturbance - little to no anthropogenic disturbance observed, fishing line in stream

4.6.10. SECTION C6.

General Observations

Riparian vegetation is dense, stream flow is relatively rapid, stream and riparian zone appear to be thriving.

Plant Community (Holland) - Southern Sycamore-Alder Riparian Woodland

Dominant Species

Salix lasiolepus, Salix laevigata - together representing 75-80% coverage on east bank, 50% on west bank, 5-7 m, at streambank throughout.

Platanus racemosa - 15% coverage, 10 m tall

Alnus rhombifolia - 5-10% coverage, 8 m tall

Umbellularia californica - scattered individuals, 10 m tall

Quercus agrifolia - 80% coverage ≥ 50 m away from east bank, scattered ≥ 20 m away from west bank, 10 m tall

Fraxinus velutina - scattered individuals on west bank, 5 m tall

Scirpus californicus - scattered individuals < 1 m tall

Other Species:

Arundo donax single young thin clump

Artemesia douglasiana, Baccharis salicifolia, Rubus ursinus

General Weediness - high herbaceous diversity on west bank, slightly less weedy on east bank, stream itself not weedy

Bank Slope - 30-60° east bank, 15-30° west bank

Stream Width – 3 m

Stream Bottom - rocky with boulders up to 2m diameter, channel lined with 5m boulders along banks

Algae - 80% on bottom, water is clear

Disturbance - moderate anthropogenic disturbance on west bank, campsites, footpath, litter

4.6.11. SECTION C7.

General Observations

Meter station with paving on banks at downstream end of section and dirt road to stream at this point. Side channel immediately upstream has dense closed canopy of mixed S.lasiolepus, S.laevigata. Floodplain area at upstream portion of section appears pristine on east bank, yet highly disturbed on west bank, dominated by large thickets of *Arundo donax*. Sandbars present. Waterfowl and fish observed.

Plant Community (Holland) - Highly disturbed Southern Willow Scrub

Dominant Species

Salix lasiolepus, Salix laevigata - together representing up to 100% coverage, individuals 5-10 m tall, at streambank to 3 m away on east bank; scattered individuals, 3 m tall, at streambank on west bank

Platanus racemosa - 10-15% coverage individuals 10-20 m tall on east bank, 10% coverage, 10-20 m tall on west bank

Quercus agrifolia - 50% coverage, 15 m tall ≥ 50 m away from east bank; scattered, 15 m tall, ≥ 50 m away from west bank

Alnus rhombifolia - 5-10% coverage, 5-8m tall

Arundo donax - large thickets, 2-3 m tall, 10-15 m wide dominate west bank riparian zone; scattered small thin clumps on east bank

Other Species:

Artemesia douglasiana, Baccharis salicifolia, Ricinus communis

General Weediness - high herbaceous diversity on west bank, only slightly weedy on east bank

Bank Slope - 0-15%

Stream Width - 15m main channel, side channels 1-3m on both sides, meanders with bars along section

Stream Bottom - sandy with small rocks occassional 1m diameter boulder

Algae - 0-10% coverage on stream bottom, patchy

Disturbance - Meter station with paving on banks at downstream end of section, wide dirt path from road to stream, west bank highly disturbed, east bank appears pristine, side channels with dense riparian vegetation and little to no disturbance evident

4.6.12. SECTION C8.

General Observations

Highly disturbed with large thickets of *Arundo donax* at downstream end of the section. Increasingly dense willow thickets toward upstream end, forming closed canopy in some areas. Little to no anthropogenic disturbance evident. Portions of this area are on private property with restricted access.

Plant Community (Holland) - Southern Willow Scrub, with transition to Southern Live Oak Forest.

Dominant Species

Salix lasiolepis, *Salix laevigata* - together representing up to 100% coverage, individuals 5-10m tall, at stream bank

Platanus racemosa - approx.10% coverage, individuals 10-20 m

Quercus agrifolia - 30-50% coverage, 15 m tall

Alnus rhombifolia - 5% coverage, 5-8 m tall, at stream bank

Arundo donax - large thickets, 2-3 m tall, 10-15 m wide dominate downstream; \ thinning to scattered clumps upstream

Other woody species

Artemesia douglasiana, Baccharis salicifolia, Ricinus communis

General Weediness - high diversity of herbaceous weeds.

Bank Slope - 0-15%

Stream Width - 10-15 m

Stream Bottom - sandy with small rocks occasional 1m diameter boulder

Algae - 30-50% coverage on stream bottom

Disturbance - Little to no anthropogenic disturbance noted in this section.

4.6.13. SECTION C9.

General Observations

Dense coverage from keystone woody riparian species except in immediate vicinity of Tapia Water Treatment Facility and on Salvation Army Camp grounds. The diversity of hardwoods near the Salvation Army Camp is the highest of any portion of lower Malibu Creek surveyed, with the possible exception of Section C1. Many individuals appear to have been planted. Fish and crustaceans were present.

Plant Community (Holland) – Southern Cottonwood-Willow Riparian Forest and Southern Sycamore-Alder Riparian Woodland, with transition to Southern Live Oak Forest.

Dominant Species

Salix lasiolepus, Salix laevigata - together representing up to 100% coverage,

individuals 5-10 m tall, at streambank

Platanus racemosa - 10-50% coverage, individuals 10-25m, at streambank to 25 m height; appear to be cultivated in some areas

Quercus agrifolia - 10-40% coverage, 15-20 m tall, rare at stream bank, to 50m away

Populus trichocarpa, Populus fremontii - scattered individuals, 10-30% coverage, 5-10 m tall, 1-5 m from stream

Juglans californica - rare individuals, 5-15 m tall, 1-5 m from stream

Alnus rhombifolia - 5% coverage, 5-8 m tall, at stream bank

Baccharis salicifolia - up to 75% coverage, 0-3 m from stream

Arundo donax - small clumps present

Other Species

Artemesia douglasiana, Acer negundo, Ricinus communis, Typha sp., Scirpus acutus, Scirpus californica

General Weediness - high diversity of herbaceous exotics

Bank Slope - 0-45%

Stream Width -5-10 m

Stream Bottom - sandy with small rocks

Algae - 25-100% coverage on stream bottom

Disturbance - Salvation Army Camp at upstream end, with bridges through creek, much anthropogenic activity, paved bank with drains at Tapia Water Treatment Facility.

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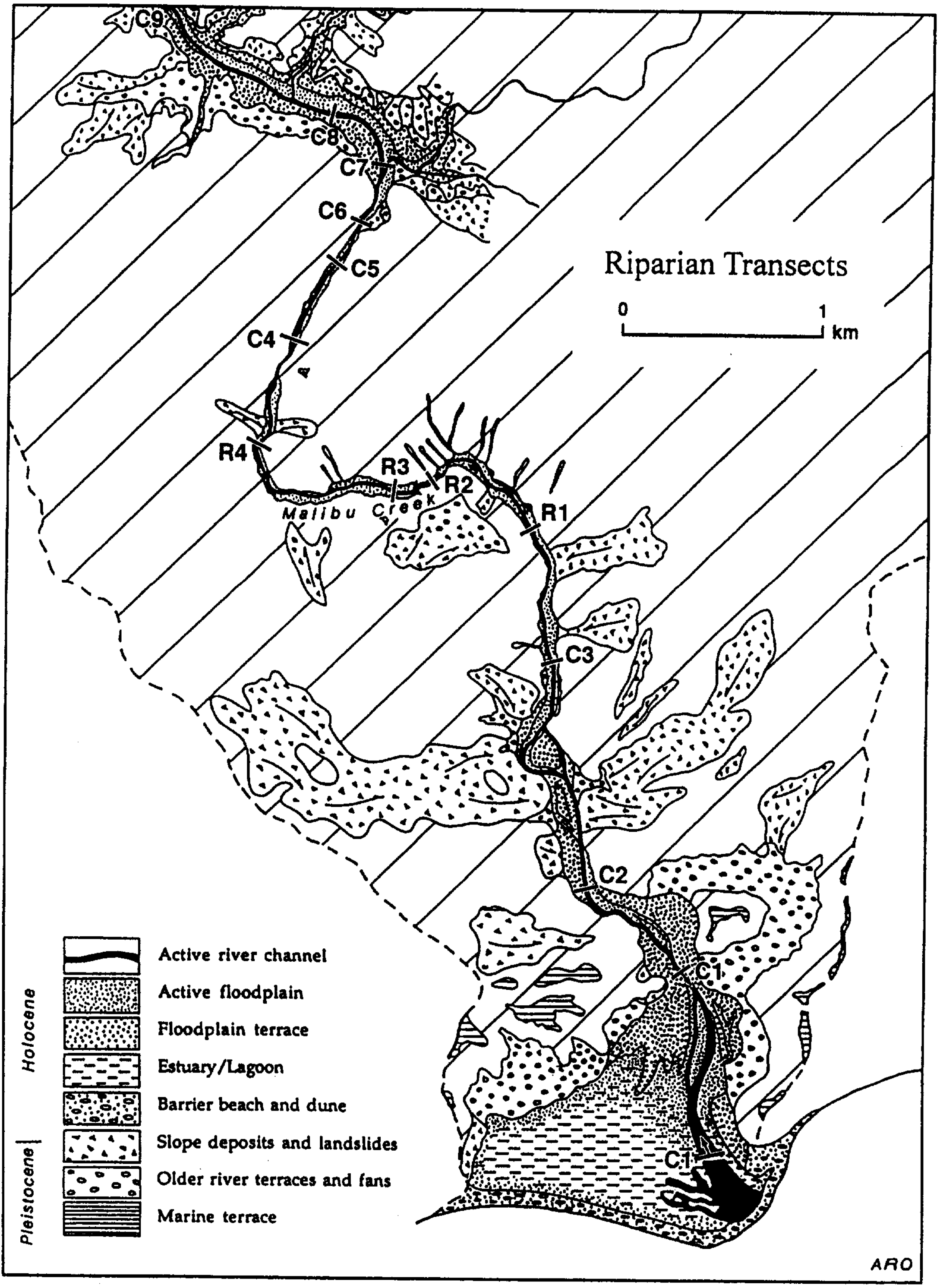

Figure 4-1. Location of vegetation mapping sections.

Chapter 5: Eutrophication

I.H. (Mel) Suffet
Shelby Sheehan

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5.1 Introduction

Malibu Lagoon is a small estuary located within the City of Malibu, approximately 35 miles (56 km) west of Los Angeles, California. The lagoon is a seasonal brackish marsh that is generally closed from the ocean by a sand barrier in the dry season, and open to the ocean in the wet season. It is the receiving water of the 109 square mile (282 km^2) Malibu Creek Watershed. The main channel is Malibu Creek, which receives waters from several lakes and tributaries, and drains into Malibu Lagoon, then empties into Santa Monica Bay (Figure 1) (Warshall 1992).

Water resource management of Malibu Lagoon is concerned with the potential problems associated with eutrophication (Warshall 1992). Eutrophication includes overenrichment of a waterbody by nutrients, primarily nitrogen and phosphorus. Nutrients limit the growth of phytoplankton (algae) and macrophytes (larger aquatic plants). Excessive levels of nutrients can cause overstimulation of aquatic plant growth, resulting in algal blooms and other detrimental consequences (Kiorboe 1996). Effects include hypoxia, algal blooms, and changes in species diversity and abundance. These changes are considered undesirable because they can affect beneficial uses and reduce biological diversity (Richardson and Jorgensen 1996). The recommended level of nutrients in estuaries and coastal ecosystems to avoid algal blooms is 0.01 to 0.1 mg P/L and 0.1 to 1.0 mg N/L (10:1 of N:P). The higher concentrations support less diversity (NOAA/EPA, 1988).

Eutrophication can be caused by either natural or anthropogenic processes. Anthropogenic, or cultural, eutrophication can proceed at an accelerated rate compared to the natural phenomenon and is a major form of water pollution (NOAA/EPA 1988). Urbanization causes an increase in cultural eutrophication by increasing the sources and delivery of nutrients to a receiving water. Evidence of eutrophication at Malibu Lagoon includes the observance of persistent algal blooms. These blooms are more likely to occur when the sand barrier restricts tidal flushing; however, a study by Ambrose et al. (1995) noted dense, floating algal mats in the Lagoon during mid-to-late summer 1994 even with the Lagoon mouth open.

Urbanization throughout the Malibu Creek watershed has caused an increase in flow of water in Malibu Creek from runoff and wastewater discharges(USDA 1995). The additional freshwater changes the character of the lagoon, and brings with it elevated concentrations of nutrients (Ambrose et al. 1992). Historically, there was little creek flow in the summer months, but water imported to support the urbanization of the watershed has altered the natural hydrology and changed the lagoon habitat (USDA 1995).

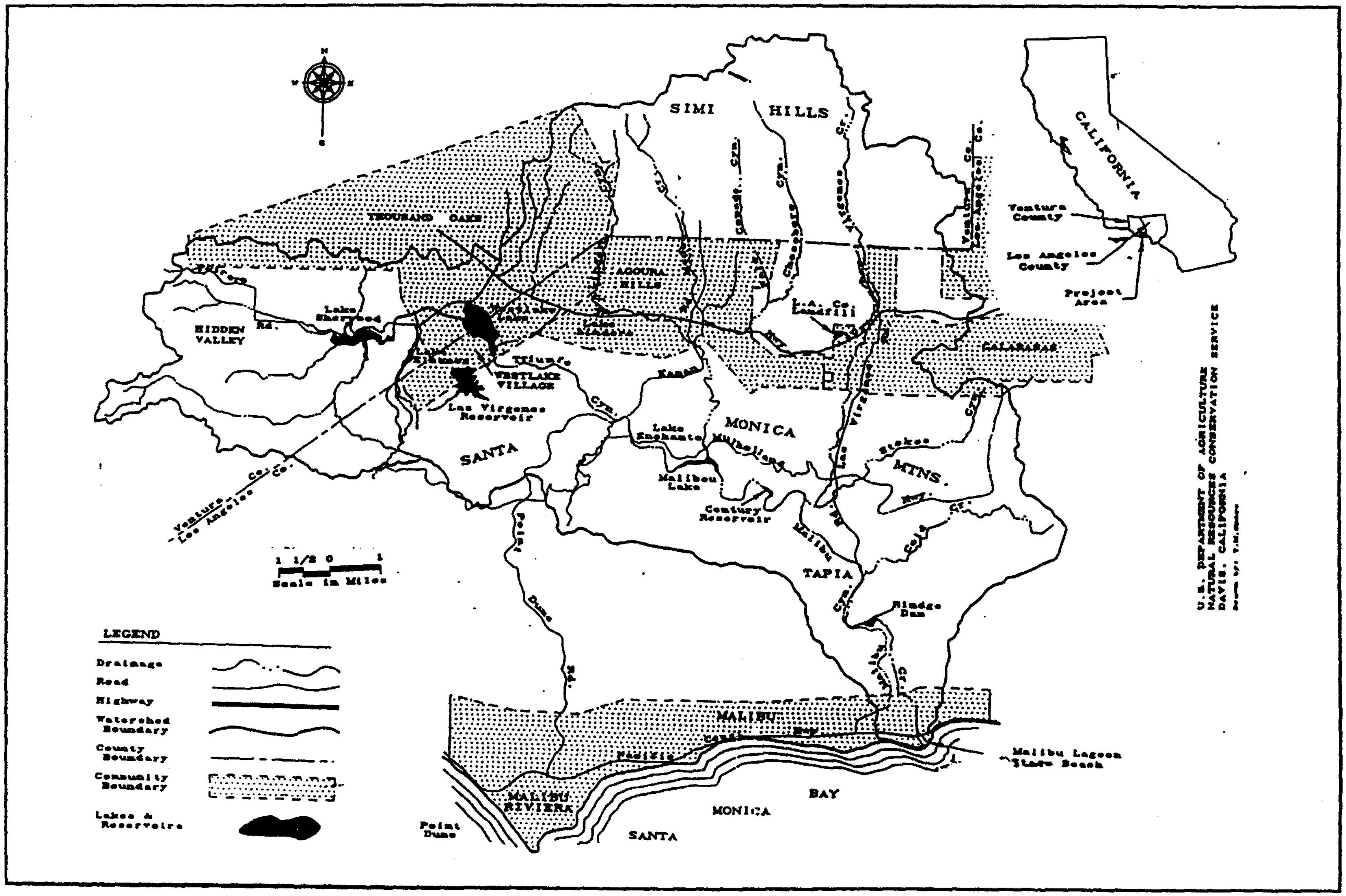


Figure 5-1. Map showing the Malibu Creek Watershed and Malibu Lagoon.

The major sources of nutrients that enter the Lagoon delivered in surface and groundwater are identified in this report. Potential sources of both nitrogen and phosphorus in the Malibu Creek watershed can include: (1) fertilizer application, (2) onsite wastewater systems (i.e., septic effluent or seepage), (3) confined animal facilities, and (4) atmospheric fallout from auto emissions deposited on roads or other surfaces. Nutrients from these sources can enter surface or groundwater through runoff or by percolating through the soil. Nutrient-laden waters then flow to Malibu Lagoon, affecting the water quality (USDA 1995). Sediment with sorbed phosphorus that is transported during storms from throughout the watershed is another source of phosphorus. The phosphorus in this sediment can be naturally occurring, from land treatment by a fire retardant (i.e., *Phoscheck*), or from fertilizer.

In this study, atmospheric deposition is not considered as a significant source of nutrients because direct deposition onto Malibu Lagoon is very small compared to the rest of the watershed. Indirect deposition from the watershed reaches the Lagoon through runoff, thus the contribution from atmospheric sources is included (Asman and Larsen 1996).

The contribution of nutrients from bird usage was determined to be insignificant for several reasons. Bird usage was noted in the Ambrose et al (1995) report and is relatively low in summer, when it may be more significant for eutrophication, especially compared to high density areas such as rookeries. Additionally, terrestrially deposited guano loses much of its nitrogen through ammonia evaporation. Birds may eat within the lagoon and therefore can be recycling nutrients already in the system. Other birds may eat within the lagoon and travel elsewhere to excrete. A literature search revealed no other articles that with similar sites characteristics noted birds as a significant source of nutrients in estuary/lagoon models. Finally, another literature search by Valiela et al (1997), noted that in semiurbanized watersheds, the amount contributed even with heavy bird use is a maximum 0.2% of all inputs.

Field data (Appendix A), monitoring reports and other literature were used in this report to estimate the load of nutrients delivered to Malibu Lagoon via surface and ground water. The specific areas of concern identified in this study are: (1) Malibu Creek flows, which include Tapia discharge, urban and stormwater runoff, and septic seepage; (2) Lagoon vicinity storm drain flows; (3) Lagoon vicinity groundwater flows, which include septic effluent and golf course fertilizer inputs; and (4) wet weather surface runoff to Malibu Lagoon. The accompanying mass balance report evaluates the eutrophication process in the wet and dry seasons and under conditions of an open and a closed sand barrier (Appendix B). A brief description of the mass balance approach is also included in the main report.

5.2 Study Site Description

The study area, Malibu Lagoon, is a small, 13-acre (0.0526 km^2) estuary located approximately 35 miles (56 km) west of Los Angeles, California. It is the receiving water of the Malibu Creek Watershed, a 109 square mile (282 km^2) area of the Santa Monica Mountains and the adjacent Simi Hills. The main channel is Malibu Creek, which receives waters from several lakes and tributaries, and drains into Malibu Lagoon, then empties into Santa Monica Bay (see Figure 1). It is a remnant of what was once a much larger seasonal freshwater marsh and is considered a valuable coastal resource. The lagoon provides habitat for fish and birds, as well as several rare and endangered species including tidewater goby, steelhead trout, snowy plover, California least tern, and brown pelican (Ambrose and Meffert 1999). The adjacent Surfrider Beach is a heavily used recreational area for surfing and sunbathing (Ambrose et al. 1995).

Malibu Lagoon has a Mediterranean-type climate characterized by mild, wet, winters, and hot, dry summers. The lagoon is open to the ocean during the wet season. In years with high rainfall, it may remain open all year, but in most years, it is closed off from the ocean by a naturally-occurring sand barrier. Inputs from the watershed can be categorized into two distinct seasons: a wet season from November to April, when almost all of the annual 18 inches (46 cm) of precipitation and stormwater discharges occur; and a dry season from May to October, when 'urban runoff' can be a major component of creek flow. Urban runoff refers to outdoor usage that occurs in the dry season such as watering and outdoor washing.

The additional water entering the Lagoon in the dry season can cause it to fill, which has been managed by artificially breaching the sand barrier because of human health concerns. Breaching also provides additionally benefits such as improvement of lagoon water quality and increased bird habitat (Capelli 1997). This management practice is controversial because of the impacts to ocean water quality, since the water leaving the lagoon contains human pathogens that can affect recreational users such as swimmers and surfers (Warshall 1992). It can also have detrimental effects on the endangered tidewater goby (Capelli 1997; Ambrose and Manion unpublished data).

Different land uses throughout the watershed can contribute water and nutrients to the creek that can then flow to the lagoon. Land uses can be classified as residential, commercial, agricultural or others, which have typical values that can be used to estimate the load from each type. For example, one component of storm runoff is from confined animal facilities (i.e., corrals) found throughout the watershed, which can contain a high concentration of nutrients as shown from field sampling for this study (Appendix A). It was not possible to separate out each of these components but it should be noted when evaluating sources from the watershed. A quantitative determination of the load from each of these land use types throughout the watershed was beyond the scope of work but may be helpful in future research efforts.

5.2.1 Sources of Nutrients

Potential sources of nutrients in the Malibu Creek watershed include: (1) fertilizer, (2) onsite wastewater systems (i.e., septic effluent or seepage), (3) Tapia tertiary-treated wastewater, (4) confined animal facilities (i.e., corrals) (5) road surfaces from automobile deposits, and (6) soils. Nutrients from these sources can enter surface or groundwater and then flow into Malibu Lagoon (USDA 1995). The amount of nutrients carried is determined by the landuse and management practices of the area from which it originates.

Wastewater treatment is a major issue in the Malibu Creek Watershed. The Tapia Wastewater Treatment Facility discharges into the creek. This tertiary-treated water contains nutrients. There are also approximately 2,300 on-site wastewater systems (i.e., septic systems) of varying capacities within the watershed. Concentrations of residential septic systems occur throughout the watershed and near the lagoon, including within Cold Creek Canyon, Serra Retreat, and Malibu Colony (USDA 1995). A concentration of large commercial septic systems also occur near the lagoon.

Septic seepage can enter the creek through subsurface transmission. Effluent can enter groundwater and effluent mixed with groundwater can reach surface waters through subsurface flow (Valiela et al, 1997). These septic systems can be influenced by large fluctuations of groundwater in the Malibu area (USDA 1995).

In the City of Malibu, groundwater fluctuates dramatically with drought, storms, effluent, and spray (i.e., landscaping) irrigation, and is considered to flow in the general direction of the topography. Soils in the area range from pure sands to pure clays. Malibu Colony septic systems are placed on an old delta with a mixture of silts, sands and clays or on imported or rearranged soils. There may also be highly transmissive layers of cobbles or gravel instead of bedrock. These soils, along with high groundwater, can contribute to high infiltration of septic seepage and/or golf course irrigation water into the Malibu Lagoon (USDA 1995).

Phosphorus in soils reach the lagoon when sediment is carried in surface waters. Most soils naturally contain phosphorus; it can also be artificially present in soils through fertilizer application, septic system failure, or as a component of the fire retardant, *Phoscheck*. Much of the Malibu Canyon is steep, and sediment can be loosened and carried with storm water runoff.

Land management practices that leave unvegetated soil can contribute significant soil loads to the lagoon. Construction activities, road maintenance, and confined animal facilities can leave unvegetated, unstable soil which can be moved during rain events. The steep canyon conveys loose sediment during storms that can be transported to the Lagoon. The phosphorus can then desorb from deposits in the lagoon.

5.2.2 Land Use in the Vicinity of Malibu Lagoon

Commercial and residential land uses in the Lagoon vicinity influence the surface and groundwater flows into the Lagoon. Several areas around the lagoon noted here are considered "Lagoon Area Sources" for the purposes of this report (Figure 2). Malibu Lagoon is part of Malibu Lagoon State Beach, which is bordered by commercial, municipal, and private land uses on three sides and by the ocean to the south. The lagoon mouth is open and water empties into the ocean during storms, but is often closed by a sandbarrier in the dry season.

The Civic Center is located north of the Lagoon. Malibu Colony, an exclusive residential community, and Malibu Colony Golf Course, are west of the lagoon. The notable commercial areas include: Malibu Colony Plaza, Malibu Country Mart, and the Cross Creek Plaza (see Figure 2). Malibu Colony homes, the Civic Center, and the commercial areas have septic systems. The Malibu Colony Golf Course lies adjacent to the Colony and the lagoon, and fertilizer on this area can enter the Lagoon through subsurface flow.

Three major storm drains direct runoff water into the Lagoon. The magnitude of the nutrient loading from the storm drains is difficult to determine and depends on rainfall during the wet season and Lagoon vicinity management practices during the dry season. The storm drains during the dry season are made up of runoff from washing the paved areas and from landscaping irrigation. This report uses field observations to determine the amount of water delivered from the commercial areas. The major storm drains that enter Malibu Lagoon are described below:

> *Malibu Colony Drain.* This drain is sometimes referred to as the 'Mystery Drain' because it is not 'claimed' by any city or county agency, although a manhole associated with this drain is labeled LA County Flood Control District. The drain originates at the corner of Webb Way and Malibu Road. It passes beneath the Bank of America parking lot, then continues east along the northern edge of Malibu Colony, and under the southern edge of the golf course into the lagoon (Warshall 1992). During the dry season, it carries runoff from parking lot washing or from irrigation and other areas in or near the Malibu Colony Plaza and from Malibu Road.

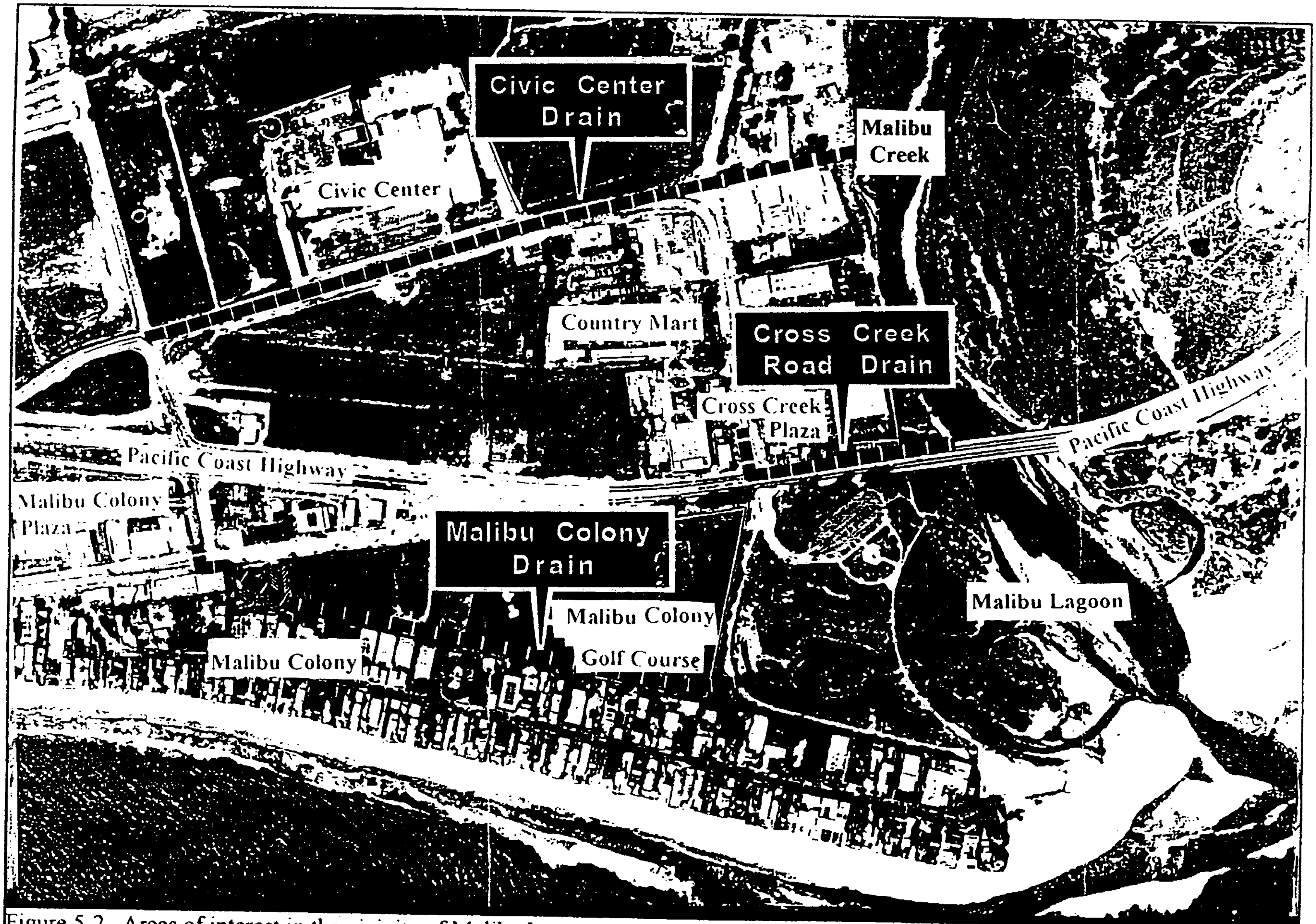


Figure 5-2. Areas of interest in the vicinity of Malibu Lagoon. Adapted from Warshall (1992).

Civic Center Drain. This is the largest drain emptying into the Lagoon. It receives storm water runoff from much of the floodplain and the surrounding steep hillslopes (Warshall 1992). Runoff from irrigation during the dry season generally does not reach the lagoon. The drain was observed to be dry during dry season sampling.

Cross Creek Drain. This drain receives water from the area between the Civic Center Drain, Pacific Coast Highway and the Lagoon (Warshall 1992). This includes the parking lot area of Cross Creek Plaza and Malibu Country Mart. Land management practices in these areas include washing down the parking lot and irrigating small areas of landscaping.

5.3 Methods

Data from field sampling and monitoring data from other studies were used to estimate nutrient loading into Malibu Lagoon. Literature values were used to estimate the magnitude of sources where site-specific data were not available. Estimations from tabular data sets from other site studies include: septic effluent nutrient concentration, groundwater characteristics, and fertilizer application rates.

Daily loads for each input were calculated by multiplying concentration values by flow estimates. The daily loads were multiplied by the number of days in each season to get the seasonal load for each input. The dry season is considered to be from May 1 to October 31 (184 days) and the wet season is from November 1 to April 30 (181 days).

The surface waters carrying nutrients from the watershed into Malibu Lagoon include: (S1) Malibu Creek; (S2) Malibu Colony Storm Drain; (S3) Cross Creek Storm Drain, and (S4) surface runoff. The Civic Center Storm Drain also empties into the Lagoon, but was observed in the field to have no flow in the dry season, and is not included. The drain inputs during the wet season are combined with (S4) surface runoff in the wet season. Groundwater flows contain nutrients from: (G1) commercial and private septic systems, and (G2) the Malibu Colony Golf Course.

Field sampling was performed during both the dry and wet seasons to quantify unknown site-specific inputs as described below. Results from these activities were coupled with available monitoring data or data from previous studies. Literature values were used to estimate the magnitude of remaining sources where site-specific data were not available.

5.3.1 Sampling Plan

Sampling sites are shown on Figure 3. Samples were collected and stored in clean, glass bottles. These were analyzed for ammonia, nitrate, total Kjeldahl nitrogen, and phosphate. Data from field sampling are provided in the Results section and Appendix A.

5.3.1.1 Dry Season Sampling

Dry season storm drain inputs were collected from the washwater leaving commercial area parking lots than in the drains because it was not possible to get water from the drains not mixed with lagoon water. The mean concentration of each of these samples was used to estimate the amount of nutrients from the storm drains in the dry season. The Civic Center Storm Drain was dry during the dry season, therefore there was no input from this drain in the dry season. Other surface water sampling locations in the dry season included the ocean, in the lagoon, and in Malibu Creek at the Arizona Crossing. Five groundwater sampling wells in the Lagoon vicinity were also sampled on several occasions (Figure 3).

5.3.1.2 Wet Season Sampling

The sampling locations were from the various surface sources of water into the Lagoon (Figure 3). The samples were taken at five different times at six locations during two major storms. The sampling sites were located at: Cross Creek Storm Drain, Civic Center Storm Drain, Malibu Colony Storm Drain, Arizona Crossing, runoff from a corral in Serra Retreat, and street runoff in the lagoon vicinity.

5.3.2 Surface Water Inputs

Surface flows enter Malibu Lagoon from the following: (S1) Malibu Creek; (S2) Malibu Colony Storm Drain, (S3) Cross Creek Storm Drain, and (S4) surface runoff. The flow in Malibu Creek (S1) can be separated into four components: (S1-1) Tapia discharge, (S1-2) septic seepage, and (S1-3) urban or (S1-4) storm runoff. The drain inputs are separated from lagoon-vicinity surface runoff in the dry season but are combined in the wet season.

Storm runoff from the watershed carries suspended sediment that has sorbed phosphorus, and although it is part of the Malibu Creek component, it is measured separately and behaves differently, therefore, it is treated separately as (S5) suspended sediment. The contribution from the ocean is noted but is not considered a part of the watershed loading inputs.

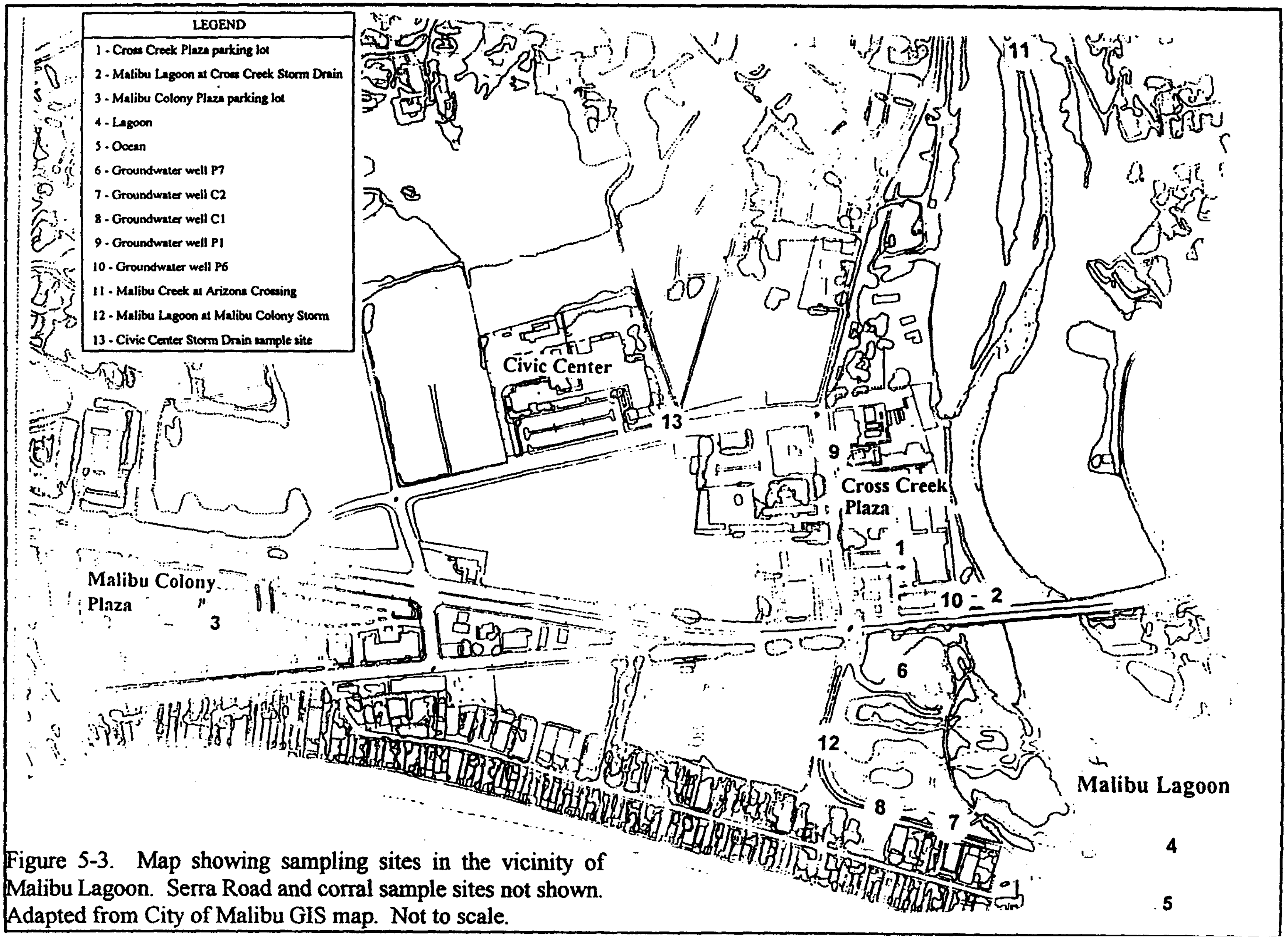


Figure 5-3. Map showing sampling sites in the vicinity of Malibu Lagoon. Serra Road and corral sample sites not shown. Adapted from City of Malibu GIS map. Not to scale.

5.3.2.1 Malibu Creek -S1

Flow and nutrient concentration data for Malibu Creek and Tapia were obtained from averaging weekly LVMWD (1997) monitoring from stream gage 11105500, located just below Cold Creek at Piuma Road. The drainage area above the gage is 105 square miles (272 km^2) (Warshall 1992). Septic seepage (S1-1) was estimated from the amount reported in USDA (1995). Nitrogen is included in the septic seepage load but phosphorus is considered insignificant because it is retained in the soil in this process (Brown 1993). Urban (S1-3) and storm (S1-4) runoff flows into the lagoon were estimated by subtracting the flows from Tapia and septic seepage (reported in USDA 1995) from the total creek flow in LVMWD (1997).

Septic seepage and runoff come from multiple sources at various points along Malibu Creek, and no reported concentration values were available. Tapia reported both concentration and flow values, allowing the load to be separated from the total (LVMWD 1997).

5.3.2.2 Storm Drains (Dry Season)-S2 and S3

Discharge from the storm drains was noted only in the dry season. This discharge included daily runoff of wastewater from washing of the parking lots and sidewalks in the commercial areas. The dry season inputs from the storm drains were derived from field data. Calculations used the average measured concentration of nutrients in washwater and the acreage of area washed. The areas washed were observed in the field and the acreage of the areas were calculated using a GIS map. The amount of washwater used was estimated from measurements in the field.

5.3.2.3 Storm Runoff (Wet Season)-S4

The nutrient load from storm runoff from the area past the gage is considered as a lagoon-area input with an area of four square miles (10.4 km^2). The mean concentrations of nutrients in storm runoff were estimated from field data.

5.3.2.4 Suspended Sediment -S5

Sediment is part of the surface water contribution because large amounts of sediment can be carried in Malibu Creek flows during wet season storms and deposited in the lagoon. These sediments have a large storage capacity for nutrients and may contain significant amounts of sorbed phosphorus, which is there naturally or by anthropogenic means (Jorgensen 1996). Data from sampling stations in the main channel of Malibu Lagoon from

Ambrose, et al. (1995) were used to calculate the amount of phosphorus desorbed from the sediment during each season. Concentration values were then multiplied by the surface area of the lagoon to calculate total loads.

This study assumed the lagoon system was at steady-state. In this case, the amount of sediment deposited in the lagoon in the wet season is equal to the amount exported to the ocean during that same time, with no net change in the amount of sediment in the lagoon during the wet season. Sediment deposited during a particular storm is flushed out with subsequent storms through the open lagoon. The critical storm is the last major storm of the wet season because sediment is retained within the lagoon throughout the dry season after the sand barrier closes. The sorbed phosphorus can then be a significant source of phosphorus during the dry season as a result of desorption processes (Jorgensen 1996).

It was assumed that the top 2.0 centimeters of the sediment is available for release into the water column because concentration values below two in Ambrose, et al. (1995) were relatively constant compared to the values in the top two centimeters, which demonstrated that the top two centimeters were disturbed with each storm. Additionally, it was assumed that approximately half of the volume was occupied by porewater.

During the wet season, the sediment deposited during a particular storm is retained in the lagoon until it is flushed out during subsequent storms when the lagoon mouth is open. Therefore, a weighted average of the mean daily concentration of phosphorus in the top layer of porewater can be used to determine the wet season load of phosphorus into the water column. A weighted average of porewater data in the top 2.0 centimeters of sediment from November 11 and 24, 1998 were selected as representative concentration values for the wet season.

Suspended sediments retained from the last major storm of the wet season are the source of sediment released phosphorus during the dry season. Field observations determined that the sediment load in the streamflow during the dry season is insignificant relative to the wet season, and does not contribute significantly to phosphorus loading in the lagoon. The difference in the phosphorus concentration in the top layer of sediment at the end of the wet season compared to the amount at the end of the dry season determined the dry season load. The mean of the concentration values for representative stations at the end of the wet season were subtracted from the wet season estimate to determine the amount released during the dry season.

5.3.3 Groundwater Inputs

Groundwater and soil characteristics are important in Malibu because of onsite wastewater disposal systems and the golf course in proximity to the creek and lagoon. Nutrients from (G1-1) commercial and (G1-2) private septic system effluents and from (G2) Malibu Colony Golf Course fertilizer can leach into the groundwater in the lagoon vicinity and then flow into the lagoon.

In order to accurately estimate the magnitude of sources, it is necessary to know the amount, direction and quality of the water flows, and the distance to the water table. However, for the Malibu area, no comprehensive studies or map of the hydrogeology of the Malibu area are available that provide detailed site specific information (Warshall 1992). Therefore, flow of groundwater and influence of groundwater inputs can only be estimated from reported values.

Groundwater flow into the Lagoon can be estimated by the Darcy equation:

$$Q = K \times A \times \text{slope},$$

where:

Q: water flow
K: hydraulic conductivity
A: cross-sectional area that water passes through
slope: slope of water gradient

The values for slope and hydraulic conductivity (K) reported in Warshall (1995) are slope= 0.0016 and K= 1.0 - 10.0 meters d^{-1}. The calculated flow from these values is 156 m^3 d^{-1} . However, because the slope can be artificially increased more than an order of magnitude due to saturated soils from septic or other influences occurring near the lagoon, the daily flows from the septic systems and golf course can be used to approximate the total daily flow of groundwater into the lagoon.

5.3.3.1 Septic Seepage-(G1)

The combination of a high, fluctuating water table and coarse soils and beach sands in the Malibu area may limit filtration capabilities of on-site wastewater systems; however, studies have not been done to document these impacts. Currently available information does not provide useful information to allow evaluation of the effectiveness and conditions of each system (USDA 1992). Therefore, the complexity of groundwater characteristics in the Lagoon vicinity allows only generalizations regarding the fate of effluent following ground disposal or movement from existing sources.

The septic system contributions in the Lagoon vicinity were estimated as follows:

Commercial = Concentration x Flow x Leaching fraction x (1-N tank removal)
where:
Concentration= 45 mg l^{-1} N
Leaching fraction= 0.5
N tank removal= 0.1

The nitrogen in septic effluent was estimated from average literature values as 45 mg l^{-1} N (Valiela et al. 1997; USDA 1992; Warshall 1995; Horsley et al. 1996). Phosphorus is not considered mobile in the soil, thus is not included in groundwater inputs (Brown 1993).

The leaching rate was estimated from literature values. On a properly sited septic system, approximately 50% of the effluent is estimated to leach into groundwater (Valiela 1997, Horsley et al. 1996). In the Lagoon vicinity, many of the systems are not properly sited, and it is reported that up to 90% may leach into the groundwater (Warshall 1992); however, in this study, the 50% leach rate was used as a conservative estimate.

Flow estimations for septic effluent from previous studies were used because there are no direct measurements of wastewater flows for residential or commercial buildings in Malibu. Previous studies have used indirect methods to determine reasonable loading rates. The commercial flows used in the equation below were reported in ESA (1997). Private septic flows from Malibu Colony were estimated from the Warshall (1992) report. Daily flows may vary.

The transport fraction is the amount of effluent in the groundwater that reaches the lagoon, based on their location with respect to Malibu Lagoon. All of the commercial septic fields are located onsite, except for Malibu Colony Plaza, which pumps its effluent to a geologically separate basin, and therefore does not affect the lagoon.

For commercial systems, the tanks are also regularly pumped, removing some of the nitrogen, therefore an additional calculation was made to account for this. Pumping was estimated to remove 10% of the nitrogen from the system (Brown 1993).

Private flows were estimated from the number of people per home from Warshall (1992) literature values for residential users (Valiela et al. 1995), and the transport fraction based on the location with respect to the lagoon. The number of homes from Malibu Colony influencing the Lagoon was determined from the homes on the inland side of the Colony. A reasonable estimate of approximately 50% of the effluent from these homes was used based on their locations and distance from the Lagoon.

Private = Persons per home x Flow per person x Homes x Transport fraction x Concentration
where:

Persons per home =	3.7
Flow per person =	0.19 $m^3 d^{-1}$
Homes =	30
Transport fraction =	0.25
Concentration=	45 mg l^{-1} N

5.3.3.2 Malibu Colony Golf Course-G2

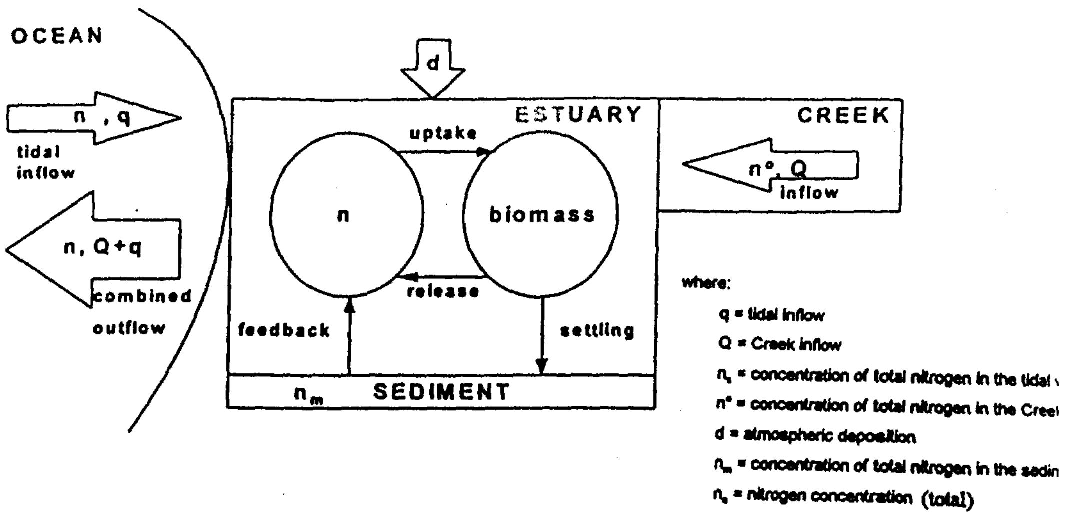
The 6.5 acre golf course is located adjacent to the lagoon, where applied fertilizer can readily leach. Site-specific data was not available, and average literature values were estimated as 52.15 kg N $acre^{-1}$ $year^{-1}$ with a leaching fraction of 0.5 (Valiela et al. 1997 and Warshall 1992).

5.3.4 Malibu Lagoon Eutrophication Model

The application of mathematical modeling techniques to water quality problems has proven to be a powerful tool in water resources management as it enables alternative management strategies to be evaluated. A mathematical model describes the mechanisms underlying the dynamics of the modeled processes (Chapra and Reckhow 1983). A model is not reality, but provides a good first estimate to identify and quantify the natural or man-made phenomena that are relevant to the water quality problem under consideration (DiToro 1983).

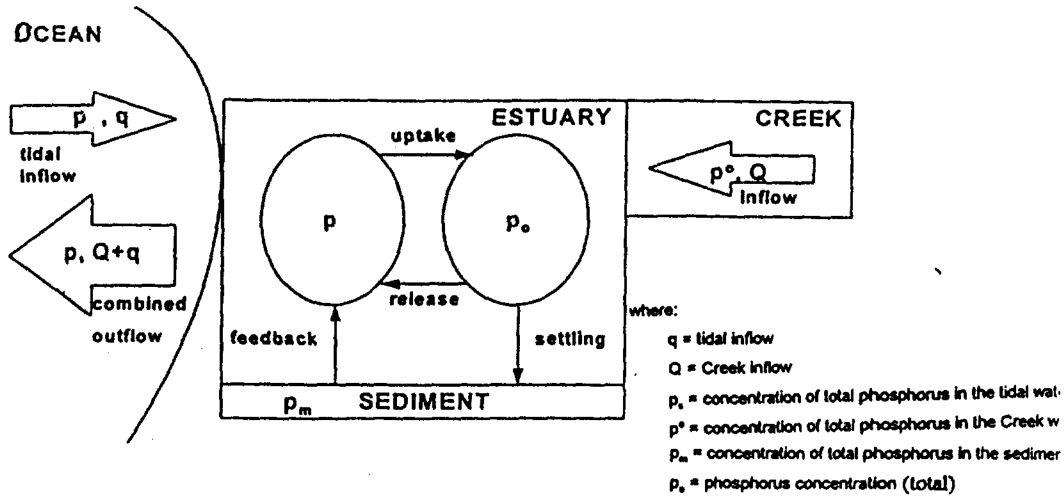
A mass balance time-variable model, the Malibu Lagoon Eutrophication Model (MEM), was developed for this project to predict nutrient loading into Malibu Lagoon. Figure 4 shows the schematics of the mass balance for Malibu Lagoon. Appendix B is a complete description of the MEM. This report gives a gross loading of the nutrients entering Malibu Lagoon from the watershed; it does not account for in-lagoon processes such as sediment feedback, biological fluxes, and tidal exchange.

The MEM was developed to take these considerations into account. The model incorporated the loading estimates and adjusted for varying hydrodynamic conditions and biological mechanisms to obtain the concentration of nutrients in the lagoon under different scenarios. The equation used to estimate the lagoon input flows and concentrations roughly follows those in this section.



where:
q = tidal inflow
Q = Creek inflow
n_t = concentration of total nitrogen in the tidal
$n°$ = concentration of total nitrogen in the Cree
d = atmospheric deposition
n_m = concentration of total nitrogen in the sedin
n_e = nitrogen concentration (total)

Nitrogen Mass Balance Model for Malibu Lagoon



where:
q = tidal inflow
Q = Creek inflow
p_t = concentration of total phosphorus in the tidal wat
$p°$ = concentration of total phosphorus in the Creek w
p_m = concentration of total phosphorus in the sedimer
p_e = phosphorus concentration (total)

Phosphorus Mass Balance Model for Malibu Lagoon

Figure 5-4. Nutrient schematics for the Malibu Lagoon mass balance model.

The mass balance equation is as follows:

$$c^o = \frac{\sum(c_i + q_i)}{Q}, \text{ or } \frac{c_m q_m + c_p q_p + c_d q_d + c_{st} q_{st} + c_r q_r}{Q}$$

where:

c^o = average nutrient concentration
Q = total flow
c_i = nutrient concentration
q_i = flow

where i:

m = Malibu Creek (S1)
(Tapia discharge (S1-1), septic seepage (S1-2), and runoff (S1-3 and S1-4))
p = North of PCH groundwater commercial septic inputs
(Country Mar t(G1-1), Cross Creek Plaza (G1-2), Malibu Colony Plaza (G1-3), and the Civic Center (G1-4))
d = South of PCH groundwater inputs
(Malibu Colony private home septic seepage(G1-5) and Malibu Colony Golf Course(G2))
st = runoff from Lagoon vicinity (S2 and S3)
(dry season washoff from Cross Creek and Malibu Colony Storm Drains only)
r = runoff from Lagoon vicinity(S4)
(wet season storm runoff including storm drain discharge and overland flow)

5.4 Results

The nutrients entering Malibu Lagoon from surface and groundwater sources occur in both the wet and dry seasons. The loads were calculated by multiplying concentration by the flow values. The dry season is considered to be from May 1 to October 31 (184 days) and the wet season is from November 1 to April 30 (181 days). Interannual variation in precipitation, Tapia discharge, or other inputs affect the contribution of nutrients from each source.

The estimates below provided data used to calculate the relative contribution and percentage of each component of the sources of nutrients into the Lagoon on an annual basis. These inputs can be separated into daily inputs on a year-round basis and are assumed to flow at a constant rate unless otherwise noted. The loading data in this section represent the gross load of nutrients into the water column of the Lagoon from the watershed. They do not represent the net concentration of nutrients in the lagoon, which is a result of tidal, sediment, and biological interactions and feedback.

5.4.1 Surface Water Inputs

Surface flows entering Malibu Lagoon are from the following: (S1) Malibu Creek, (S2) Malibu Colony Storm Drain, (S3) Cross Creek Plaza Storm Drain, (S4) surface runoff and (S5) suspended sediment. The Civic Center Storm Drain is dry during the dry season so is not included. The contribution of the ocean is also noted but is not considered a part of the watershed loading inputs.

5.4.1.1 Malibu Creek -S1

Monitoring data from LVMWD (1997) were used in order to evaluate the load of nutrients into Malibu Lagoon for that year. This provides one scenario to enable evaluation of the identified inputs. Interannual variation in precipitation, Tapia discharge, or other inputs affect the contribution of nutrients from each source. Flow and nutrient concentration data for Malibu Creek and Tapia were obtained from LVMWD (1997). Malibu Creek data were collected from stream gage 11105500, located just below Cold Creek at Piuma Road. The drainage area at the gage is 272 km^2.

The flow for Malibu Creek during the 1997 dry season was calculated as 3.522×10^6 cubic meters (m^3) with 1.06 mg l^{-1} N and 0.46 mg l^{-1} P. The total nutrient load during the 1997 dry season was 3,733 kilograms (kg) N and 1,620 kg P (LVMWD 1997). The total flow during the wet season was calculated as 2.808×10^7 m^3, with 3.90 mg l^{-1} N and 0.60 mg l^{-1} P. The nutrient load for the wet season was 109,510 kg N and 16,848 kg P.

Tapia is the only point discharge reported in Malibu Creek, so it is the only contribution separated from the total. Septic seepage and runoff are from multiple sources at various points along Malibu Creek, and in-stream removal processes can lower the amount that reaches the lagoon. Therefore, it was not possible to separate the loading from these sources in this study.

S1-1. Tapia. The average concentration of nutrients Tapia effluent in 1997 were 12.05 mg l^{-1} N and 1.88 mg l^{-1} P. The dry season flow was calculated as 2.137×10^5 m^3 with a nutrient load of 2,575 kg N and 402 kg P. The wet season flow was calculated as 2.824×10^6 m^3, with a nutrient load of 34,024 kg N and 5,309 kg P. The total load for Tapia may be overestimated as instream processes may remove some of the nutrients on the way to the lagoon. A more accurate quantitative estimate would require further field work and was beyond the scope of this project.

S1-2-Septic Seepage; S1-3-Urban runoff; and S1-4-Storm runoff. The USDA (1995) report estimated septic seepage flow to the Creek as 500 acre-feet/yr (201 m^3). Nitrogen comes from this source but phosphorus is considered insignificant because it is retained in the soil in this process (Brown 1993). Urban (S1-3) and storm runoff (S1-4) flows in the creek were estimated by subtracting Tapia and septic seepage from the total creek flow. The dry season urban runoff was calculated as 3.308×10^6 m^3 and the wet season storm runoff flow was calculated as 2.523×10^7 m^3. Concentration estimates from these sources were not available because there are numerous input points along the creek, therefore loading estimates combine septic seepage and runoff estimates. The contribution from the combination of septic seepage and runoff during the dry season (S1-2 and S1-3) was 1,158 kg N and 1,218 kg P. The contribution from septic seepage and storm runoff in Malibu Creek in the wet season (S1-2 and S1-4) was 75,481 kg N and 11,539 kg P.

5.4.1.2 Storm Drains (Dry Season)-S2 and S3

Discharge into the storm drains is only noted in the dry season. This discharge includes daily runoff of wastewater from hosing down of the parking lots and sidewalks in the commercial areas. Malibu Colony Storm Drain (S2) receives discharge from the Malibu Colony Plaza and the adjacent commercial area to the south along Pacific Coast Highway. Cross Creek Storm Drain (S3) receives discharge from Cross Creek Plaza and the Malibu Country Mart. No other areas were observed to be washed. The Civic Center Storm Drain was observed to be dry during sampling, therefore it is not considered as a source in the dry season. The dry season inputs from the storm drains were derived from field data. Calculations used the measured concentration of nutrients in washwater and the acreage of area washed. The amount of water used was 0.4725 m^3 (125 gallons)/acre. The mean concentration of nutrients was measured to be 16.06 mg l^{-1} N and 0.36 mg l^{-1} P (Appendix A). The areas washed were observed in the field and the acreage of the areas were calculated using a GIS map. The acreage of each area is as follows: Country Mart (1.75 acres), Cross Creek Plaza (3.94 acres), Malibu Colony Plaza (8.97 acres), and the Malibu Colony Plaza adjacent commercial area (2.19 acres), a total of 16.85 acres of washed areas that discharge into the two storm drains.

The estimate of storm drain inputs during the dry season from washwater may not be representative of the inputs from all sources. It may be high because the estimate was based on the amount of water that entered the drain. Some of the water may be lost during transport through the drain. Alternatively, the estimate may be low because there may be other unidentified inputs such as landscape water runoff. There may also be other unidentified dry weather inputs contributing nutrients to these drains, however, private land ownership or other accessibility issues made other contributions difficult to determine.

Table 1. Storm drain inputs into Malibu Lagoon during the dry season.

STORM DRAIN	ACRES	NITROGEN	PHOSPHORUS
S2-Malibu Colony Storm Drain	5.69	8 kg	0.2 kg
S3-Cross Creek Storm Drain	11.16	16 kg	0.4 kg
TOTAL	16.85	24 kg	~1 kg

5.4.1.3 Storm Runoff (Wet Season)-S4

The nutrient load from storm runoff from the area past the gage is considered as a lagoon-area input. The nutrient load was estimated from the area of the creek after the streamgage and the concentrations from field data (Appendix A). The concentrations used were: 2.20 mg l^{-1} N and 0.12 mg l^{-1} P; and the storm runoff was approximately 1.067×10^6 m^3. The resulting loads were 2,351 kg N and 128 kg P.

The nutrient load that enters Malibu Lagoon from the storm drains during the wet season is higher because runoff from the entire drainage basin flows in from all sides, not just from specific areas. The total from the lagoon vicinity during the wet season enters from storm drain discharge as well as from overland surface runoff directly entering the lagoon. However, the sand barrier is generally open during the wet season, so the contribution to eutrophication is lessened because these nutrients are exported out of the lagoon.

5.4.1.4 Suspended Sediment -S5

Sediment is part of the surface water contribution because large amounts of sediment are carried in Malibu Creek flows during wet season storms and deposited in the lagoon. Most soils naturally contain large amounts of phosphorus (Jorgensen 1996); it can also be artificially present in soils from fertilizer application, septic system failure, or as a component of the fire retardant, *Phoscheck*.

The amount of sediment deposited in the lagoon in the wet season is equal to the amount exported to the ocean during that same time, with no net change in the amount of sediment in the lagoon during the wet season. The concentration value in the dry season was a result of the difference from the end of the wet season to the beginning of the dry season from representative stations. The concentration values were obtained from sampling stations from Ambrose, et al. (1995) in the main channel of Malibu Lagoon at stations T1/T2 and T3/T4 (Figure 5). Approximately half of the volume was assumed to be occupied by porewater. Values were then multiplied by the surface area of the Lagoon and the number of days in each season to calculate total loads.

The weighted average of the mean daily concentration of phosphorus in the top 2.0 centimeters of porewater from representative stations in the wet season was 1.58 mg l^{-1} (see Figure 5). The contribution of phosphorus from the sediment into the water column during the dry season was 1.36 mg l^{-1} P. The total load of phosphorus in the wet season was 150 kg, and for the dry season it was 132 kg. Further studies are recommended to better quantify the phosphorus load from the sediments by desorption kinetics each season.

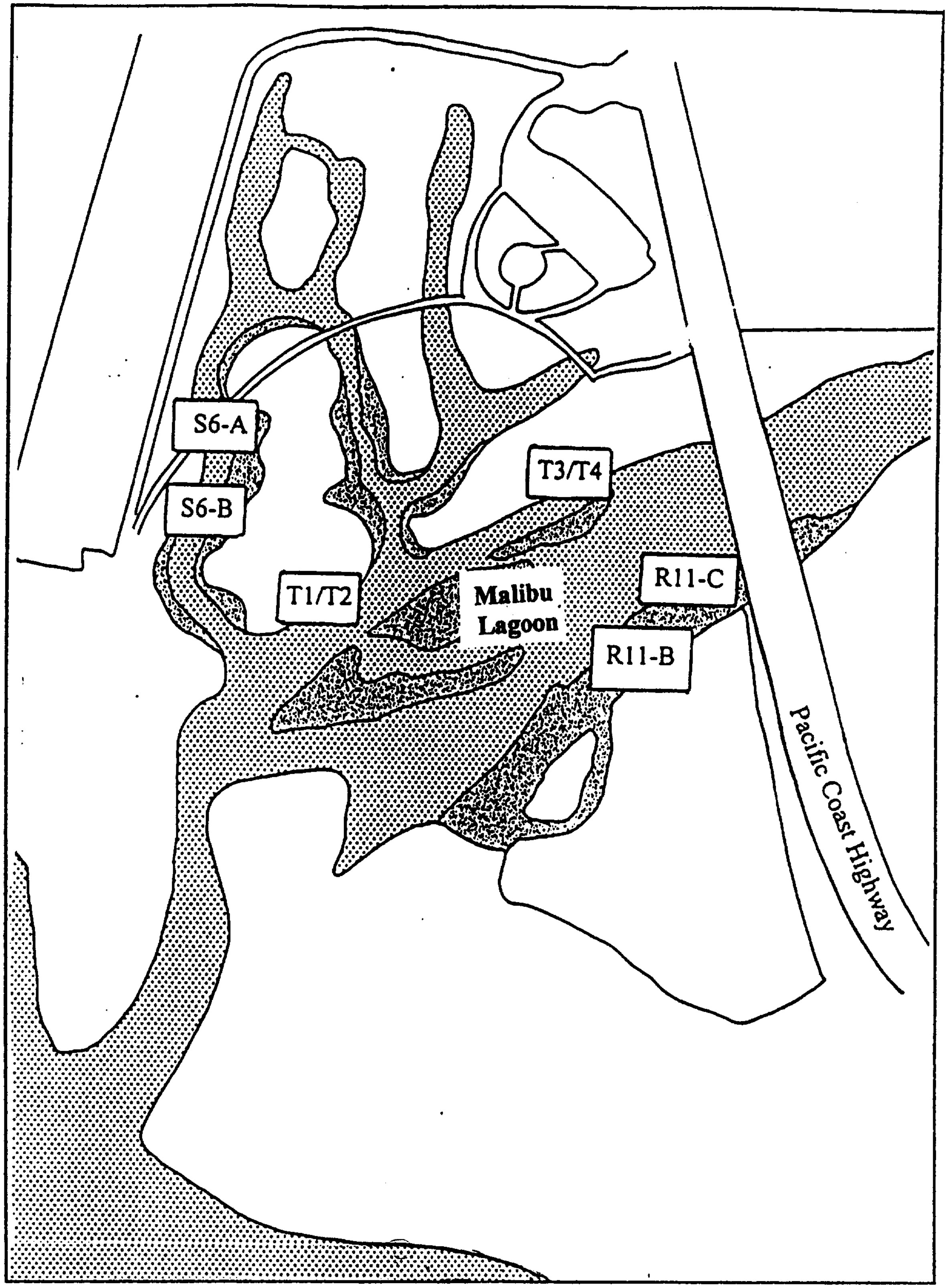


Figure 5-5. Sediment sampling stations from Ambrose et al. (1995).

5.4.1.5 Ocean

The ocean is noted here because ocean waters mix with Malibu Lagoon water, and is therefore part of the mass balance. It is not considered a significant source because of the low concentration of ocean-originating nutrients and Lagoon water is generally exported out to the ocean. The concentration of nutrients in ocean water was measured as 1.0 mg N l^{-1} and 'nondetect' (<0.05 mg l^{-1}) for phosphorus. The ocean is generally a sink for nutrients, the amount of which depends on tidal height and the condition of the sand barrier. The amount of water exchanged with the ocean is determined by sand barrier conditions and tidalinfluence. The height of the tide determines when and how much water is exchanged when the lagoon is open, or the amount that flows over the sand barrier when it is closed.

5.4.2 Groundwater Inputs

Groundwater can contain nutrients from (G1-1) commercial and (G1-2) private septic system effluents and (G2) Malibu Colony Golf Course fertilizer that can leach into the groundwater in the lagoon vicinity and then flow into the lagoon. Because the flow of groundwater can be affected by flows from the septic systems and the golf course, these were used to approximate the total daily flow of groundwater into the lagoon.

Moody (1996) states that evidence of human contamination of groundwater is noted by nitrate concentrations greater than 3.0 mg/L, which can be indicative of fertilizer use and wastewater disposal. Data gathered in the field from groundwater wells (see Figure 3) was not sufficient to make conclusions; however, Warshall (1992) reported a nitrate concentration of 25 mg nitrate/L, which can be indicative of human influence.

5.4.2.1 Septic Seepage -G1

The loads from the septic systems were calculated as shown in Section 5.3.3. The resulting annual load of nutrients from septic systems are shown in Table 2.

Table 2. Estimated annual load of nitrogen from septic systems into Malibu Lagoon.

SYSTEM	DRY (KG)	WET (KG)	ANNUAL (KG)
Country Mart (G1-1)	334	328	662
Cross Creek Plaza (G1-2)	583	574	1157
Civic Center (G1-3)	135	133	268
Malibu Colony homes (G1-4)	44	43	87

5.4.2.2 Malibu Colony Golf Course -G2

Fertilizer applied to turfgrass at the Malibu Colony Golf Course can leach into the groundwater and enter the lagoon. Site-specific data was not available, therefore the amount estimated may not be representative. The load of 52.15 kg (115 lbs) N/acre/year with a leaching fraction of 0.5 was obtained from literature values (Warshall 1992, Valiela et al. 1997). The nitrogen loading from the 6.5 acre golf course (G2) was estimated as 170 kg yr^{-1} N; with a mean daily load of about 0.46 kg d^{-1} N. Fertilizer is generally applied in the spring and, depending on irrigation practices, it can leach into the groundwater at varying rates.

5.4.3 Seasonal Inputs Summary

The above estimates provided data used to calculate the relative contribution and percentage of each component of the sources of nutrients into the Lagoon. Calculations are provided below. Tables 3 and 4 show the annual load of nutrients from the watershed and the areas surrounding Malibu Lagoon. Figure 6 shows graphic representations of the same information and the relative percentages. The loading data in this section represent the gross load of nutrients into the water column of the Lagoon from the watershed. They do not represent the net concentration of nutrients in the lagoon, which is a result of tidal, sediment, and biological interactions and feedback.

Calculations Summary for the Malibu Lagoon Nutrient Budget

Equations with mg l^{-1} and m^3 must be multiplied by a conversion factor of 10^{-3} to obtain kg loads.
DRY SEASON = 184 days

S1: Malibu Creek Dry Season Total Loads= 3,733 kg N; 1,620 kg P
= Flow x Concentration x Conversion
Flow= 3.522×10^6 m^3
Concentrations =1.06 mg l^{-1} N, .46 mg l^{-1} P

S1-1: Tapia Dry Season Load = 2,575 kg N; 402 kg P
= Flow x Concentration x Conversion
Flow = 2.137×10^5 m^3
Concentration = 12.05 mg l^{-1} N; 1.88 mg l^{-1} P.

S1-2 and S1-3: 1,158 kg N; 1,218 kg P
=Remainder Dry Season Load = Total - Tapia
Nitrogen =3,733 kg N - 2,575 kg N
Phosphorus = 1,620 kg P - 402 kg P

Septic Systems (S1-2) Dry Season Flow = 101 m^3
Urban Runoff (S1-3) Flow = 3.308×10^6 m^3
=Total-(Tapia+Septics) = 3.522×10^6 m^3-(2.137×10^5 m^3+ 101 m^3)

Septic Systems (S1-2) Dry Season Flow = 101 m^3
Urban Runoff (S1-3) Flow = 3.308 x 10^6 m^3
=Total-(Tapia+Septics) = 3.522 x 10^6 m^3-(2.137 x 10^5 m^3+ 101 m^3)

Lagoon Area Dry Season Total Loads= 1,206 kg N; 716 kg P
S2 and S3: Storm Drains
S2: Malibu Colony Drain (5.69 acres) = 8 kg N; 0.2 kg P
S3: Cross Creek Drain = (11.16 acres) = 16 kg N; 0.4 kg P
= Acres x 0.4725 m^3 Water/Acre x Concentration x Conversion x # days
Concentration = 16.06 l^{-1} N; 0.36 l^{-1} P
Acres = 5.69 for Malibu Colony Drain; 11.16 for Cross Creek Drain

S5: Suspended Sediment Load = 132 kg P
= 13 acres x 0.00405 km^2/acre x (2.0 cm/2) x Concentration x # days
Concentration = 1.36 mg l^{-1} P
Conversions for this equation: 1.0 km^2 = 1 x 10^{10} cm^2; 1.0 liter = 1000 cm^3; 1.0 kg = 10^6 mg

G1: Septic Seepage:
Commercial:
G1-1: Country Mart = 334 kg N
G1-2: Cross Creek Plaza = 583 kg N
G1-3: Civic Center = 135 kg N
=Concentration x Daily Flow x Leaching fraction x (1-N tank removal) x Transport x Conversion x # days
where:
Concentration= 45 mg l^{-1} N
Daily Flow:
G1-1: Country Mart = 89.59 m^3
G1-2: Cross Creek Plaza = 156.50 m^3
G1-3: Civic Center = 72.58 m^3
Leaching fraction= 0.5
N tank removal= 0.1
Transport:
G1-1: Country Mart = 1.0
G1-2: Cross Creek Plaza = 1.0
G1-3: Civic Center = .5

G1-4: Private Septics: 44 kg N
=Persons per home x Flow/person/day x Homes x Transport fraction x Concentration x Conversion x # days
where:
Persons per home = 3.7
Flow per person = 0.19 m^3 d^{-1}
Homes = 30
Transport fraction = 0.25
Concentration= 45 mg l^{-1} N

G2: Golf Course = 0.072 kg N $acre^{-1}$ day^{-1} x 6.5 acres x 184 days = 86 kg N

WET SEASON = 181 days

S1: Malibu Creek Wet Season Total Loads = 109,512 kg N; 16,848 kg P.
= Flow x Concentration x Conversion
Flow = 2.808×10^7 m^3
Concentrations = 3.90 mg l^{-1} N; 0.60 mg l^{-1} P.

S1-1: Tapia Wet Season Load = 34,029 kg N; 5,309 kg P
= Flow x Concentration x Conversion
Flow = 2.824×10^6 m^3
Concentrations = 12.05 mg l^{-1} N; 1.88 mg l^{-1} P.

S1-2 and S1-4:= 75,481 kg N; 11,539 kg P
= Remainder Wet Season Load = Total - Tapia
Nitrogen = 109,510 kg N - 34,029 kg N
Phosphorus = 16,848 kg P- 5,309 kg P

Septic Systems (S1-4)Wet Season Flow = 100 m^3

Storm Runoff (S1-4) Flow = 2.523×10^7 m^3
=Total- (Tapia+Septics) = 2.808×10^7 m^3- (2.824×10^6 m^3 + 100 m^3)

Lagoon Area Wet Season Total Loads = 3,509 kg N; 278 kg P

S4: Storm Runoff Wet Season loads = 2,347 kg N; 128 kg P
= Flow x Concentration x Conversion
Flow = 1.067×10^6 m^3
Concentration = 2.20 mg l^{-1} N; 0.12 mg l^{-1} P

S5: Wet Season Suspended Sediment Load = 150 kg P
-same calculation as above except:
Concentration = 1.58 mg l^{-1} P
Wet Season = 181 days

G1: Septic Seepage:
Commercial:
G1-1: Country Mart = 328 kg N
G1-2: Cross Creek Plaza = 574 kg N
G1-3: Civic Center = 133 kg N
-same calculation as above except multiply by 181 days

G1-4: Private : 43 kg N
-same calculation as above except multiply by 181 days

G2: Golf Course = 84 kg N
-same calculation as above except multiply by 181 days

Table 3. Contribution of nitrogen from each source in the Malibu Creek Watershed.

NITROGEN-DRY SEASON		NITROGEN-WET SEASON	
LAGOON AREA SOURCES	KG	LAGOON AREA SOURCES	KG
G1-1: Country Mart septics	334	G1-1: Country Mart septics	328
G1-2: Cross Creek Plaza septics	583	G1-2: Cross Creek Plaza septics	574
G1-3: Civic Center septics	135	G1-3: Civic Center septics	133
G1-4: Malibu Colony septics	44	G1-4: Malibu Colony septics	43
G2: Malibu Colony Golf Course	86	G2: Malibu Colony Golf Course	84
S2: Malibu Colony Drain washoff	8	S4: Lagoon vicinity storm runoff	2,347
S3: Cross Creek Drain washoff	16		
SUBTOTAL	1,206	SUBTOTAL	3,509
WATERSHED SOURCES	KG	WATERSHED SOURCES	KG
S1-1: Tapia	2,575	S1-1: Tapia	34,029
S1-2 and S1-3: septic seepage and urban runoff	1,158	S1-2 and S1-4: septic seepage and storm runoff	75,481
SUBTOTAL	3,733	SUBTOTAL	109,510
TOTAL	**4,939**	**TOTAL**	**113,019**

5.4.4 Model Results

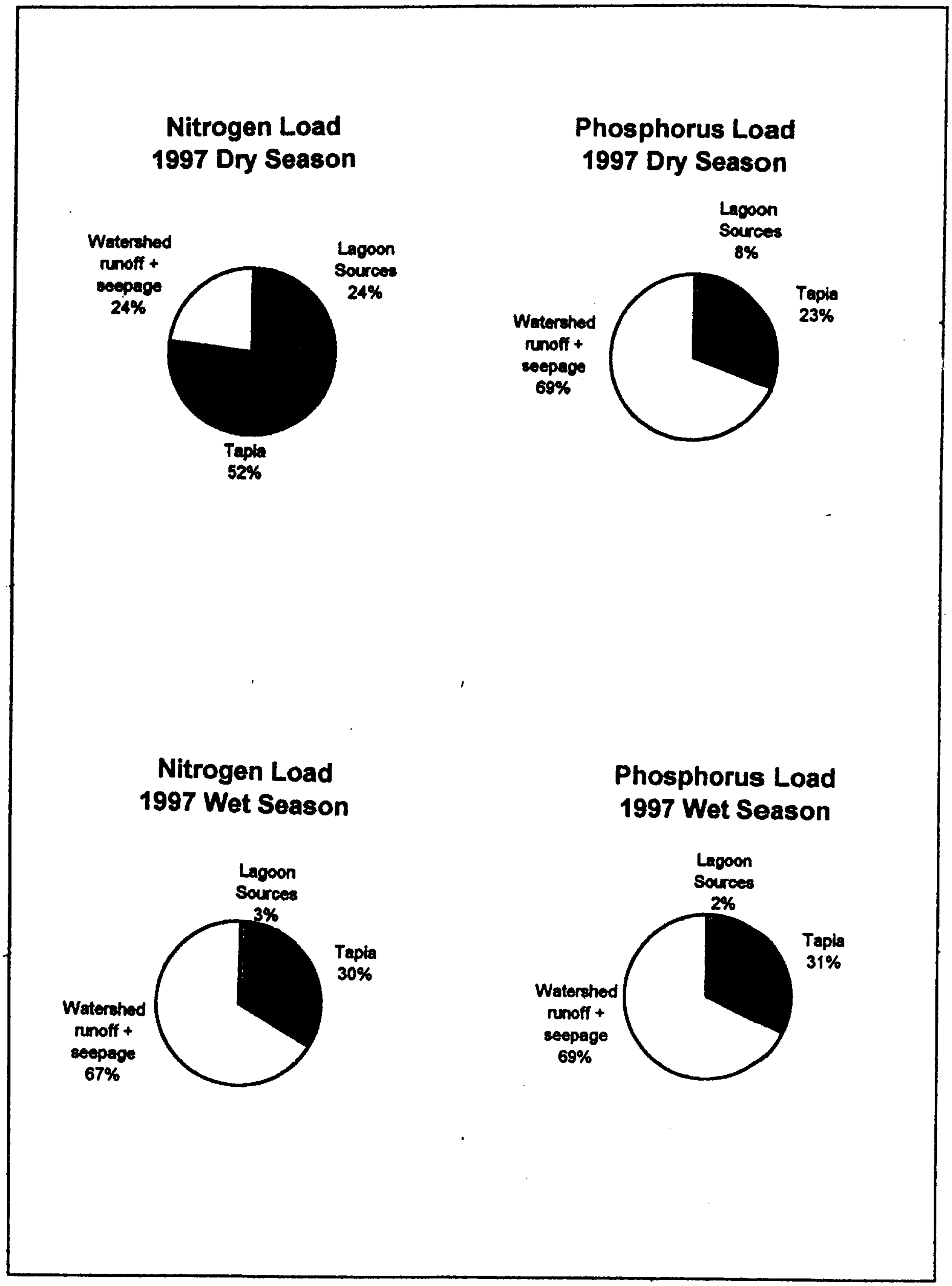
The values of applicable sources identified above were used as inputs to the MEM. The model was used to estimate nutrient loading and derive a water column concentration in the Lagoon using a time-variable solution. The results were used to determine conditions under which eutrophication could occur.

Figure 4 shows the nitrogen and phosphorus mass balance diagrams. A complete description of these schematics and the model for Malibu Lagoon are included in Appendix B. Whenever the sources are similarly described, nutrient loading predictions obtained from the MEM were the same order of magnitude as those based on field data. These results reflect the effectiveness of the model in predicting which variables have a more significant impact during the dry or wet season.

Table 4. Contribution of phosphorus from each source in the Malibu Creek Watershed.

PHOSPHORUS-DRY SEASON		**PHOSPHORUS-WET SEASON**	
LAGOON AREA SOURCES	KG	LAGOON AREA SOURCES	KG
S2: Malibu Colony Drain washoff	0.2	S4 Lagoon vicinity storm runoff:	128
S3: Cross Creek Plaza Drain washoff	0.4		
S5: Lagoon-sediment release (prior wet season's sediment-sorbed contribution)	132	S5: Lagoon-sediment release (current wet season sediment-sorbed contribution)	150
SUBTOTAL	133	SUBTOTAL	278
WATERSHED SOURCES	KG	WATERSHED SOURCES	KG
S1-1: Tapia	402	S1-1: Tapia	5,309
S1-3: urban runoff (soluble)	1,218	S1-4: storm runoff (soluble)	11,539
SUBTOTAL	1620	SUBTOTAL	16,848
TOTAL	**1,753**	**TOTAL**	**17,126**

The model predicts that sediment feedback is the dominant source of nitrogen during the dry season. However, nitrogen does not significantly adsorb onto sediment; thus, sediment feedback predictions may be too high. These limitations do not reduce the validity of the predictions regarding relative loading of each source entering the lagoon from the watershed. The MEM was developed to serve as a predictive tool to determine the nutrient loading of sources into Malibu Lagoon; however the use in predicting eutrophication conditions at Malibu Lagoon is limited. Further discussion of these constraints are provided in Appendix B.



Nitrogen Load 1997 Dry Season

Phosphorus Load 1997 Dry Season

Nitrogen Load 1997 Wet Season

Phosphorus Load 1997 Wet Season

Figure 5-6. Pie charts showing relative percentages of nutrient loads into Malibu Lagoon.

5.5 Discussion

This study evaluated the sources of nutrients into Malibu Lagoon. Management of the lagoon is concerned with reducing eutrophic conditions that lead to algal blooms, which are most likely to occur during the dry season, especially when the sand barrier is closed and tidal flushing is restricted. This has been achieved through artificial breaching of the sand barrier. Alternative management strategies are currently being sought.

It was determined that most of the nutrients in Malibu Lagoon are entering from Malibu Creek. The amount from each source varied according to season. Significant sources of nutrients in Malibu Creek were identified as: (S1-1) Tapia Wastewater Treatment Plant, (S1-2) septic seepage, (S1-3) urban runoff, and (S1-4) storm runoff. Tapia was the only point source into the Creek determined in this study. The remainder were nonpoint sources with varying input points along the Creek. The distance of the source from Malibu Lagoon determined the relative impact of that source on the Lagoon, as in-stream processes may effectively remove some of the nutrients. Further separation of the sources of nutrients in Malibu Creek was beyond the scope of this project but may be useful in the selection of future management options.

The results of this study showed that in the 1997 dry season, Tapia contributed about 50% of the nitrogen load into Malibu Lagoon. The remainder of the Malibu Creek components (i.e., septic seepage and urban runoff), contributed another 25%, and sources surrounding Malibu Lagoon contributed 25% of the nitrogen load. These percentages represent relative contributions, which change each year. For example, in a dry year, there is less storm runoff and the other sources become higher percentages. Additionally, changes in 1998 Tapia permit allows discharges into Malibu Creek only in the wet season, therefore Tapia no longer contributes to nutrient loading in the dry season when effects are more likely to occur.

Management of Malibu Lagoon is concerned with reducing eutrophic conditions that lead to algal blooms. This is most likely to occur during the dry season, especially if the sandbarrier is closed and tidal flushing is restricted. Nutrient control strategies must consider whether Malibu Lagoon is nitrogen or phosphorus limited. Nitrogen is generally the primary limiting nutrient in estuarine systems and if the system is supplied with high levels of nitrogen, algal blooms will occur. An estuary is nitrogen-limited when the N:P is less than 16:1 (Jaworski 1981); and the recommended level of nutrients in estuaries and coastal ecosystems to avoid algal blooms is 0.1 to 1.0 mg N l^{-1} and 0.01 to 0.1 mg P l^{-1} (10:1 of N:P) (NOAA/EPA 1986).

A comparison of this study with results from the LVMWD (1997) monitoring in Malibu Lagoon (at station R11, see Figure 5) is favorable. The results from this study showed a mean dry season concentration approximately 1.39 mg l^{-1} N and 0.49 mg l^{-1} P, with an N:P of 3:1. The monitoring data showed mean dry season concentrations on the same order of magnitude and of the same N:P as the results of this study. The wet season results showed an N:P of 6:1 with 4.03 mg l^{-1} N and 0.62 mg l^{-1} P and were also comparable to the monitoring data. Therefore, in both seasons, the system was nitrogen-limited and the concentration of nutrients was higher than the NOAA/EPA recommended standard.

The sediment was shown to be a significant contributor to the phosphorus load from the lagoon area during the dry season. Storm runoff from the previous season carries with it large amounts of sediment transported via Malibu Creek into Malibu Lagoon. The amount released during the dry season depends on the amount that is deposited during the last major storm of the previous wet season. Therefore, soil conservation measures that would minimize sediment transport during storms are recommended where possible.

The comparison above assumes that the net change in concentration from other in-lagoon processes is negligible. It should be noted that a better comparison of the loading data presented here and the LVMWD monitoring data is achieved with a model that accounts for the various in-lagoon processes. The MEM in Appendix B was developed for this purpose and to model other scenarios.

The MEM was developed as a predictive tool to determine nutrient loading of variable sources into Malibu Lagoon. As shown, the model predictions are of the same magnitude as those observed (LVMWD 1997). This is a significant progress in providing tools for the better management of eutrophication issues at Malibu Lagoon. There is no precedent to the progress achieved to date.

While the model is a sufficient predictive tool, there are limitations to its application. For example, a number of the parameters are based on literature default values. While the developers of the model have taken sufficient precaution in selecting only those numbers that closely mimic the site-specific conditions at Malibu, a field program to collect those same parameters would produce more accurate results than those shown here. Additionally, the source classifications in the MEM are broad; further development of the model could be performed to disaggregate these classifications into separated components. In its current state, the MEM is not user friendly and providing inputs and changing parameters may cumbersome to a number of users. Thus, a future version of the MEM may involve programming commands that will automate a number of the input processes. As mentioned previously, a model adjustment procedure would also be useful.

The methods in this study allowed evaluation of the loading assumptions used for the near-lagoon area by separating the creek components from the sources near the lagoon. The results show there was a significant nitrogen contribution from the septic systems around Malibu Lagoon in the dry season. This study results for phosphorus were three times higher than the monitoring data, indicating the estimates used in this study for the amount of phosphorus released from lagoon sediments may be high. More information about desorption kinetics would be necessary to further quantify this source. The wet season load for phosphorus is much less sensitive to the sediment-release contribution, and are comparable to the monitoring data.

The concentration of nutrients that produce algal blooms in Malibu Lagoon has not been studied, and it is not known whether the NOAA/EPA standard is appropriate at this site. It has been shown that at higher concentrations than the standard, algal blooms are not necessarily present (Ambrose, et al 1995). Algal blooms may not occur because other factors such as temperature or light constraints or other in-lagoon dynamics.

There are many opportunities for future research in the Malibu Creek watershed. For example, a more detailed examination of Malibu Creek is needed to evaluate nonpoint sources. Quantitative loading estimates of nutrients from each land use type and the input points to Malibu Creek throughout the watershed would enable a more comprehensive budget that would be useful in future management throughout the watershed. Additionally, the assumption for groundwater inputs around Malibu Lagoon were based literature values and could be refined with site-specific data. A field program that correlates nutrient concentrations with periods of algal blooms would provide site-specific data on the conditions that occur during algal blooms.

Development of a nutrient budget is a crucial step in management of eutrophication at a Mediterranean-type estuary. Once the sources of nutrients are quantified, the proper control strategy can be employed. The methods in this study can be applied to assess nutrient loading in other watersheds with these types of estuaries.

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5.7 Appendices

APPENDIX A: RESULTS OF FIELD SAMPLING AT MALIBU LAGOON.

Table A1. Field Sampling Results at Malibu Lagoon All results are mg/l. Phosphate is used to represent total Phosphorus (TP). Blanks boxes mean the sample was not tested. Nitrite analysis was not included in analysis of total nitrogen (TN). All samples were taken in 1997-8.

#	Location	Date	Nitrate/ N	Total Keldahl Nitrogen	Ammonia/ N	TN	Phosphate/ TP
DRY							
1	Cross Creek Plaza parking lot	09/10		9.8	1.24		
2	Cross Creek Plaza parking lot	10/06	7.04	9.2	1.01	16.24	0.36
3	Lagoon/ Cross Creek Plaza Storm Drain	09/16	<0.01	1.8	0.29	0.2	<0.01
4	Malibu Colony Plaza parking lot	09/16	4.13	9.1	0.63	13.23	0.39
5	Lagoon	09/17	<0.01	1.5	0.13	1.5	<0.01
6	Ocean	09/16		0.8	0.07		
8	Cross Creek Plaza parking lot	09/17	1.91	16.8	1.32	18.71	.32
9	Cross Creek Plaza backside(washed once/ week)	09/16	13.23	247.9	19.76	261.13	31.30
10	well-P7	10/06	0.18	3.4	2.56	3.58	<0.01
11	well-C2	10/28	0.15	2.0	3.05	2.15	<0.01
12	well-C1	10/28	0.11	7.7	0.02	7.81	<0.01
13	well-P1	10/28	9.37	2.5	0.02	11.87	<0.01
14	well-P6	1028	0.25	5.1	nd	5.35	<0.01
15	Malibu Creek at Arizona Crossing	10/28	4.98	2.0	0.04	6.98	.39
16	Ocean	11/04	<0.01	1.2	0.03	1.2	<0.01
WET							
17	back side of Cross Creek Plaza during rain	11/05	<0.01	19.8	2.39	19.8	2.03
18	back side Cross Creek Plaza pipe flow	11/05	0.02	18.5	1.81	18.52	1.05
19	well-P1	11/05	6.08	2.0	0.07	8.08	<0.01
20	Malibu Creek at Arizona Crossing- light rain	11/05	6.29	6.7	0.99	12.99	.38
21	well-C2	11/05	0.53	1.8	7.86	2.33	0.77
22	well-P7-	11/05	0.27	1.3	21.89	1.57	0.22
23	well-C1-	11/05	<0.01	9.2	5.39	9.2	<0.01
24	well-P6-	11/05	<0.01	5.1	2.24	5.1	<0.01

Table A1. Field Sampling Results at Malibu Lagoon. All results are mg/L. Phosphate is used to represent total Phosphorus (TP). Blanks boxes mean the sample was not tested. Nitrite analysis was not included in analysis of total nitrogen (TN) All samples were taken in 1997-8.

#	Location	Date	Nitrate/ N	Total Keldahl Nitrogen	Ammonia/ N	TN	Phosphate/ TP
25	Mystery Drain-1a	01/28	0.50	3.1	<0.1	3.61	0.12
26	Cross Creek Plaza Storm Drain -1a	01/28	5.82	2.1	<0.1	7.92	<0.01
27	Civic Center Storm Drain -paved runoff-1a	01/28	0.11	0.8	<0.1	.19	<0.01
28	Civic Center Storm Drain -Grass runoff-1a	01/28	0.71	0.2	<0.1	.73	0.03
29	Serra Road runoff-1a	01/28	4.08	2.4	<0.1	6.48	0.65
30	Malibu Creek at Arizona Crossing-1a	01/28	5.18	0.3	0.10	5.38	0.34
31	Malibu Colony Storm Drain flow-1b	02/03	0.56	0.6	<0.1	1.16	0.03
32	Cross Creek Plaza Storm Drain flow 1b	02/03	0.19	0.3	<0.1	.49	<0.01
33	Civic Center Storm Drain flow-1b	02/03	0.15	0.7	<0.1	.85	<0.01
34	Corral runoff -1b	02/03	0.22	94.2	1.42	94.42	4.34
35	Serra Road runoff-1b	02/03	0.27	6.2	0.27	6.47	0.24
36	Malibu Creek at Arizona Crossing-1b	02/03	1.15	7.0	0.18	8.15	0.18
37	Civic Center Storm Drain flow-2a	02/23	0.32	0.2	<0.1	.52	<0.01
38	Malibu Colony Storm Drain flow-2a	02/23	0.35	0.5	0.14	.85	0.06
39	Cross Creek Plaza Storm Drain flow-2a	02/23	0.23	0.1	<0.1	.33	<0.01
40	Corral runoff-2a	02/23	1.04	18.2	<0.1	19.24	2.77
41	Serra road runoff-2a	02/23	0.66	0.3	<0.1	0.96	0.12
42	Malibu Creek at Arizona Crossing-2a	02/23	1.68	0.4	<0.1	2.08	<0.01
43	Malibu Colony Storm Drain flow-2b	02/24	0.91	0.1	<0.1	1.01	0.07
44	Cross Creek Plaza Storm Drain flow -2b	02/24	0.41	0.4	<0.1	.81	<0.01
45	Civic Center Storm Drain flow-2b	02/24	0.37	0.7	<0.1	1.07	<0.01
46	Corral runoff-2b	02/24	0.37	11.9	<0.1	12.27	1.67
47	Serra road runoff-2b	02/24	0.52	0.2	<0.1	.72	0.06
48	Malibu Creek at Arizona Crossing-2b	02/24	1.37	0.9	<0.1	2.27	0.03
49	Corral runoff-2c	02/24	1.48	11.2	<0.1	12.68	2.40
50	Serra road runoff-2c	02/24	8.36	1.6	<0.1	9.96	0.86
51	Malibu Creek at Arizona Crossing-2c	02/24	1.53	0.6	<0.1	2.13	0.08
52	Civic center Storm Drain runoff-2c	02/24	0.18	0.1	<0.1	.28	0.08
53	Cross Creek Plaza Storm Drain runoff-2c	02/24	0.26	0.7	<0.1	.96	<0.01
54	Malibu Colony Plaza Storm Drain flow-2c	02/24	0.74	1.0	<0.1	1.74	0.10

Table A2. Water Quality parameters and methods.

Parameter	Standard Method Number
Nitrate - N	4110 - NO_3 -Ion Chromatography
Ammonia - N	4500 - NH_3 - F- Ion Selective Electrode
Organic N	4500 Norg - A, C (Completed by DANR Labs, Davis, CA)
PO4 - P	4110 - PO_4 - Ion Chromatography

APPENDIX B1: DEVELOPMENT OF A MASS BALANCE MODEL TO DETERMINE NUTRIENT LOADING INTO A SMALL MEDITERRANEAN-TYPE ESTUARY WITH SEASONAL SAND-BARRIER: CASE STUDY - MALIBU LAGOON, CA, USA

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ABSTRACT: A mass balance model was developed to predict nutrient loading for a small Mediterranean-type estuary in Southern California: Malibu Lagoon. This coastal estuary model was a modification of nutrient loading models initially developed for lakes. This was necessary to reflect the geographic and physical conditions existing for Malibu Lagoon especially the formation of sandbars during the summer season which frequently opens to the ocean during the winter season. Hypoxic water conditions are also minimized in this type of estuary. A time variable solution was calculated that accounts for most of the major variables affecting the nutrient loading into system. The general development of the model was for a condition when the sandbarrier is closed but adjustments were made on the equations to predict nutrient loading even in open sandbarrier conditions. The model was calibrated using typical environmental values found in literature. A sensitivity analysis was established. While the model performs its intended purpose, it has to be validated using field collected values in the Malibu Lagoon and Creek watershed.

B1.1 INTRODUCTION

Mathematical models are often used to describe and help resolve water quality issues. A mechanistic model mathematically describes the relevant mechanisms underlying the dynamics of the modeled processes (Chapra and Reckhow, 1983). The application of mathematical modeling techniques to water quality problems has proven to be a powerful tool in water resource management (DiToro, 1983) as alternative management strategies can be evaluated.

A model is not reality; it is an attempt to include the natural or man-made phenomena which are relevant to the water quality problem under consideration. Sensitivity analysis is necessary to identify the primary control mechanisms.

One of the most important problems facing our society is the increased occurrence of eutrophication in different areas around the world. Fortunately, the consequences and causes of eutrophication in fresh water and estuarine systems are fairly well understood. Lowery (1998) provides sufficient literature outlining the development of the understanding of the eutrophication concept. Much research has been conducted specifically on eutrophication control and modeling (Chau and Jin, 1998). In the 1970's, eutrophication modeling focused on seasonal steady-state conditions. In the 1980's, time variable modeling for an entire year was explored with reasonable success (Thomann and Mueller, 1987; Ambrose et al., 1988; Orlob, 1983; and Lung, 1993). Now, these

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Key Words: eutrophication, nutrinet modeling, tivevariable solution, medditerranenan-type estuary, Malibu Lagoon and Creek

modeling approaches can be used to study different types of aquatic systems such as this study on small Mediterranean type estuary with a seasonal sand barrier and distinct wet and dry weather conditions.

The early eutrophication models incorporated nutrient loading, lake volumetrics, trophic status, and flushing rates parameters improving the predictive capability of each advanced model. The foundation for a number of these models was the Vollenweider modeling approach in which the analysis was based on the eutrophication mechanisms in lakes (Lowery, 1998). The usefulness of the approach inspired interest in developing similar evaluation techniques for estuaries. Unfortunately, the relationships controlling estuarine eutrophication are more complex than those controlling lake eutrophication. Consequently, water resource management of estuaries have not had the benefit of being able to approximate the ranges of nutrient loadings corresponding to permissible and critical loadings for their particular estuary. At the present time, the forefronts of eutrophication modeling are the integration of hydrodynamic and water quality models and the incorporation of sediment layers to investigate the long-term recovery of an ecosystem (Cerco and Cole, 1993).

While it is clear that significant progress on eutrophication modeling research has been achieved for large estuaries, application of the same models to smaller estuaries such as the Mediterranean-type Malibu Lagoon are limited at best. A major difference between Malibu Lagoon and other Mediterranean-type lagoons is the formation of sandbars during the summer season which frequently opens to the ocean during the winter season. Hypoxic water conditions are also minimized in this type of estuary.

A first attempt modeling effort to study nutrient loading to Malibu Lagoon is made in this case study to demonstrate an approach in developing a model describing the summer dry season in a Mediterranean-type estuary as Malibu Lagoon. One of the major concerns for Malibu Lagoon is defining the natural seasonal cycle of nutrient loading and the frequency of natural blooms. Currently, there are no standards or goals for the seasonal loading and variation of nutrients for the embayment. Also, there have been no historical reconstructions of Malibu lagoon under "pristine" conditions that address the question of natural vs. cultural algal blooms. Paerl (1997) provides an overview of the significance of atmospheric deposition and groundwater as important sources of nitrogen and other nutrients. We have incorporated these inputs into our model as well.

Previous evaluations of the Malibu embayment suggest it suffers from an extraordinary number and extent of algal blooms (Coats and Warshall, 1991). In fact, when algal blooms die off, eutrophic embayments have low dissolved oxygen which, in extreme, can kill fish but more frequently emanate foul odors. Persistent eutrophication can lead to changes in the species composition of plants and animals inhabiting the aquatic system. In some cultures that cultivate fish, this is considered an advantage: higher fish productivity. In Malibu lagoon, this shift is considered negative to the extent that it reduces biological diversity.

The opening and closing of the Malibu lagoon by natural sandbar formation also plays a dramatic part of the process especially during the summer dry season (April though September). However, the lagoon also experiences the same cycle during the wet seasons but at highly reduced frequency. The lagoon is mostly open to the ocean during the wet season.

The most practical steps to reduce algal blooms include changing the nutrient loading, changing the internal circulation pattern within the lagoon, and changing the flushing pattern (the opening of the sandbar). Along with recording the location and events surrounding each algal bloom, a "nutrient budget" is needed as the first step in understanding the relative importance of variable loadings of nitrogen and phosphorus. It is an essential step in reducing human-caused eutrophication and returning the lagoon back to a natural rhythm of eutrophication events.

However, an important nutrient management question for an estuarine system is: which nutrient should be controlled in order to achieve water quality improvements (Thomann and Linker, 1998). It is important then to assess whether nitrogen or phosphorus or both are important in controlling phytoplankton growth and subsequently in the flux of organic carbon to the sediments for subsequent oxidation. Imperatively, the issue is to use models to determine whether there are any counter intuitive results to be expected. If so, the model will help to explain the occurrence of such results and therefore aid in the decision process.

Two modeling approaches were previously performed to assess the nutrient loading to Malibu Lagoon (Coats et al., 1991; Warshall and Coats, 1992). However, these were inadequate approaches since neither of the models could predict nutrient loading specifically during the summer season. Contemporary watershed models can be used to calculate the time-variable responses of the watershed to precipitation inputs and for varying land uses (e.g., atmospheric, agriculture, urban, forest) (Thomann and Linker, 1998). However, for most watersheds, it is generally not possible to apply classical stream quality advective-dispersive models for water quality throughout the basin because of the large number of computational segments that would be required. Thus, for ease of computation, completely mixed segments are used to represent large reaches of the river drainage network. Since spatial integration is necessary, each sub-basin with the associated completely mixed stream reach aggregates all input loads into a single input load point. The development of a new model that would accomplish such objective is therefore needed. In this paper, we present the approach taken to create such a model. The modeling approach taken in this case study should be valuable for other *Mediterranean-type* lagoons, especially those that form sand barriers and have distinct wet and dry weather flow conditions.

B1.2 BACKGROUND - MALIBU CREEK WATERSHED AND WATER QUALITY

B1.2.1 DESCRIPTION OF THE MALIBU CREEK WATERSHED

The total drainage of the Santa Monica Bay watershed is 328 square miles. Of that total drainage, the Malibu Creek sub-watershed drains an area of approximately 109 square miles in the Santa Monica Mountains and the Simi Hills. About two-thirds of the Malibu Creek watershed lies in the Los Angeles County and one-third in Ventura County. Cities in the watershed include parts of Malibu, Calabassas, Agoura Hills, Westlake Village, Hidden Hills, and Thousand Oaks (USDA-SCS, 1992).

Malibu Creek flows through a steep-sided canyon. In the upper Santa Monica Mountains, it has a mushroom shaped tributary system which is controlled by geologically young, uplifted valleys bounded by east-west trending reverse faults (Trim, 1994). Historically, there is little flow in the summer months; much of the natural flow that occurs in the summer in the upper tributaries comes from springs and seepage areas. The springs and seepages primarily originate in the Lower Topanga Formation which is dominated by coarse grained sandstone and conglomerate. The major springs are in the upper Cold Creek, La Sierra Canyon, and an unnamed tributary south of Century reservoir. Seepage areas occur in porous stream alluvium and frequently form ponds or flowing surface water (Flowers, 1972). Although the watershed flow is low during the dry season, it is important to note that the overall annual water volume is large, as is typical of Southern California Creeks. Over 70% of the annual runoff occur during winter storms (SCAG, 1988). Imported water discharged by point sources or contributed by non-point sources have altered the natural hydrology of the watershed. At present during the summer months, the effluent from the Las Virgines Municipal Water District make up most of the flow of water to Malibu Lagoon.

Malibu Creek terminates at the Malibu Lagoon, an area of about 13 acres of shallow brackish water that provides a nursery habitat for certain fish species and a winter stopover for migrating birds (TLVRCD, 1989). The creek and the lagoon are the southernmost steelhead trout run on the west coast (CalTrout, 1990). Malibu lagoon is a small surviving remnant of wetland in Southern California (Philip Williams et al., 1992).

B1.2.2 EUTROPHICATION ISSUES AT MALIBU LAGOON

Excess nutrients in aquatic systems can lead to eutrophication. Eutrophication is an accumulation of plant biomass that can cause water quality problems leading to nuisance odors, fish kills, and other undesirable effects as a rapid growth of a few species to the detriment of biodiversity. Eutrophication can also encourage the invasion of non-indigenous species, especially those adapted to disturbed conditions. At Malibu Lagoon, eutrophication is most likely to develop when tidal flushing is restricted (Ambrose et al., 1995). This is specifically true during summer months (April through September) when natural sand barriers form.

In order to understand and control eutrophication in Malibu Lagoon, a nutrient budget was developed. Sources and sinks for both organic and inorganic forms of nitrogen and phosphorus were determined and their magnitude estimated or measured under different conditions to evaluate the eutrophic state of the lagoon.

The lagoon is very dynamic and thus the approach selected for this modeling exercise was defined on the basis of variable physical and temporal conditions in the lagoon. It must be recognized that the ecological reaction of the lagoon is not instantaneous. For example, under calm conditions of minimal flow during summer months, two conditions can be initially projected:

1. when the lagoon is open to the ocean (sandbar open)
2. when the lagoon is closed to the ocean (sandbar closed).

Each condition is a function of the time lapsed under the condition and the buildup of nutrients just previous to the condition. Also, the buildup of nutrients from migrating bird populations can be significant.

Another example is between storms during the rainy season. Here, the time between storms, the severity of the storms, and the sediment outflow to the Bay from the lagoon and sediment inflow to the lagoon from the watershed must be evaluated. Under these scenarios, the key sources (inputs) and outputs were assessed.

A steady state solution was initially developed as a first attempt in predicting nutrient loading into Malibu Lagoon. However, steady state conditions may not be a true representation of lagoon conditions. Therefore, a time variable solution model was developed in order to fully account for the variabilities comprising the nutrient loading into Malibu Lagoon. The time variable solution attempts to predict nutrient loading throughout the year. The development of this model is the subject of this paper.

B1.3 BUDGET MODELS

Budget models are designed to predict the state of a system by determining the flows of matter across their boundaries. Thus, the internal structure or resolution of the system is only important if it influences inputs and outputs. As a rule, budget models applicable to aquatic systems are internally homogeneous or well mixed and a single mass balance equation is used to characterize the dynamics (Chapra and Reckhow, 1983). Because of their simplicity, such models provide easily calculated estimates of water quality that often are quite useful in water resource planning and management.

The basic organizing principle of such models is the conservation of mass. In quantitative terms, the principle is expressed as a mass balance equation that accounts for all transfers of matter across the system's boundaries and all transformations occurring within the system. This could be represented by the following equation:

$$V \frac{dc}{dt} = W(t) - Qc \pm \left(V \frac{dc}{dt} \right)_{reaction} \quad (1).$$

where:

d/dt = Change with respect to time $[T^{-1}]$
V = System's volume $[L^3]$
c = Concentration of the substance $[M\ L^{-3}]$

W(t) = the rate of mass loading $[M\ T^{-1}]$
Q = volumetric system flowrate $[L^{-3}\ T^{-1}]$

Surface losses are not included because they often can be treated as first order reactions.

A completely mixed aquatic model is appropriate for a system in which the contents are well mixed and uniformly distributed. As such, this model is a satisfactory first approximation for many systems in which wind-induced turbulence causes substances to be dispersed fairly homogeneously in the horizontal plane. Although there are a variety of ways in which this idealization might be violated for the particular case of Malibu Lagoon (e.g., gradients due to tidal and creek inflow), the model should find broad application to the Malibu-type systems because of its simplicity and success in providing order of magnitude estimates of water quality. Chapra (1997) and Thomann and Mueller (1987) provide an excellent discussion on the modeling of processes in estuaries. The equations provided in these texts provide the backbone of the model development used for this case study. From this initial formulation, we have developed a model that would be predictive of the nutrient loading taking into account the site-specific characteristics of a small Mediterranean type estuary with a seasonal sand barrier and distinct wet and dry weather conditions like Malibu Lagoon.

A succinct discussion of the mass balance development for phosphorus and nitrogen along with parameters included as significant inputs and potential outputs of the model are provided. The following discussions provide the background of the models created for Malibu Lagoon.

B1.4 MODEL CONSTRUCTION FOR PHOSPHORUS LEVELS

From a water-quality perspective, phosphorus is important because it is an essential nutrient and usually in short supply relative to the other macronutrients as it is not abundant in the earth's crust and does not exist in a gaseous form. Phosphate tends to sorb strongly to fine-grained particles in the water column. The settling of these particles, along with sedimentation of organic particles containing phosphorus, serves to remove phosphorus from the water to the bottom sediments. For cases where the water in contact with the sediments contains oxygen, such sediment phosphorus becomes chemically trapped.

Many anthropogenic activities result in phosphorus discharge to natural waters. Human and animal wastes both contain substantial amounts of phosphorus. In particular, detergents add phosphorus to aquatic environments. Similarly, non-point sources from agricultural fertilization and urban land both contribute excess phosphorus. Moreover, human uses lead to soil erosion, which also enhances phosphorus transport into waters. Phosphorus in natural waters can be subdivided in several ways. Here, we distinguished between soluble inorganic phosphorus and organic phosphorus.

The mass balance equation for soluble phosphorus concentration in the estuary during a period of time of one day, assuming a completely mixed homogeneous system, is:

$$[\text{mass variation}] = [\text{sources}] - [\text{sinks}] \tag{2}$$

Figure 1 shows the sources and the sinks associated with this model. A description of the model and corresponding variables are provided as follows.

In a first approximation, the tidal water and the waterflow from the creek were considered as inputs due to water transport and the outflow from the estuary as the only output due to water transport. Settling to the bottom and feedback from the sediment were treated as an input and an output surface processes, respectively. Furthermore, uptake by living organisms (output) and release from their activity and decomposition (input) were the two reactions included.

Thus, the mass variation of soluble phosphorus is:

$$V \frac{dp}{dt} = \sum_{i=1}^{n} \left(V \frac{dp}{dt} \right)_i \tag{3}$$

where:

d/dt = the change with respect to time $[T^{-1}]$
V = the system's volume $[L^3]$
p = the concentration of soluble phosphorus in the estuary $[M\ L^{-3}]$
i = individual processes causing mass variations

A time period of one day was considered. Further, the volume of water contained by the estuary was assumed to be constant (at least between two points at a distance of a tidal period).

B1.4.1 SOURCES OF SOLUBLE PHOSPHORUS

The number of sources of soluble phosphorus includes: influent tidal water, inflow from Malibu Creek, feedback from the sediment, and release from non-available forms.

The influent tidal water was modeled as a mass transport process by means of advection:

$$\left(V \frac{dp}{dt} \right)_{\text{tidal inflow}} = W_s(t) = q\ p_s \tag{4}$$

where:

$W_s(t)$ = Mass loading due to tidal water advective transport of phosphorus $[M\ T^{-1}]$
q = Tidal inflow $[L^3\ T^{-1}]$
p_s = Concentration of phosphorus in the tidal water $[M\ L^{-3}]$.

The inflow from the creek was also modeled as a purely advective mass transport process:

$$\left(V\ \frac{dp}{dt}\right)_{creek\ inflow} = W(t) = Q\ p^0 \tag{5}$$

where:

$W(t)$ = Mass loading due to creek water advective transport of phosphorus $[M\ T^{-1}]$
Q = Creek inflow $[L^3\ T^{-1}]$
p^0 = Concentration of phosphorus in the creek water $[M\ L^{-3}]$.

On the other hand, feedback from the sediment was modeled as a surface-based change of phase:

$$\left(V\ \frac{dp}{dt}\right)_{feedback} = v_f A_m\ p_m \tag{6}$$

where:

v_f = the feedback velocity across the sediment's surface $[L\ T^{-1}]$
A_m = the sediment's surface area $[L^2]$
p_m = the concentration of total phosphorus in the sediment pore water $[M\ L^{-3}]$.

Release from the non-available forms was grouped under the term organic phosphorus. It was modeled as a first-order reaction process:

$$\left(V\ \frac{dp}{dt}\right)_{release} = k_r V\ p_o \tag{7}$$

where:

k_r = the release reaction's coefficient $[M\ T^{-1}\ L^{-3}]$
p_o = organic phosphorus concentration in the estuary $[M\ L^{-3}]$.

B1.4.2 SINKS OF SOLUBLE PHOSPHORUS

The number of sinks of soluble phosphorus includes: combined outflow water, settling to the sediment, and uptake by living organisms.

The combined outflow water was assumed to be the sum of the ebb tidal flow and the creek inflow. Therefore, the average volume of the estuary was assumed to be constant for the mass balance modeling time period. It was modeled as a mass transport process by means of advection:

$$\left(V\ \frac{dp}{dt}\right)_{outflow} = -(Q + q)\ p \tag{8}.$$

Similarly, the settling phosphorus to the sediment was modeled as a surface based change of phase. The equation is:

$$\left(V \frac{dp}{dt}\right)_{settling} = -v_s A_s p_o \tag{9}$$

where:

v_s = the settling velocity [L T^{-1}]
A_s = the estuary's surface area [L^2].

The uptake by living organisms was modeled as a first-order reaction process:

$$\left(V \frac{dp}{dt}\right)_{uptake} = -k_u V p \tag{10}$$

where:

k_u = the uptake reaction's coefficient [M T^{-1} L^{-3}].

All sources and sinks were then combined and a preliminary overall mass balance equation was produced:

$$V\frac{dp}{dt} = q\,p_s + Q\,p^0 + v_r A_m p_m + k_r V\,p_o - (Q+q)\,p - v_s A_s p_o - k_u V\,p \qquad (11).$$

B1.4.3 MASS BALANCE TRANSFORMATION

Lorenzen (1974) and Lorenzen et al. (1976) developed a simple model of sediment-water interactions for total phosphorus. The following mass balance for the total phosphorus concentration in the sediment pores was developed:

$$V_m \frac{dp_m}{dt} = -v_r A_m p_m + (1 - f_b)\, v_s A_s p_t \tag{12}$$

where:

V_m = the volume of the sediment matrix [L^3]
f_b = the fraction of phosphorus buried directly to the deep sediments [L T^{-1}]
p_t = total phosphorus concentration in the estuary [M L^{-3}].

This mass balance equation was designed for an annual or seasonal time frame. Therefore, a partition coefficient between deep and shallow sediments was used (f_b) to characterize the effect of the seasonal processes on the long-term predictions. Lorenzen (1974) interpreted f_b as the fraction of the sediment phosphorus that is unavailable for reintroduction into the water column. On the contrary, we worked on a daily time frame. This is one of the reasons why we assumed the buried fraction to be zero, e.g. the burying effect was considered to be negligible on a daily basis. Besides, in order to adapt the variables used by Lorenzen (1974) to our variables, we divided the total phosphorus into our soluble and organic phosphorus. Finally, we assumed that the concentration of total phosphorus into the pores of the sediment was constant on a daily basis, so we solved the equation for the steady-state ($dp_m/dt = 0$):

$$v_f A_m p_m = v_s A_s p_t \qquad (13)$$

and

$$v_f A_m p_m = v_s A_s (p + p_o) = v_s A_s p + v_s A_s p_o \qquad (14).$$

Substituting 14 into 11 the new expression for the mass balance is:

$$V \frac{dp}{dt} = q\, p_s + Q\, p^0 + v_s A_s\, p + k_r V\, p_o - (Q + q)\, p - k_u V\, p \qquad (15).$$

It must be noted that with the transformation, the term including the settling velocity appears in the mass balance with a positive sign, i.e., as a source. At first, this might seem contradictory, but from the construction of the model it is clear that this is the result of substituting the feedback term by equation 14, derived from the Lorenzen model for exchange of total phosphorus between water and sediment. The part of the Lorenzen model including the soluble phosphorus has been canceled by the settling term of the general model.

Whenever the sandbarrier is formed, a new mass balance will be applied:

$$V \frac{dp}{dt} = Q\, p^0 + v_s A_s\, p + k_r V\, p_o - k_u V\, p \qquad (16).$$

B1.4.5 STEADY-STATE SOLUTIONS

A steady state solution was developed for any small Mediterranean-type estuary with or without seasonal sand barrier. The solution assumes the change in concentration of soluble phosphorus in the estuary is negligible on a daily basis, i.e., sinks counterbalance sources ($dp/dt = 0$).

Solving equation 16 for p, the concentration of soluble phosphorus in the estuary when it is open to the ocean is given by:

$$p = \frac{q\, p_s + Q\, p^0 + k_r V\, p_o}{(Q + q) + k_u V - v_s A_s} \qquad (17).$$

Solving equation 16 for p, the concentration of soluble phosphorus in the estuary when the sandbarrier is formed is given by:

$$p = \frac{Q\, p^0 + k_r V\, p_o}{k_u V - v_s A_s} \qquad (18).$$

B1.5 MODEL CONSTRUCTION FOR NITROGEN LEVELS

Although nitrogen is just as necessary for life as phosphorus, the two elements differ in three ways:

1. Nitrogen has a gas phase. Further, certain blue-green algae are capable of fixing free nitrogen. This gives them a competitive advantage in situations where other forms of nitrogen are in short supply. This state of affairs can sometimes occur when advanced treatment includes nitrogen removal. In such cases, blue-green algae can become dominant.

2. Inorganic forms of nitrogen do not sorb as strongly to particulate matter as does phosphorus. Consequently, although particulate forms of nitrogen are carried to the sediments by settling, they are more easily introduced back into the water. In addition inorganic forms of nitrogen (particularly nitrate) are more mobile in groundwater.

3. Denitrification represents a purging mechanism that does not occur for phosphorus. Because it occurs only in the absence of oxygen, denitrification is insignificant for many surface waters. However, for productive systems where denitrification can occur in anoxic sediments, a deficiency of nitrogen can be created.

As with phosphorus, nitrogen discharges to natural water result from anthropogenic activities. Human and animal wastes both contain substantial amounts of nitrogen. In addition, non-point sources from agricultural and urban land both contribute excess nitrogen. As mentioned above, because forms such as nitrate do not associate strongly with solid matter, they can be easily transmitted to surface waters along with groundwater flow.

Most of the characteristics imply that phosphorus has usually been identified as the primary controllable nutrient governing the eutrophication process in fresh waters. However, productive estuaries can tend to be nitrogen limited.

The primary forms of nitrogen are: free nitrogen (N_2), ammonium (NH_4^+)/ammonia (NH_3), nitrite (NO_2^-), nitrate (NO_3^-), and organic nitrogen. The organic nitrogen can be broken down further into particulate and dissolved components. Some of the major processes governing the dynamics of these groups are: ammonia and nitrate assimilation by phytoplankton, ammonification, nitrification, denitrification and nitrogen fixation. For the purposes of our study, we grouped ammonia, nitrite, nitrate and organic nitrogen as total nitrogen due to the number of forms in which it appears and the number of processes occurring.

Analogous to phosphorus, the mass balance equation for total nitrogen concentration in the Malibu estuary during a period of one day, assuming a completely mixed homogeneous system is:

$$[\text{mass variation}] = [\text{sources}] - [\text{sinks}] \qquad (19)$$

Figure 2 shows the sources and the sinks associated with this model. A description of the model and corresponding variables are provided as follows.

In a first approximation, the tidal water and the waterflow from the creek were considered as inputs due to water transport and the outflow from the estuary as the only output due to water transport. Settling to the bottom and feedback from the sediment were treated as input and output surface processes, respectively. Atmospheric deposition was also considered to be a source of nitrogen. Further, uptake by living organisms (output) and release from their activity and decomposition (input) were two reactions included.

Following the same mathematical development for the phosphorus model, the following mass balance equation was established:

$$V\frac{dn}{dt} = \sum_{i=1}^{n}\left(V\frac{dn}{dt}\right)_i \qquad (20)$$

where:

d/dt = the change with respect to time $[T^{-1}]$
V = the system's volume $[L^3]$
n = the concentration of total nitrogen in the estuary $[M\ L^{-3}]$
i = individual processes causing mass variations.

Similarly, developing each individual process in the same way as phosphorus, we would obtain:

$$V\frac{dn}{dt} = qn_s + Qn^0 + dA_s + v_f^{\,n}A_m n_m + k_r^{\,n}Vn_o - (Q+q)n - v_s^{\,n}A_s n_o - k_u^{\,n}Vn \qquad (21)$$

where:

q = Tidal inflow $[L^3\ T^{-1}]$
n_s = Concentration of total nitrogen in the tidal water $[M\ L^{-3}]$
Q = Creek inflow $[L^3\ T^{-1}]$
n^0 = Concentration of total nitrogen in the creek water $[M\ L^{-3}]$
d = Atmospheric deposition rate $[M\ L^{-2}\ T^{-1}]$
A_s = System's surface area $[L^2]$
$v_f^{\,n}$ = Feedback velocity across the sediment's surface $[L\ T^{-1}]$
A_m = Sediment's surface area $[L^2]$
n_m = Concentration of total nitrogen in the sediment pores $[M\ L^{-3}]$
$k_r^{\,n}$ = Release reaction's coefficient $[M\ T^{-1}\ L^{-3}]$
n_o = Nitrogen in biomass concentration $[M\ L^{-3}]$
$v_s^{\,n}$ = Settling velocity $[L\ T^{-1}]$
$k_u^{\,n}$ = Uptake reaction's coefficient $[M\ T^{-1}\ L^{-3}]$.

Applying the Lorenzen modified model to total nitrogen sediment-water interactions, we determined the following relationships:

$$v_f^{\,n} A_m n_m = v_s^{\,n} A_s n_t \tag{22}$$

$$v_f^{\,n} A_m n_m = v_s^{\,n} A_s (n + n_o) = v_s^{\,n} A_s n + v_s^{\,n} A_s n_o \tag{23}$$

Substituting 23 into 21 the new expression for the mass balance is:

$$V \frac{dn}{dt} = q\, n_s + Q\, n^0 + d\, A_s + v_s^{\,n}\, A_s\, n + k_r^{\,n}\, V\, n_o - (Q + q)\, n - k_u^{\,n}\, V\, n \qquad (24).$$

B1.5.1 UPTAKE AND RELEASE FACTORS

Two more changes were introduced, one affecting the release factor and one affecting the uptake factor.

B1.5.1.1 Release factor

The N:P relationship in biomass is assumed to average 7.2. The assumption was made that nitrogen and phosphorus released by the decay of biomass kept the same proportion:

$$\left(V \; \frac{d\,n_o}{d\,t}\right)_{release} = 7.2 \left(V \; \frac{d\,p_o}{d\,t}\right)_{release} \tag{25}$$

therefore:

$$k_r^{\,n}\, V n_o = 7.2\, k_r V p_o \qquad (26).$$

Since:

$$n_o = 7.2 p_o \tag{27}$$

it follows that:

$$k_r^{\,n} = k_r \qquad (28).$$

B1.5.1.2 Uptake Factor

Similarly, considering biomass takes nitrogen and phosphorus in the same proportion that is found to constitute it, the uptake factor could be represented as:

$$\left(V \; \frac{dn}{dt}\right)_{uptake} = 7.2 \left(V \; \frac{dp}{dt}\right)_{uptake} \qquad (29).$$

therefore:

$$k_u^{\,n}\, V n = 7.2\, k_u V p \qquad (30).$$

Solving for $k_u^{\,n}$:

$$k_u^{\,n} = 7.2\; k_u \; \frac{p}{n} = \frac{7.2}{n{:}p}\; k_u \qquad (31).$$

Since n and p are both variables, we should solve first the phosphorus balance to be able to solve the nitrogen balance. In order to get an independent equation, we substituted n:p for an estimated N:P ratio. In that way we also prevented the phosphorus model to become a source of error for the nitrogen model. Finally:

$$k_u'' V n = \frac{7.2}{N:P} k_u V n \qquad (32).$$

Substituting 30 and 32 into 24 we obtained the final mass balance for nitrogen:

$$V \frac{dn}{dt} = q n_s + Q n^0 + d A_s + v_s'' A_s n + 7.2 k_r V p_o - (Q + q) n - \frac{7.2}{N:P} k_u V n \qquad (33).$$

Whenever the sandbarrier is formed, a new mass balance will be applied:

$$V \frac{dn}{dt} = Q n^0 + d A_s + v_s'' A_s n + 7.2 k_r V p_o - \frac{7.2}{N:P} k_u V n \qquad (34).$$

B1.5.2 STEADY-STATE SOLUTIONS

A steady state solution for nitrogen loading is developed for any small Mediterranean-type estuary with or without a seasonal sand barrier. The solution assumes the change in concentration of total nitrogen in the estuary is negligible on a daily basis, i.e., sinks counterbalance sources (dn/dt = 0).

Thus, the concentration of total nitrogen in the estuary when it is open to the ocean is

$$n = \frac{q n_s + Q n^0 + d A_s + 7.2 k_r V p_o}{(Q + q) + \frac{7.2}{N:P} k_u V - v_s'' A_s} \qquad (35)$$

On the other hand, the concentration of total nitrogen in the estuary when the sandbarrier is formed is

$$n = \frac{Q n^0 + d A_s + 7.2 k_r V p_o}{\frac{7.2}{N:P} k_u V - v_s'' A_s} \qquad (36).$$

B1.6 DETAILED STUDY OF NUTRIENT SOURCES: CASE STUDY MALIBU

In the development of these models, the only sources that have been considered are the inflow from the creek and the tide, the feedback from the sediment, and the release from decaying biomass. However, Malibu Lagoon receives nutrients from several other sources. We identified the following: water coming from the washing of commercial areas parking lots; the so-called 'Mystery Drain' which supposedly drains the Malibu Colony and brings the water into the lagoon; flow originated by the septic tanks system of the area that finally reaches the lagoon through the groundwater; and during the rainy season, storm-runoff water that directly collects into the lagoon.

All these sources were represented by their corresponding flow and nutrients concentration and they were included in the model together with the inflow water coming from Malibu Creek. That is:

$$Q = q_m + q_p + q_d + q_{st} + q_r \tag{37}$$

and

$$c^0 = \frac{c_m q_m + c_p q_p + c_d q_d + c_{st} q_{st} + c_r q_r}{Q} \tag{38}$$

where:

Q = Total inflow (except tidal inflow) [$L^3 T^{-1}$]
q_i = Inflow for every source [$L^3 T^{-1}$]
c^0 = Average nutrient concentration (phosphorus or nitrogen) [$M L^{-3}$]
c_i = Nutrient concentration for every source (phosphorus or nitrogen) [$M L^{-3}$]
m = Malibu Creek
p = Commercial areas parking lots
d = Mystery Drain
st = Septic tanks
r = Storm-runoff water

B1.7 TIME VARIABLE SOLUTIONS: CASE STUDY MALIBU

The set of differential equations composing the model was earlier solved assuming steady-state conditions. Using that procedure, equations 15, 16, 33 and 34 were solved giving rise to equations 17, 18, 35 and 36. However, such conditions are rarely achieved. Therefore, time-variable solutions for equations 15, 16, 33 and 34 were also developed.

Due to the temporal variability of the parameters used to construct the model, and to the lack of idealized functions that described them, the fourth-order Runge-Kutta numerical method was used in finding time-variable solutions (Chapra and Reckhow, 1983; and Chapra, 1997).

B1.7.1 SENSITIVITY ANALYSIS

We developed a mechanistic ordinary differential equation model based on parameterized physiological processes and mass conservation, time-dependent and non-linear. As it is common for mechanistic models, this is a deterministic model: although it is recognized that initial conditions, parameters, and forcing functions of the model have stochastic properties, which are not accounted for. These stochastic properties affect the confidence that can be placed in the model output. This implies that confidence generally is inversely related to variability. Analysis of this variability is important in a management context to establish error bounds on predictions. The prediction errors indicate the value of the information provided by the model. Because eutrophication models are crude representations of highly variable, stochastic systems, to ignore such important attributes often results in naive confidence or unwarranted disbelief in the model's solutions. For these models to become more generally accepted and effectively used, they must be placed in the proper perspective. Evaluating the effects of input (forcing function and parameter) variability on model output provides some of the needed perspective.

In order to understand the general behavior of the model, we conducted a first-order sensitivity analysis. For simplicity, we illustrate first-order sensitivity analysis for the phosphorus concentration model under open conditions, which at steady-state can be solved for:

$$p = \frac{q\ p_s + Q\ p^0 + k_r V\ p_o}{(Q + q) + k_u V - v_s A_s} \tag{39}$$

Based on this formula, p is a function of each of the model parameters and forcing functions; that is $p = f(q, p_s, Q, p^0, k_r, V, p_o, k_u, v_s, A_s)$. Thus, one way of visualizing the dependence of the solution on one of the parameters is using the derivative of the function with respect to the parameter as an estimate of the sensitivity. One way to derive it is to employ first-order Taylor-series expansions of the model around the value of the parameter. For example, forward and backward expansions for phosphorus concentration around the value of the release constant can be written as:

$$p(k_r + \Delta k_r) = p(k_r) + \frac{\partial\ p(k_r)}{\partial\ k_r} \Delta k_r \tag{40}$$

$$p(k_r - \Delta k_r) = p(k_r) - \frac{\partial\ p(k_r)}{\partial\ k_r} \Delta k_r \tag{41}$$

Equation 40 can be subtracted from 41 resulting in

$$\Delta p = \frac{p(k_r + \Delta k_r) - p(k_r - \Delta k_r)}{2} = \frac{\partial\ p(k_r)}{\partial\ k_r} \Delta k_r \tag{42}$$

Note that for this formula the sign of the derivative indicates whether a positive variation of the parameter results in a positive or negative variation of the prediction.

The propagation of the relative error of the parameter into the relative error of the prediction can be done through the condition number for the parameter (Chapra and Canale 1988). For the first-order sensitivity analysis such a number can be derived by dividing both sides of equation 54 by the prediction (p in our example). Then the right-hand-side can be multiplied and divided by the parameter k_r/k_r. Thus,

$$\frac{\Delta p}{p} = CN_{k_r} \frac{\Delta k_r}{k_r} \tag{43}$$

where CN_{k_r} is the condition number for the parameter k_r:

$$CN_{k_r} = \frac{k_r}{p}\frac{\partial p}{\partial k_r} \qquad (44)$$

B1.8 ESTIMATING TIDAL FLOWS

The effect of tidal action must also be considered in modeling the water quality in a *Mediterranean-type* lagoon. At this writing, the actual tidal flow data is still being collected by other investigators. To compensate, we developed a rough estimate of the flood flow (q). As it was stated, our model assumed that ebb flow equaled all the input flows including an amount equivalent to the flood flow (Q+q).

The amount of daily flood flow depends mainly in three factors: the dimensions of the breaching of the sandbarrier, the inflow other than flood flow, and the daily variation in tidal height. At this point only tidal height variations data are available. More specifically, our database contained maximum ebb and flood tidal heights and time of the day when they occurred. In order to obtain the flood flow estimate from such a poor database, a number of assumptions were made:

1. The basis of the breach was supposed to be placed at the minimum daily tidal height (or maximum ebb tidal height).
2. The water level in the estuary (due to all the inflows) was supposed to be equal to the average tidal height, considering the two minimum ebb (h_e) and two maximum flood (h_f) heights of the studied day. Whenever the tidal height was higher than the average tidal height we assumed the tide to be in the flood period and whenever the tidal height was lower than the average tidal height we assumed the tide to be in the ebb period. The extreme tidal heights were recalculated using the average tidal height as a zero level.
3. The tidal height was assumed to change in a linear fashion in order to determine the duration of the ebb (T_e) and flow (T_f) periods of the day. Whenever the line between two tidal extremes crossed the horizontal line corresponding to the average height, a new ebb or flow period was supposed to begin.
4. The tidal flow variations were idealized as half-sinusoid curves. Simple sinusoidal approximation of the tidal flow can be used to estimate the net estuarine flow (Chapra, 1997).

First of all, we considered a unique flood period idealized as a half-sinusoid curve that reached the maximum (q_f^{max}) at the maximum flood tidal height (h_f). The tidal flood flow at any time t (q_f) can be described by:

$$q_f = q_f^{max} \sin\frac{\pi t}{T_f} \qquad (45).$$

The maximum flood flow was assumed to be related to the maximum tidal flood height through the opening of the sandbarrier (l) and the velocity (v) at which the water crosses the breach:

$$q_f^{max} = l \ h_f \ v \qquad (46)$$

An estimate for the velocity was then developed. It was assumed that at the minimum tidal ebb height all the inflow into the lagoon (Q) was equal to the outflow through the breach, and the water was flowing with a height equal to the minimum ebb tidal height (h_e) throughout the opening of the sandbarrier (l). That is:

$$Q = l \ h_e \qquad (47).$$

Equation 47 can be solved for v:

$$v = \frac{Q}{l \ h_e} \qquad (48)$$

Substituting equations 46 and 48 into equation 45 we obtained:

$$q_f = \frac{h_f}{h_e} \ Q \ \sin \frac{\pi \ t}{T_f} \qquad (49).$$

In order to obtain the average flood flow (q) during a single flood period we integrated the instant flood flow through the period and then we divided by the duration of the period (T_f):

$$q = \frac{\int_0^{T_f} q_f \ dt}{T_f} \qquad (50).$$

After solving equation 50, the following relationship was found:

$$q = \frac{2}{\pi} \frac{h_f}{h_e} Q \qquad (51).$$

During a complete day, there are approximately two tidal cycles, thus, there are two flood periods. An average flood flow weighted by the duration of the flood periods relative to the total tidal cycle was calculated as:

$$q = \varphi \ Q \qquad (52).$$

Based on previous calculations, the phi coefficient could be represented as:

$$\varphi = \frac{2}{\pi} \frac{\frac{h_f^1}{h_e^1} T_f^1 + \frac{h_f^2}{h_e^2} T_f^2}{T_f^1 + T_e^1 + T_f^2 + T_e^2} \qquad (53).$$

Therefore, we estimated the tidal flood flow from the daily total inflow (except tidal inflow). The phi coefficient values varied between 0.3 and 1.2.

B1.9 ESTIMATING ORGANIC PHOSPHORUS CONTENTS

As a result of its theoretical development, our simple budget model for a well mixed system included the organic phosphorus concentration (p_o) as a variable. However, the database that was used to calibrate and verify the model did not contain information on organic phosphorus concentrations. Therefore, we constructed an estimate for p_o in a three-phase approach.

The first step was to redefine the organic phosphorus as the phosphorus contained in the phytoplankton biomass. By doing so, other fractions that were originally included into this variable would be neglected. It is known that phosphorus constitutes about one percent of the average dry weight phytoplankton biomass. Therefore,

$$p_o = 0.01\, b \qquad (54)$$

where

p_o = organic phosphorus concentration in water $[M\, L^{-3}]$
b = biomass concentration in water $[M\, L^{-3}]$

In the second step, we related biomass contents to an estimated *chlorophyll a* content in water. According to the Standard Methods the following relationship exists between levels of biomass and *chlorophyll a*:

$$b = 67\, c_a \qquad (55)$$

where

c_a = *chlorophyll a* concentration in water $[M\, L^{-3}]$

The third and final step consisted of estimating *chlorophyll a* concentrations through soluble phosphorus concentrations. Phosphorus concentration is a variable contained in our database. Due to the changing dynamics characterizing estuaries, different correlation equations were used for phosphorus-limited conditions and nitrogen-limited conditions.

Whenever the estuary behaved as a phosphorus-limited system the Bartsch and Gakstatter (1978) approach was followed:

$$c_a = 0.64\, p^{0.807} \tag{56}$$

where:

p = soluble phosphorus concentration in water (mg m^{-3})
c_a = biomass concentration in water (mg m^{-3}).

The organic phosphorus fraction under phosphorus-limited conditions, is finally estimated by substituting equations 55 and 56 into 54:

$$p_0 = 0.429\, p^{0.807} \tag{57}$$

In contrast, for nitrogen-limited conditions in the estuary, the Smith and Shapiro (1981) correlation curve was applied:

$$c_a = p^{1.55} (0.0032(TN:TP) + 0.052)^{1.55} \tag{58}$$

where:

c_a = biomass concentration in water (mg m^{-3})
p = soluble phosphorus concentration in water (mg m^{-3})
TN:TP = total nitrogen to phosphorus ratio.

The organic phosphorus fraction under nitrogen-limited conditions, is finally estimated by substituting equations 55 and 58 into 54:

$$p_o = 0.67\, p^{1.55} (0.0032(TN:TP) + 0.052)^{1.55} \tag{59}$$

Both the Bartsch and Gakstatter (1978) and Smith and Shapiro (1981) approaches related total phosphorus concentrations to *chlorophyll a* concentrations, instead of soluble phosphorus concentrations. However, due to the limitations of our existing database this change was introduced. The same caveat applies for the TN:TP ratio calculation.

B1.10 PARAMETER VALUES

In order to use a budget mass-balance model to simulate the daily cycle, it is necessary to choose values for the parameters. As summarized in Table 1, these parameters have broad ranges and, therefore, calibration is necessary to obtain the appropriate estimates. Optimization techniques can be used to determine the set of parameter values that minimize the sum of the square of the residuals between the data and the model computations. Alternatively, direct measurements of processes can sometimes be used to estimate parameters. However, in the present case this is complicated by the fact that some of the terms have nebulous physical meaning. For example, since p_0 is composed of several particulate and dissolved fractions, a settling velocity to characterize the sedimentation of this pool would be difficult to measure.

For the present modeling effort, we use an approach that is intermediate between optimization and direct estimation. We used the latter approach wherever possible to estimate some of the parameters directly. Then, we can back-calculate the remaining values on the basis of a calibration to the data.

B1.11 DIRECT ESTIMATION

The two direct estimation methods that can be used for model calibration are primary production and hypolimnetic oxygen depletion.

Primary production estimates provide a measure of the uptake of soluble phosphorus as defined by the following equation (Chapra and Reckhow, 1983):

$$P_C\ A_s\ a_{pc} = k_u V\ p \tag{60}$$

where:

P_C = Primary production as organic carbon [M L^{-2} T^{-1}]
A_s = Surface area of the estuary [L^2]
a_{pc} = Ratio of phosphorus to carbon in organic matter
k_u = Uptake constant [T^{-1}]
V = Volume of the estuary [L^3]
p = Soluble phosphorus concentration in the estuary [M L^{-3}].

Equation 60 can be solved for k_u:

$$k_u = \frac{P_C\ A_s\ a_{pc}}{V\ p} \qquad (61).$$

Several transformations and estimations which contain data on primary production expressed as an organic carbon daily rate were applied. First of all, the primary production was expressed in terms of organic phosphorus instead of organic carbon:

$$P_P = P_C\ a_{pc} \tag{62}$$

where:

P_P = Primary production as organic phosphorus [M L^{-2} T^{-1}].

As a result, equation 61 converts into:

$$k_u = \frac{P_P\ A_s}{V\ p} \qquad (63).$$

Then, P_P was estimated through the amount of organic phosphorus per unit area in the estuary. Assuming that all the present phosphorus has been produced during the day (the latter assumption has to be considered when it comes to the consistency of the units):

$$p_P = \frac{p_o V}{A_s} \qquad (64)$$

Finally, equation 64 is substituted into equation 63 leading to the following expression for the uptake constant estimate:

$$k_u = \frac{p_o}{p} \qquad (65)$$

As mentioned, our database did not contain measurements of organic phosphorus. This is the reason why p_o was again estimated using the Bartsch and Gakstatter (1978) and Smith and Shapiro (1981) adapted approaches.

Two uptake constants were estimated: one for the wet season and one for the dry season. These values will be discussed in the future, when the final validation of the model takes place.

In a similar fashion, the oxygen depletion rate provides an estimate of the hypolimnetic remineralization rate in lakes, both in summer and winter season. Besides, since whole-lake conditions in winter are similar this value is assumed to apply to release in both surface and bottom layers during the winter (Chapra and Reckhow, 1983). Due to the highly dynamic conditions that prevail in the modeled system we considered it to be completely mixed during the whole year. Therefore, we used this approach only to estimate the remineralization rate constant during the wet season (equivalent to winter) at Malibu lagoon.

The oxygen depletion rate due to oxidation is related to the release rate by:

$$\mathbf{OD\ V\ a_{po} = k_r V\ p_o} \qquad (66)$$

where:

OD = Oxygen depletion rate $[M\ L^{-3}\ T^{-1}]$
V = Volume of the estuary $[L^3]$
a_{po} = Ratio of phosphorus to oxygen in oxidation process
k_r = Release constant $[T^{-1}]$
p_o = Organic phosphorus concentration in the estuary $[M\ L^{-3}]$

Equation 66 can be solved for k_r:

$$\mathbf{k_r = \frac{OD\ a_{po}}{p_o}} \qquad (67)$$

The ratio of phosphorus to oxygen (mgP gO_2^{-1}) can be estimated on the basis of the general equation for the oxidation of organic matter (Stumm and Morgan 1981):

$$C_{106}H_{263}O_{110}N_{16}P + 138\ O_2 \qquad (68)$$

Based on equation 68, a_{po} can be estimated as:

$$a_{po} = \frac{1(31)gP}{138(32)gO}\frac{10^3\ mgP}{gP} = 7.0\frac{mgP}{gO} \qquad (69).$$

In order to estimate the oxygen depletion rate, we adapted a method suggested by Chapra and Canale (1991). They found out a direct correlation between the areal hypolimnetic oxygen demand with total phosphorus concentration in the system:

$$AOD = 0.043(p + p_o)^{0.478} \qquad (70)$$

where:

AOD = Areal oxygen depletion rate ($gO_2\ m^{-2}\ d^{-1}$)
p = Soluble phosphorus concentration in the estuary ($mg\ m^{-3}$)
p_o = Organic phosphorus concentration in the estuary ($mg\ m^{-3}$).

The areal oxygen depletion rate is transformed into the oxygen depletion rate by:

$$OD = \frac{AOD\ A_s}{V} \qquad (71)$$

Substituting equations 71 and 72 into 67, the following relationship is established:

$$k_r = 0.043(p + p_o)^{0.478}\frac{A_s\ a_{po}}{V\ p_o} \qquad (72)$$

Using equation 72, a value for the winter release constant was calculated.

Finally, the settling velocities for nitrogen and phosphorus were estimated. In contrast to the case of the uptake and release constants, the settling velocities for nitrogen and phosphorus were not theoretically related in the construction of the model. Nevertheless, in a first attempt the estimated settling velocity, nitrogen was considered to be equal to the estimated settling velocity for phosphorus.

Data analysis by a number of individuals (Chapra 1975, Dillon and Rigler 1975, Thomann and Mueller 1987) determined that the settling velocity most commonly takes on values in the range from about 5 to 20 m yr^{-1}. However, values have been reported from less than 1 to over 200 m yr^{-1} (Chapra, 1997).

Chapra (1975) demonstrated that for simple phosphorus mass-balance models for a well-mixed system considering loading, flushing and settling as ongoig processes, the settling velocity can be estimated by:

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$$v_s = \frac{Q}{A_s} \sqrt{R_t} \qquad (73)$$

total water flow into the system ($m^3\ d^{-1}$)
surface area of the estuary (m^2)
residence time (yr)

ce time estimated by:

$$R_t = \frac{V}{365\ Q} \qquad (74)$$

ituted equation 74 into equation 73 to obtain:

$$v_s = 0.052 \frac{(Q\ V)^{1/2}}{A_s} \qquad (75)$$

t weather season settling velocities were estimated. The values of these e discussed during the final validation.

JSION

model was developed to predict nutrient loading into a Mediterranean- a seasonal sand-barrier and distinct wet and dry weather condition such 1. An initial steady state solution was calculated. However, steady state t be applicable to the conditions of Malibu Lagoon. Therefore, a time was calculated that accounts for most of the major variables affecting ng into the lagoon. While the general development of the model is for a the sandbarrier is closed, modification was made of the equations to oading even in open sandbarrier conditions. The model was calibrated ironmental values found in literature. A sensitivity analysis procedure Tidal values were estimated. While the model performs its intended o be validated using field collected values in the Malibu Lagoon and . The accompanying paper provides the results of the validation

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Table 1. Typical Ranges of Parameters for Modeling Phosphorus in lakes. Values are taken primarily from Imboden (1974) and Snodgrass (1974)

Parameter	Season	Symbol	Range	Units
Uptake rate	Summer	k_u	0.1-5.0	d^{-1}
	Winter		0.01-0.5	d^{-1}
Release rate	Summer	k_r	0.01-0.1	d^{-1}
	Winter		0.003-0.07	d^{-1}
Settling velocity	Annual	v_s	0.05-0.6	$m\ d^{-1}$

Figure 1. Phosphorus Mass Balance Model for Malibu Lagoon

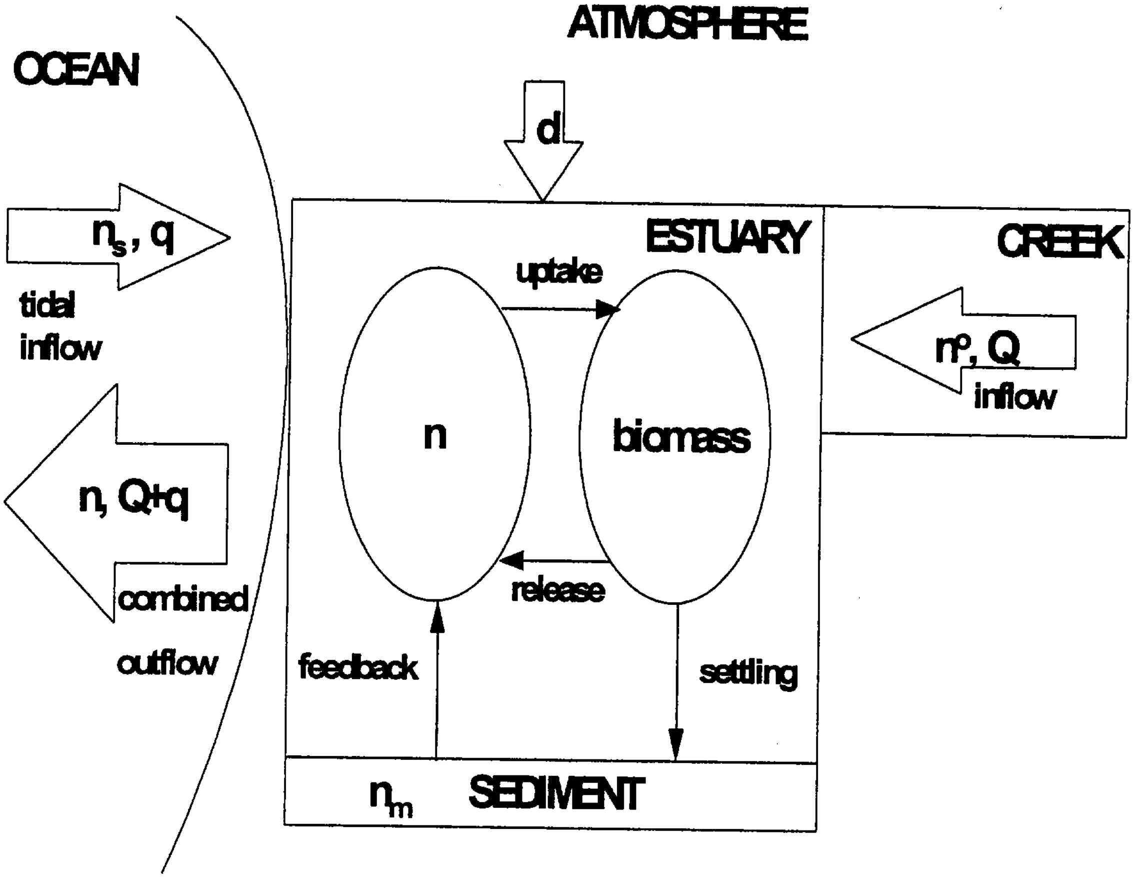
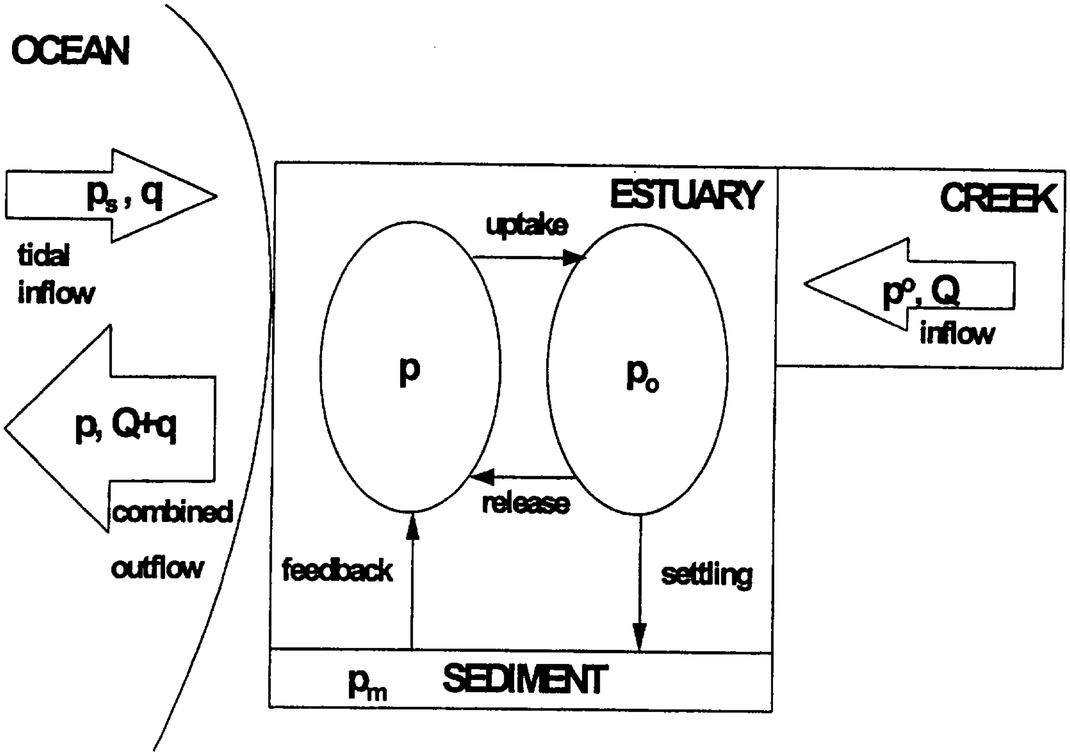


Figure 2. Nitrogen Mass Balance Model for Malibu Lagoon.



APPENDIX B2: MALIBU EUTROPHICATION (MEM) MODEL VALIDATION

By Cris B. Liban[1], Shelby Sheehan[2], and Irwin H. (Mel) Suffet[3]

ABSTRACT: The Malibu Eutrophication Model (MEM) was developed based on the principles presented in the preceding paper. A model validation study was conducted to determine the model's applicability to the Malibu Creek and Lagoon. Locations selected correspond to those where actual field measurements were taken. Loading predictions using the model for each nutrient were compared to those loading values calculated based on field data. The values predicted by the MEM as well as the field values in each source and sink category were consistent with one another. This reflects the effectiveness of the model in predicting which of the lagoon nutrient sources and sinks have a more significant impact during the dry or wet season.

B2.1. INTRODUCTION

The Malibu Eutrophication Model (MEM) was developed as described in Appendix B1. The model was adjusted based on the existing information for the components of the Malibu watershed. The data were either estimated or literature value obtained where information were not available. The principal model equations and the mass balance relationship diagrams were also presented in Appendix B1 (Moragrega et al., 1999). The model was written as a spreadsheet in Excel 97 format. A number of the cell parameters may have to be manually changed to run the model.

This appendix is divided into several parts. Section 1 presents the constraints of the MEM inputs. These inputs were defined according to geographic groupings and is consistent with those presented in Chapter 5 of this report. Section 2 presents the resulting sensitivity analysis after all constraints have been entered. Section 3 provides information on the time variable solution of the model on an annual basis. This section also provides information on various sources and sinks and their relative magnitudes. Seasonal output tables are also shown in this section. Section 4 provides the comparison of field measured values to model predicted values. Section 5 presents the value of this model in providing a realistic mass balance picture at the Malibu Lagoon. The section ends by defining the limitations of the model and potential future work.

B2.2. MODEL INPUTS

Inputs to the MEM were categorized based on the potential for their individual nutrient contribution to the eutrophication of the Malibu Lagoon. These categories include creek

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Key Words: eutrophication, Malibu, modeling, nutrients, estuary nutrient loading

inflow, north of Pacific Coast Highway commercial, south of Pacific Coast Highway commercial, stormdrains and runoff, tidal inflow, atmospheric deposition, and sediment feedback and release. Outputs were selected based on categories that would likely be sinks in the system. These include oceanic washoff, nutrient settling, and sediment uptake.

Selected dates reflect those days when actual Malibu Creek monitoring data were available. The time variable solution allows the prediction of concentration based on an initial condition (i.e., January 7 1997). The model adjusts itself to reflect the monitoring data for a subsequent date.

For ease of calculation, initial assumptions also included the closure of the sand barrier at the "dry season" dates and its opening during the "wet season" dates. Dry season has been defined to begin on 1 May 1997 and ends on 31 October 1997. The MEM adjusts the closing and opening of the sand-barrier during the calculation of the time-variable solution. Thus, while the input value may show that the sand-barrier may be closed during the dry season, because of the variables defined in the model, it may be expected that the sand-barrier may naturally open up at certain dates beyond that date.

B2.2.1 CREEK INFLOW

Creek Inflow is that component of the MEM input that incorporates any upstream source. These would include those beyond the Las Virgines Municipal Water District (LVMWD) Gauging Station 11105500 at Cold Creek Creek and Piuma Roads. For the purposes of this model, the individual contributions of each of the sub-components of this category were not distinguished. However, the sub-components could include Tapia discharges, upstream septics, and upstream run-on and run-off described in the previous chapter. Monitoring data for both streamflow (in cubic meters per day [m^3/d]) and nutrients (mg per cubic meter [(mg/m^3)]) were obtained directly from the records of the LVMWD. The inputs are shown in Table 1.

B2.2.2 NORTH OF PACIFIC COAST HIGHWAY COMMERCIAL

This category includes the septic nutrient loading contributions from the Civic Center, Country Mart, Cross Creek Plaza, and Malibu Colony Plaza. The flow values obtained for each component of this category were adopted from the flow information supplied in the main report. These are daily flow values assumed to be constant regardless of season. The flows were further adjusted based on the transport fraction (*tf*) value associated with each category component. A transport fraction is the ratio of the amount of water that would be transported from the source to the lagoon based on the type of subsurface lithology. The Civic Center has a *tf* of 0.5; Country Mart has a *tf* of 1; Cross Creek Plaza *tf* is 1; and Malibu Colony Plaza *tf* is 0.1.

Nutrient concentrations used were obtained from literature. Nitrogen concentration used was 45 mgN/L. This concentration was converted to milligram per cubic meters to conform with the units requirements of the model. A conversion factor equal to 0.045 was applied to the nitrogen concentration value to reflect the leaching fraction, transport fraction, and tank removal fraction components. The nature of these fractions is explained in the main report.

Phosphorus is not considered mobile in the subsurface. Any phosphorus input in the system will remain sorbed to soil particles. Thus, a phosphorus concentration of 0 mgP/L was used.

B2.2.3 SOUTH OF PACIFIC COAST HIGHWAY COMMERCIAL

The south of Pacific Coast Highway commercial category includes loading from the Malibu Golf Course and the Malibu homes. These components are located south of the Pacific Coast Highway and west of the Malibu Creek and Lagoon. Approximately 85,000 gallons per day (328 m^3/d) are used to maintain the golf course in the dry season. An estimate of approximately 6,000 gallons per day (28 m^3/d) of water are used during the wet season. Approximately 0.5 mgN/L fertilizer content was estimated to be used for the golf course. There is no phosphorus data used for the golf course.

Private homes located in the Malibu Colony were delineated as a separate source category. Daily flowrate into the lagoon was estimated to be approximately 1,400 gallons per day (5.3 m^3/d). This value was based on 3.7 persons living in a typical home for an average of 30 homes potentially contributing to lagoon nutrient loading, and approximately 50 gallons per day (0.2 m^3/d) per person. The flowrate from this source was further adjusted by multiplying the value by a factor of 0.25. The factor reflects a 0.5 leaching fraction as well as a 0.5 transport fraction. The concentration of nutrients used in septic effluent was 45 mgN/L. Phosphorus concentration used was 0 mg/L.

B2.2.4 STORMDRAINS AND RUNOFF

Stormdrains and runoff include those sources associated with the Malibu Colony Plaza and Cross Creek Plaza Stormdrains. Washwater (runoff) flowrate reflects the dry weather flow value. The estimated washwater flowrate was calculated as approximately 2,100 gallons per day (8 m^3/d). Wet season flowrate from this source category was estimated to be 1.4 million gallons per day (5,525 m^3/d). For the dry weather flow, nitrogen concentration was estimated to be 16.06 mgN/L while phosphorus concentration was approximately 0.36 mgP/L. Wet season nitrogen concentration was approximately 2.2 mgN/L while phosphorus concentration was 0.12 mgP/L.

B2.2.5 TIDAL INFLOW

Tidal inflow flowrate is a function of the overall flowrate from all sources and the tidal cycling explained in Appendix B1. The nutrient loading is also a function of the season. Measured nutrient concentration is 1.0 mg/L for nitrogen and non-detect (0.2 mg/L) for phosphorus. It is assumed that 25% of these concentrations do not contribute to nutrient loading during the wet season.

B2.2.6 ATMOSPHERIC DEPOSITION AND SEDIMENT FEEDBACK AND RELEASE

Standard published parameters have been provided to account for the contribution of atmospheric deposition and sediment feedback and release. Seasonal and temporal adjustments were performed on these parameters. Tidal inflow and outflow adjustments were also performed based on the sandbarrier closure conditions.

B2.3 SENSITIVITY ANALYSIS

A sensitivity analysis was performed on the parameters defined for the MEM. The overall flowrate, Q, is a very sensitive component of the system in influencing the loading contributions into the Malibu Lagoon. Overall flowrate includes the flowrate from the major input categories that include the Malibu Creek, the north PCH commercial, the south PCH commercial, and stormwater and runoff. This variable produces an uncertainty of approximately 120% for both nitrogen and phosphorus concentrations in open conditions. It produces an uncertainty of approximately 180% for both nitrogen and phosphorus concentrations in closed conditions. Other model parameters are relatively insensitive in either open or closed conditions. As such, varying the other parameters would not significantly alter model predictions as altering flowrates. Thus, it is very important that proper flowrates be carefully determined prior to running the model.

B2.4 TIME VARIABLE SOLUTION

A time variable solution for each nutrient provides a better illustration of determining the contributions of every defined parameter in Section B2.2. This section provides the results of the source and sink contribution per nutrient on an annual basis. Each of the sources and sinks are then divided into seasons. An average is taken of each source per season. The ratio of the averages (dry/wet) is then computed to get the relative importance of each component per season.

B2.4.1 ANNUAL COMPARISON

Results of the modeling show that the Malibu Creek is the most significant source of nitrogen and phosphorus loading into the Malibu Lagoon. This is an expected result. However, it should also be noted that sediments play a major role in nutrient loading. Collectively, sediments are responsible to approximately contribute 17% of the total nitrogen and 19% of the total phosphorus going into the lagoon. Between the processes associated with sediments, sediment feedback has a greater impact than sediment release. Sediment feedback is that process where the nutrients are released from the solid phase into the liquid phase resulting from disequilibrium of the system. The ocean is another significant source of nutrients but is of lesser importance than Malibu Creek and the sediment processes. The model predicts that the other potential sources of nutrients are insignificant compared to these major sources.

On an annual basis, the MEM predicts that much of the nutrients would be washed off into the ocean. The amount of nutrients washed-off is almost two times as much as the amounts settling in the creek or is taken up by sediment. A summary of the MEM predictions for both nitrogen and phosphorus are shown in Tables 2 and 3. Figures 1 and 2 and 3 and 4 show the annual loading and sink distribution per source for nitrogen and phosphorus, respectively.

B2.4.2 SEASONAL COMPARISON

Tables 4 and 5 present the comparative nutrient loading for each nutrient of each source per season. A comparison of the different system sources and sinks is also shown. These values are illustrated in Figures 5 and 6 (dry season) and 7 and 8 (wet season) for nitrogen; and 9 and 10 (dry season) and 11 and 12 (wet season) for phosphorus.

A different picture emerges when a seasonal comparison is performed to determine loading contributions of the different sources into the lagoon. Malibu Creek is a major source of nutrients to the lagoon during the wet season. It contributes almost four times as much nitrogen and phosphorus as the total of the other sources during the wet season.

During the dry season, however, nutrients released to the lagoon through sediment processes become dominant. Sediment feedback contributes almost twice as much nitrogen and almost as much phosphorus as those coming from the creek. It also contributes twice as much nitrogen and almost three times as much phosphorus as those coming from direct sediment release.

The MEM predicts the ocean to be a more significant nutrient source in the wet season than in the dry season. The prediction is consistent with the idea that nutrients going into the lagoon from the ocean resulting from tidal influx would be minimized as a consequence of the closed sand barrier.

Equally compelling is the prediction that the commercial sources are insignificant nutrient contributors regardless of the season. As expected, stormdrain and runoff are only significant during the wet season. Finally, atmospheric deposition is not expected to be major nitrogen source.

A large amount of sediment is washed-off into the ocean during the wet season. However, among those categories of nutrients that serve as sinks of the lagoon, it is evident that a significant amount of nutrients remain in the system through sediment uptake. Nutrients that do not wash off into the ocean could potentially replenish the nutrient loading into the lagoon during the dry season.

Sediment uptake is a more significant nutrient sink during the dry season than nutrient settling. This process is a more pronounced process for phosphorus than for nitrogen. Oceanic washoff, which is a function of an open lagoon is insignificant during the dry season.

B2.4.3 RATIO COMPARISON

A ratio of the average loading in the dry season versus the wet season was calculated to determine the relative importance of each source or sink to nutrient loading into the lagoon. An average greater than 1.0 means that the component is a more important nutrient loading factor in the dry season than in the wet season. The closer the value is to zero, the greater is its importance in lagoon nutrient loading contribution during the wet season than in the dry season.

As shown in Tables 6 and 7, sediment feedback and sediment release are more important sources during the dry season than in the wet season. Between the two, sediment release is of greater importance. Creek inflow is a more significant source of nutrients into the lagoon during the wet season than in the dry season. As expected, ocean tidal flows are most significant during the wet season for nitrogen. For phosphorus, stormdrains and runoff are more significant sources during the dry season. Sources north of PCH are equally important sources of nitrogen for both the dry and wet seasons. Sources south of PCH are more important during the wet season for nitrogen. Atmospheric deposition is an insignificant source of nitrogen regardless of the season.

Based on MEM predictions, nutrient settling is a more significant nutrient sink during the dry than in the wet season. Sediment uptake is almost as significant of a nitrogen sink in the wet season as in the dry season. However, it is a more significant phosphorus sink in the dry season than in the wet.

B2.6 VALIDATION

Loading predictions for each nutrient were also compared to those loading values calculated based on field data. Where field or literature data were available, the values predicted by the MEM as well as the field values in comparable categories are consistent with one another. The predictions came up to the same order of magnitude as the field measured or literature values. Table 8 shows the model prediction compared to a number of the loading values calculated from field data. Model prediction values were converted to mass loading per year to be consistent with other units in the report. Field values for a number of these categories were not collected and thus a comparison cannot be performed.

Except for the north PCH category for nitrogen and the sediment release category for phosphorus, the magnitude of each predicted value is very close to those measured in the field. More significantly, the MEM predictions are within 5 percent of the actual field values for the Creek. These results reflect the effectiveness of the model in predicting which of the variables have a more significant impact during the dry or wet season.

A limitation must be mentioned. The model predicts that sediment feedback is the dominant source of nitrogen during the dry season. However, this is not consistent with physical observations. Nitrogen does not physically adsorb onto particles and remains soluble throughout its fate in the environment. Thus, the preceding conclusion regarding sediment feedback as a dominant source is flawed. A model adjustment procedure is necessary to correct this condition. This limitation does not reduce the validity of the predictions regarding relative loading of each categorical source.

B2.7 MODEL VALUE AND LIMITATIONS

The MEM was developed to primarily serve as a predictive tool in determining nutrient loading of variable sources into Malibu Lagoon. As shown, the model predictions would be in the same magnitude as those observed in reality. This is a significant progress in providing tools for the better management of eutrophication issues at Malibu Lagoon. There is no precedent to the progress achieved to date.

While the model is a sufficient predictive tool, several limitations must also be mentioned. The model sources classification is broad. It does not narrow its focus to particular sources that could be controlled in any future eutrophication management. Further development of the model could be performed to disaggregate these classifications into more specific components.

A number of the parameters are based on literature default values. While the developers of the model have taken sufficient precaution in selecting only those numbers that closely mimic the site-specific conditions at Malibu, a field program to collect those same parameters would produce more accurate results than those shown here. As mentioned previously, a model adjustment procedure is also necessary.

In its current state, the MEM is not user friendly and providing inputs and changing parameters may be cumbersome to a number of users. Thus, a future version of the MEM may involve programming commands that will automate a number of the input processes. Recognition of its limitations and sole use in predicting eutrophication conditions at Malibu Lagoon is warranted.

B2.8 REFERENCE

Moragrega, J., C.B. Liban, I.H. Suffet, and R. Ambrose, (In Preparation). Development of a Mass Balance Model to Determine Nutrient Loading Into A Small Mediterranean-Type Estuary with Seasonal Sand-Barrier: Case Study - Malibu Lagoon, CA, USA.

Table 1. Creek Input Parameters and Values

Dates Collected	Flowrate (m^3d^{-1})	N (mg/m^3)	P (mg/m^3)
01/07/97	190,580	3710	450
02/03/97	415,900	3210	550
03/11/97	109,602	5630	1000
04/01/97	68,257	3520	900
05/13/97	42,569	3380	850
06/03/97	25,198	720	610
07/01/97	15,707	110	550
08/05/97	10,422	720	250
10/07/97	9,810	1400	500
11/10/97	35,474	4630	600
12/01/97	106,911	2720	180

Table 2. Time Variable Solution - Nitrogen

Sources/Sinks	Average Annual Value (kg/day)	Percentage (%)
Source		
Ocean and Tidal Flow	33	8
Creek Inflow	322	73
N. of PCH Commercial	<1	<1
S. of PCH Commercial	2	<1
Stormdrain/Runoff	7	2
Sediment Feedback	55	13
Sediment Release	19	4
Atmospheric Deposition	<1	<1
Sinks		
Oceanic Washoff	334	68
Settling	29	6
Sediment Uptake	125	26

* Percentages may exceed 100 due to rounding off errors.

Table 3. Time Variable Solution – Phosphorus

Sources/Sinks	Average Annual Value (kg/day)	Percentage (%)*
Source		
Ocean and Tidal Flow	7	9
Creek Inflow	54	72
N. of PCH Commercial	0	0
S. of PCH Commercial	0	0
Stormdrain/Runoff	<1	<1
Sediment Feedback	11	15
Sediment Release	3	4
Sinks		
Oceanic Washoff	62	70
Settling	4	4
Sediment Uptake	23	26

* Percentages may exceed 100 due to rounding off errors.

Table 4. Time Variable Solution - Nitrogen, Per Season

Sources/Sinks	Average Value (kg/day) – Dry	Average Value (kg/day) – Wet
Source		
Ocean and Tidal Flow	<1	61
Creek Inflow	37	559
N. of PCH Commercial	1	1
S. of PCH Commercial	<1	3
Stormdrain/Runoff	<1	12
Sediment Feedback	62	49
Sediment Release	34	6
Atmospheric Deposition	<1	<1
Sinks		
Oceanic Washoff	<1	613
Settling	43	18
Sediment Uptake	76	165

Table 5. Time Variable Solution - Phosphorus

Sources/Sinks	Average Value (kg/day) – Dry	Average Value (kg/day) – Wet
Source		
Ocean and Tidal Flow	<1	12
Creek Inflow	14	88
N. of PCH Commercial	0	0
S. of PCH Commercial	0	0
Stormdrain/Runoff	<1	1
Sediment Feedback	15	9
Sediment Release	5	1
Sinks		
Oceanic Washoff	<1	115
Settling	6	2
Sediment Uptake	21	25

Table 6. Time Variable Solution - Nitrogen, Seasonal Comparison

Sources/Sinks	Ratio of Averages (Dry Average/Wet Average)
Source	
Ocean and Tidal Flow	0.016
Creek Inflow	0.066
N. of PCH Commercial	1
S. of PCH Commercial	0.33
Stormdrain/Runoff	0.083
Sediment Feedback	1.27
Sediment Release	5.67
Atmospheric Deposition	1
Sinks	
Oceanic Washoff	0.0016
Settling	2.39
Sediment Uptake	0.46

Table 7. Time Variable Solution - Phosphorus, Seasonal Comparison

	Sources/Sinks	Ratio of Averages (Dry Average/Wet Average)
Source		
	Ocean and Tidal Flow	0.083
	Creek Inflow	0.016
	N. of PCH Commercial	NA*
	S. of PCH Commercial	NA*
	Stormdrain/Runoff	1
	Sediment Feedback	1.67
	Sediment Release	5
Sinks		
	Oceanic Washoff	0.0087
	Settling	3
	Sediment Uptake	0.84

* The values for both dry and wet weather flow are "0".

Table 8. Comparison of MEM Predictions vs. Measured Nutrient Values

Sources/Sinks	Average Annual Predicted Value (kg of N)	Average Annual Measured Value (kg of N)	Average Annual Predicted Value (kg of P)	Average Annual Measured Value (kg of P)
Source				
Ocean and Tidal Flow	12,045	NM	2,555	NM
Creek Inflow	117,530	113,243	19,710	18,468
N. of PCH Commercial	<365	2,087	0	NM
S. of PCH Commercial	730	257	0	NM
Stormdrain/ Runoff	2,555	2,371	<365	129
Sediment Feedback	20,075	NM	4,015	NM
Sediment Release	6,935	NM	1,095	282
Atmospheric Deposition	<365	NM	0	NM
Sinks				
Oceanic Washoff	121,910	NM	22,630	NM
Settling	10,585	NM	1,460	NM
Sediment Uptake	45,625	NM	8,395	NM

NM = Not Field Measured

The "Average Annual Predicted Value" for both N and P were calculated by multiplying the values in Tables 2 and 3 bv 365 days, respectively.

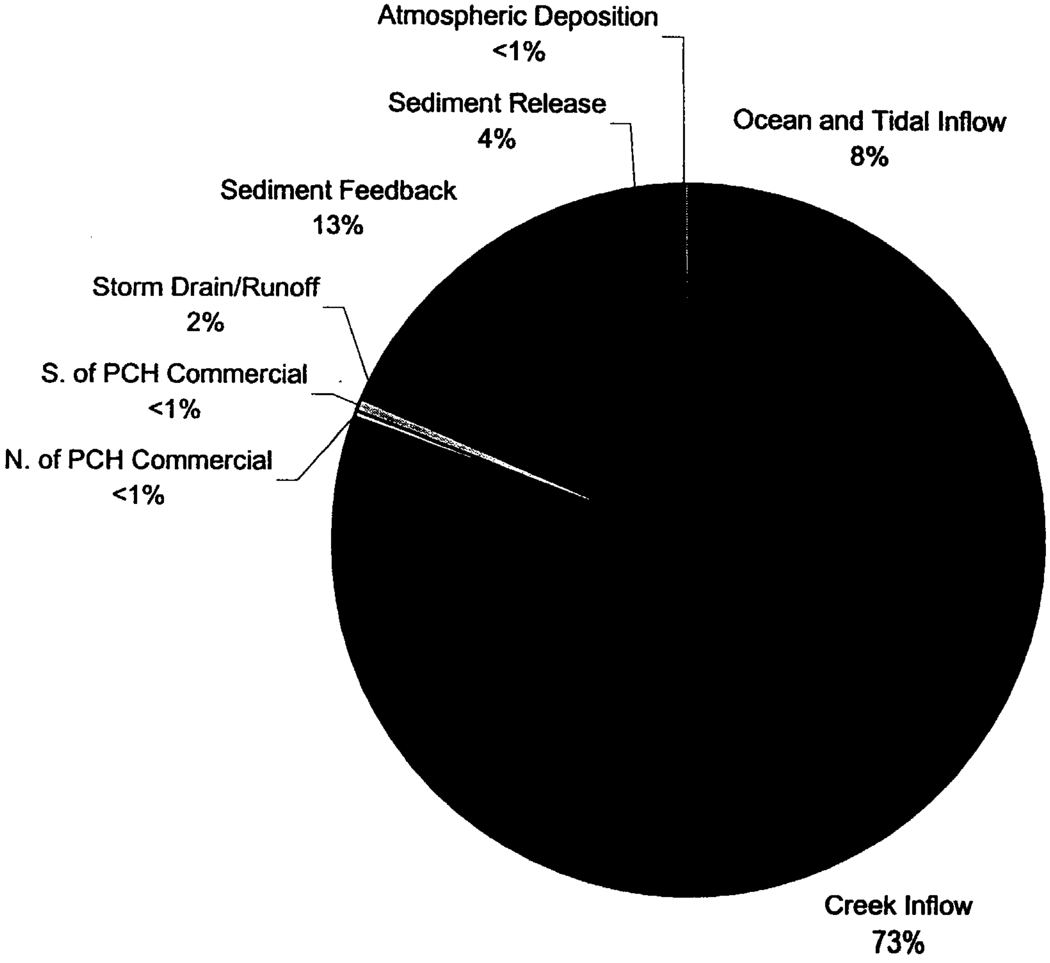


Figure 1. Annual N Loading - Sources

Figure 2. Annual N Loading - Sinks

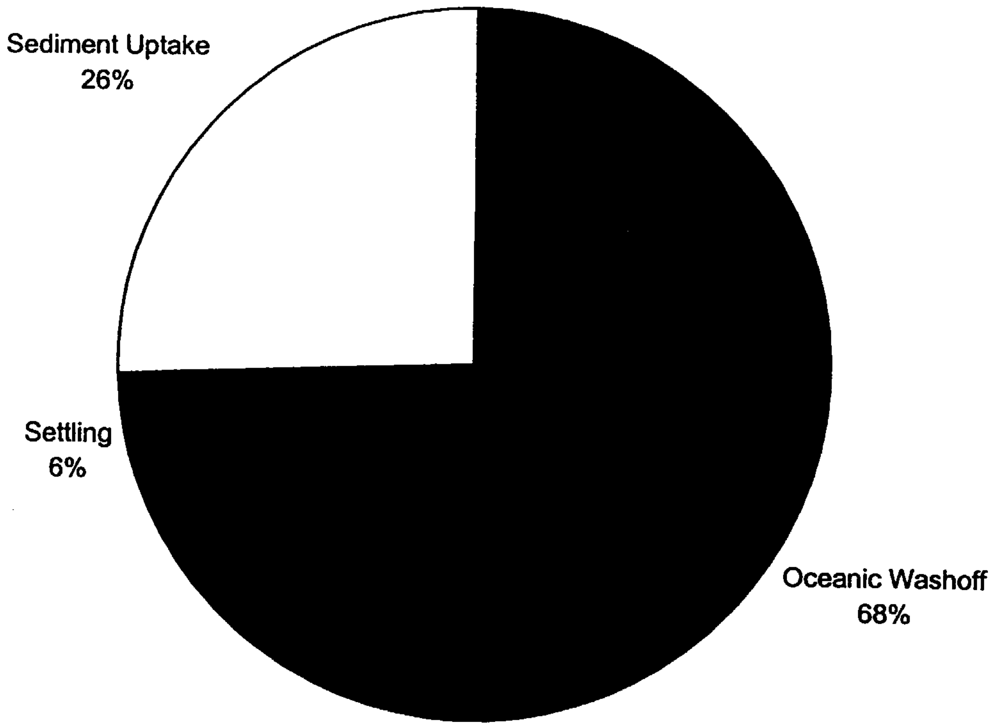


Figure 3. Annual P Loading - Sources

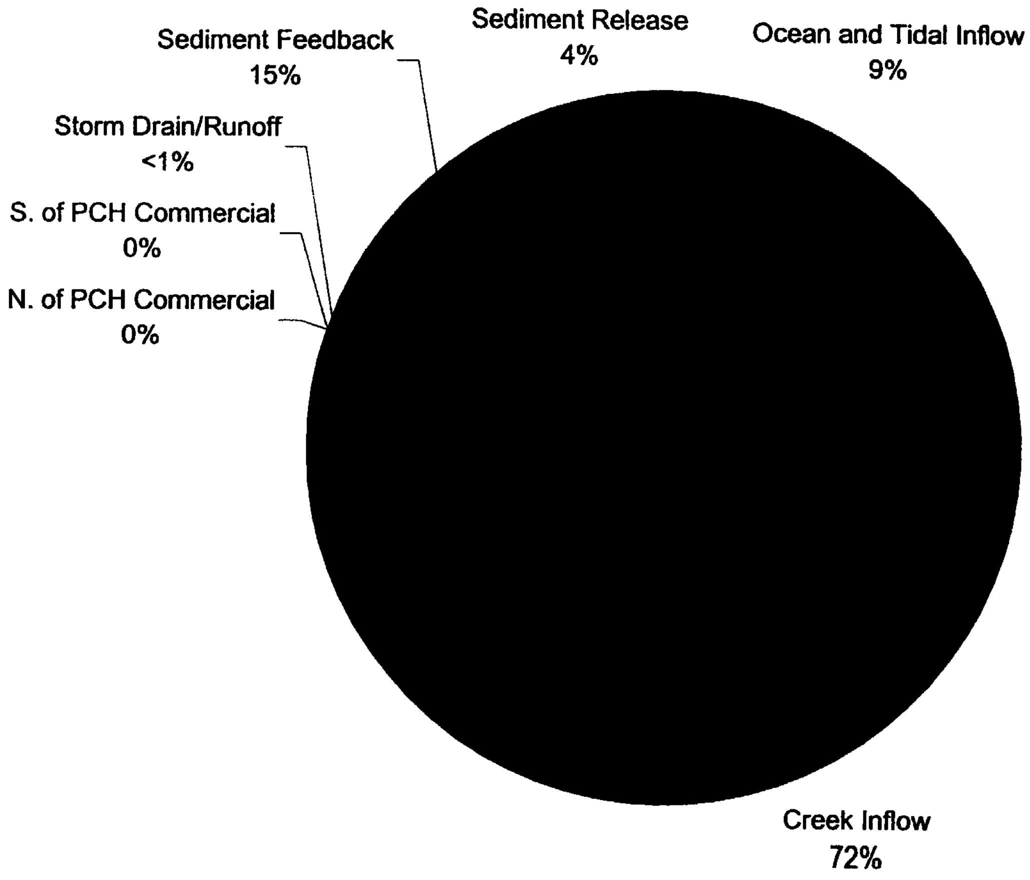


Figure 4. Annual P Loading - Sinks

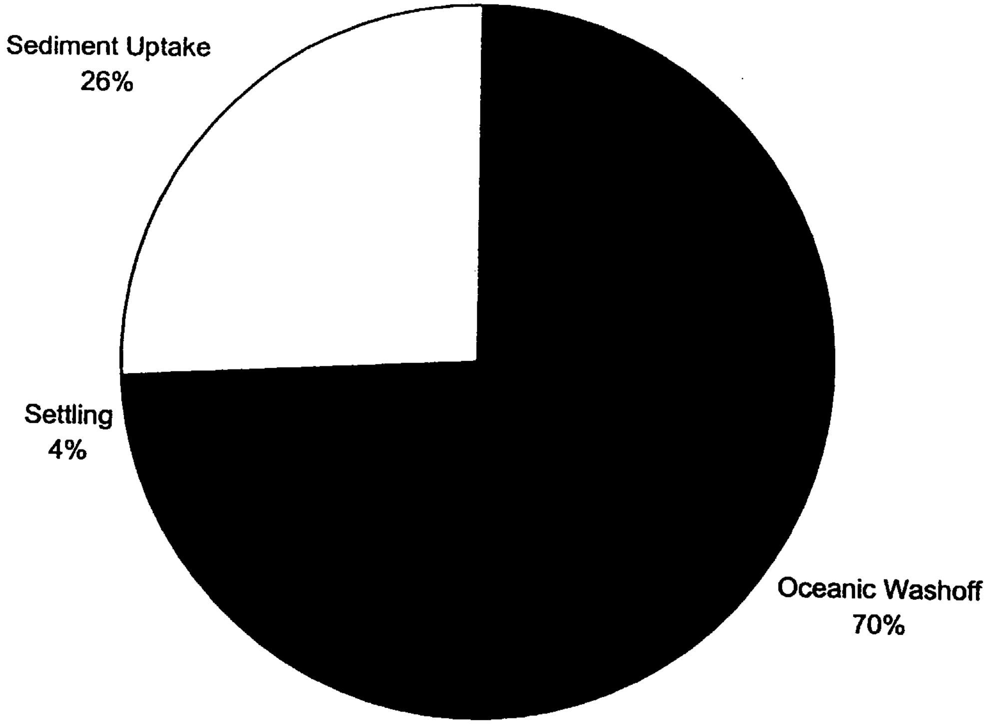


Figure 5. Seasonal N Loading - Dry, Sources

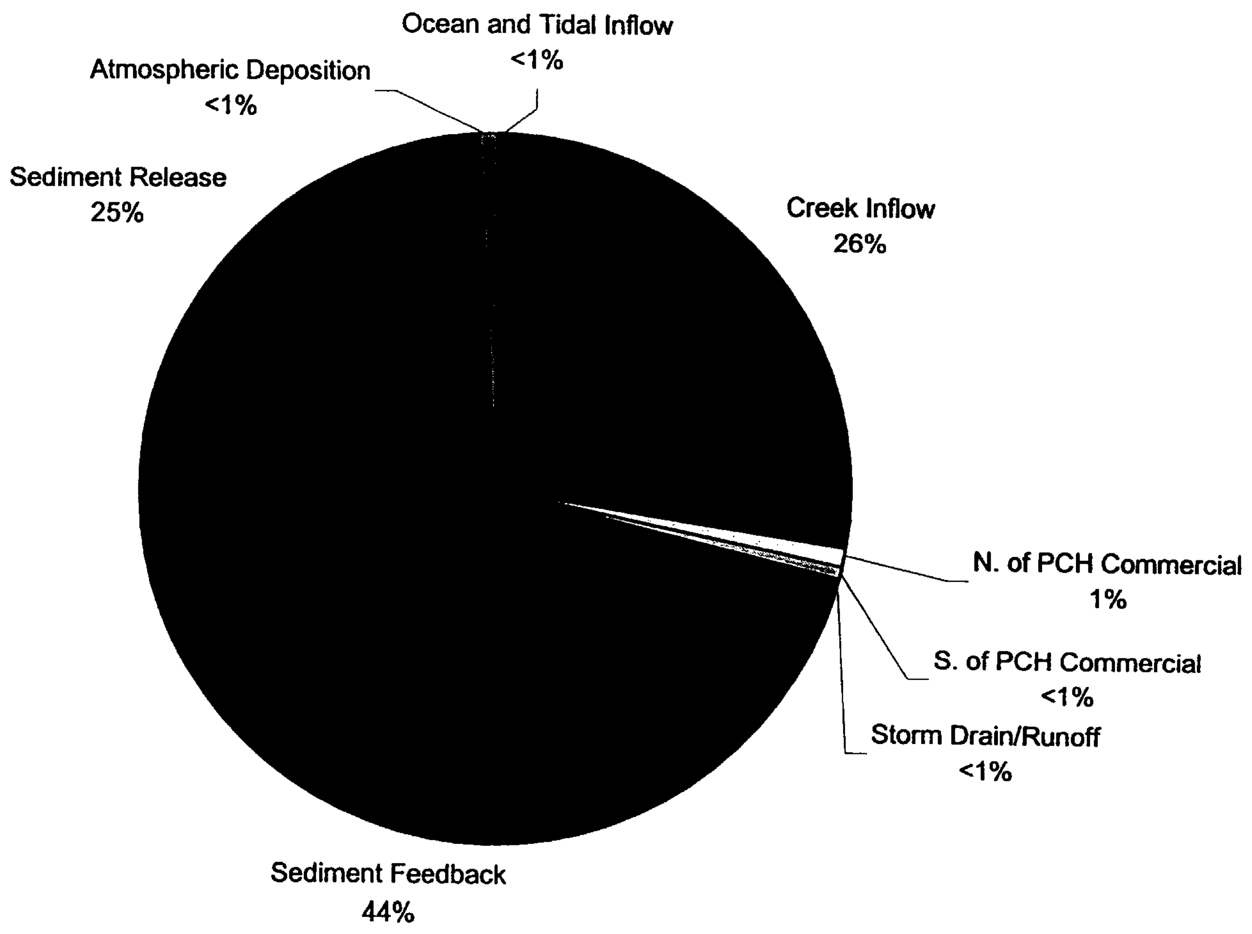


Figure 6. Seasonal N Loading - Dry, Sinks

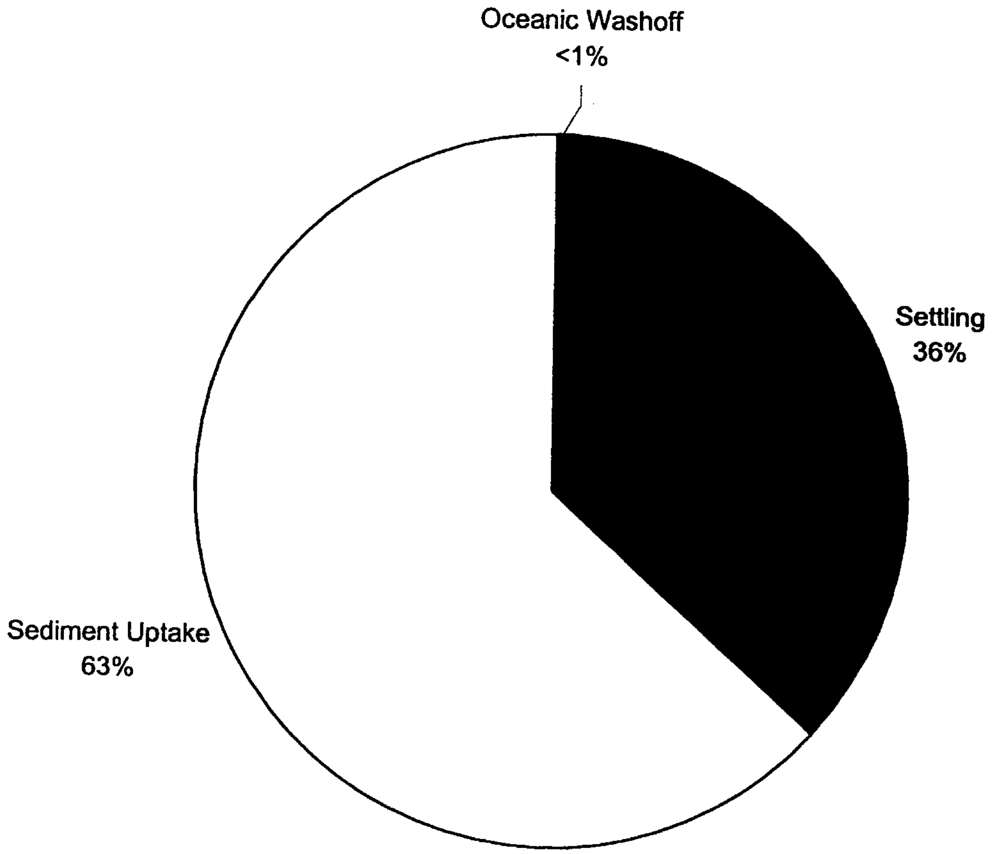


Figure 7. Seasonal N Loading - Wet, Sources

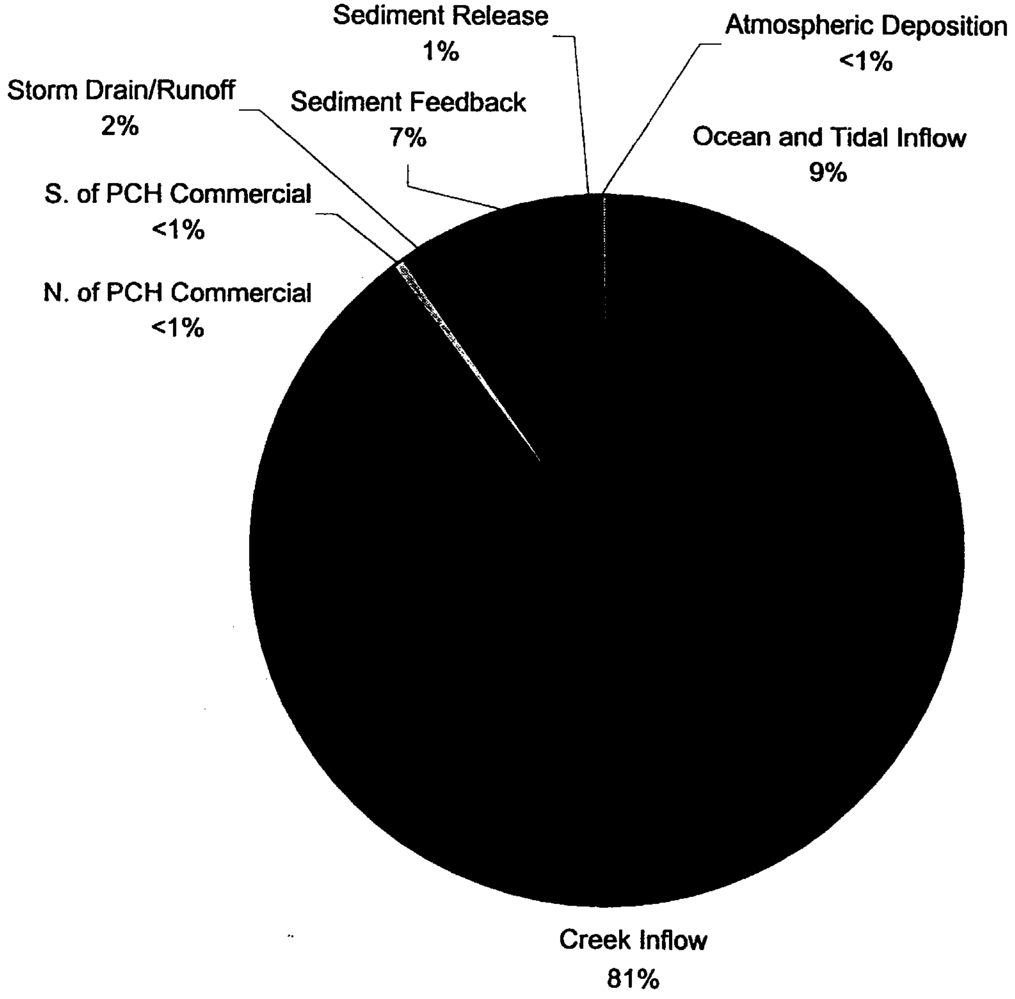


Figure 8. Seasonal N Loading Wet, Sinks

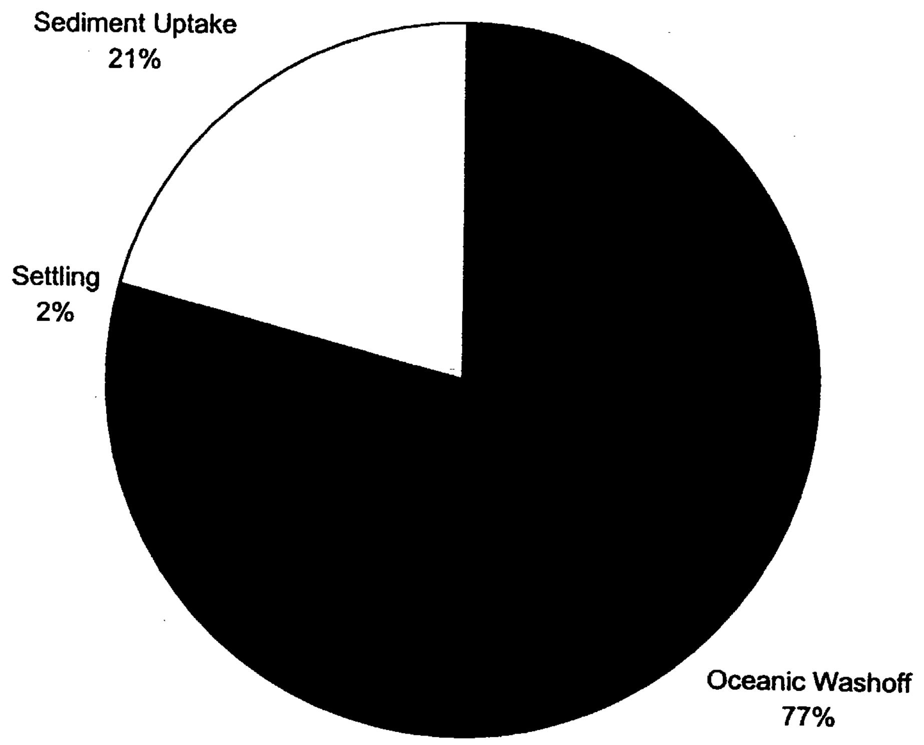


Figure 9. Seasonal P Loading, Dry, Sources

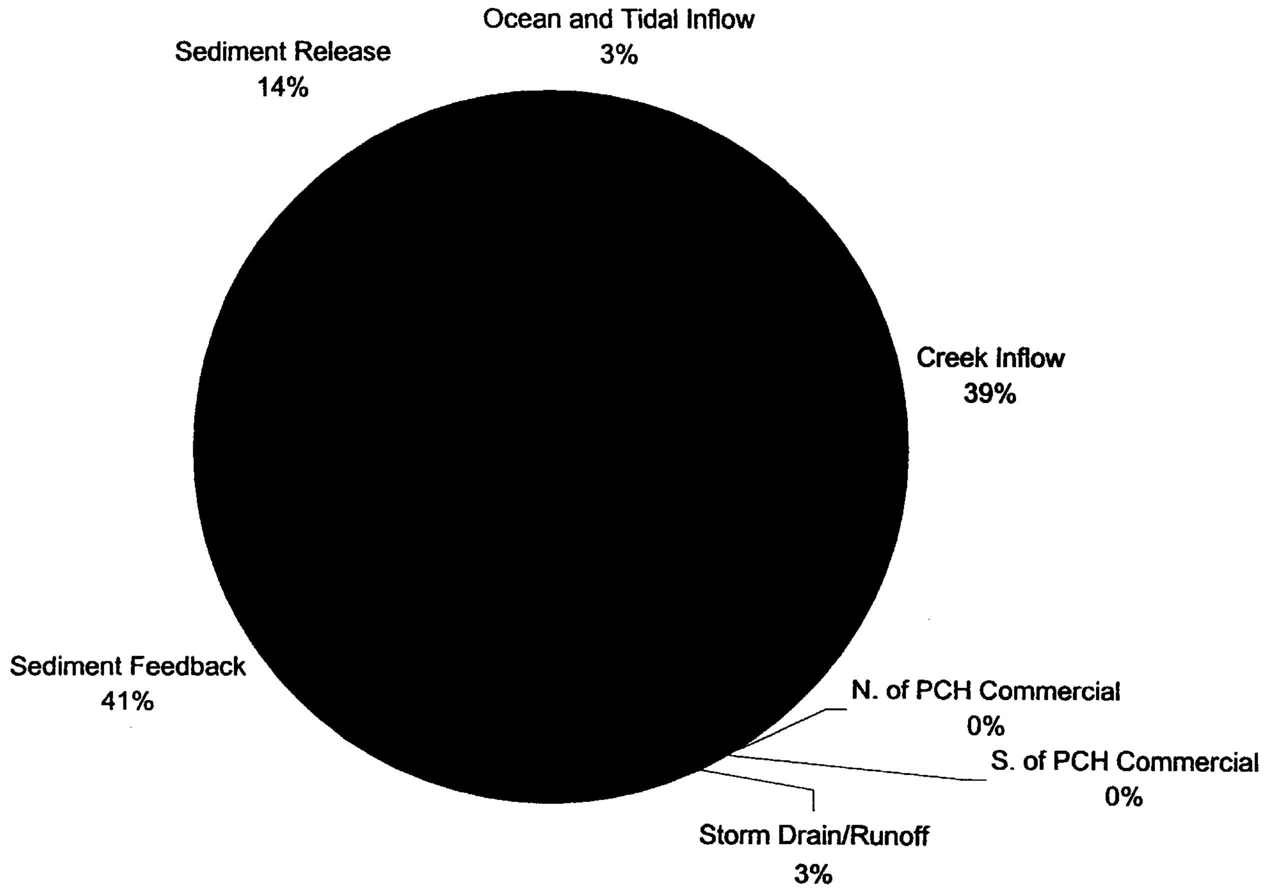


Figure 10. Seasonal P Loading - Dry, Sinks

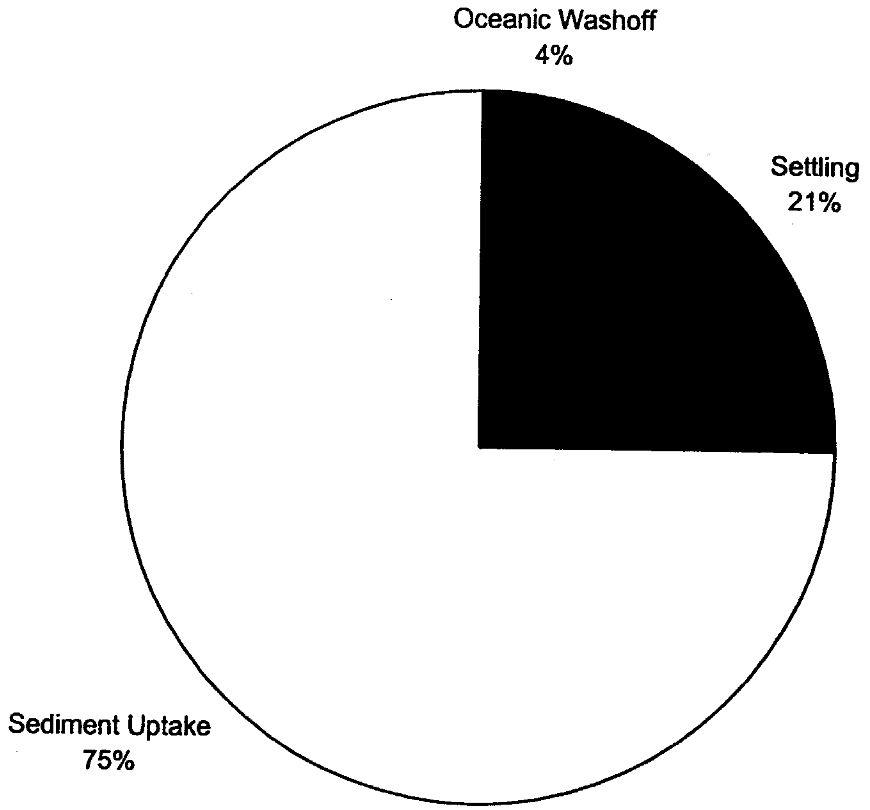


Figure 11. Seasonal P Loading - Wet, Sources

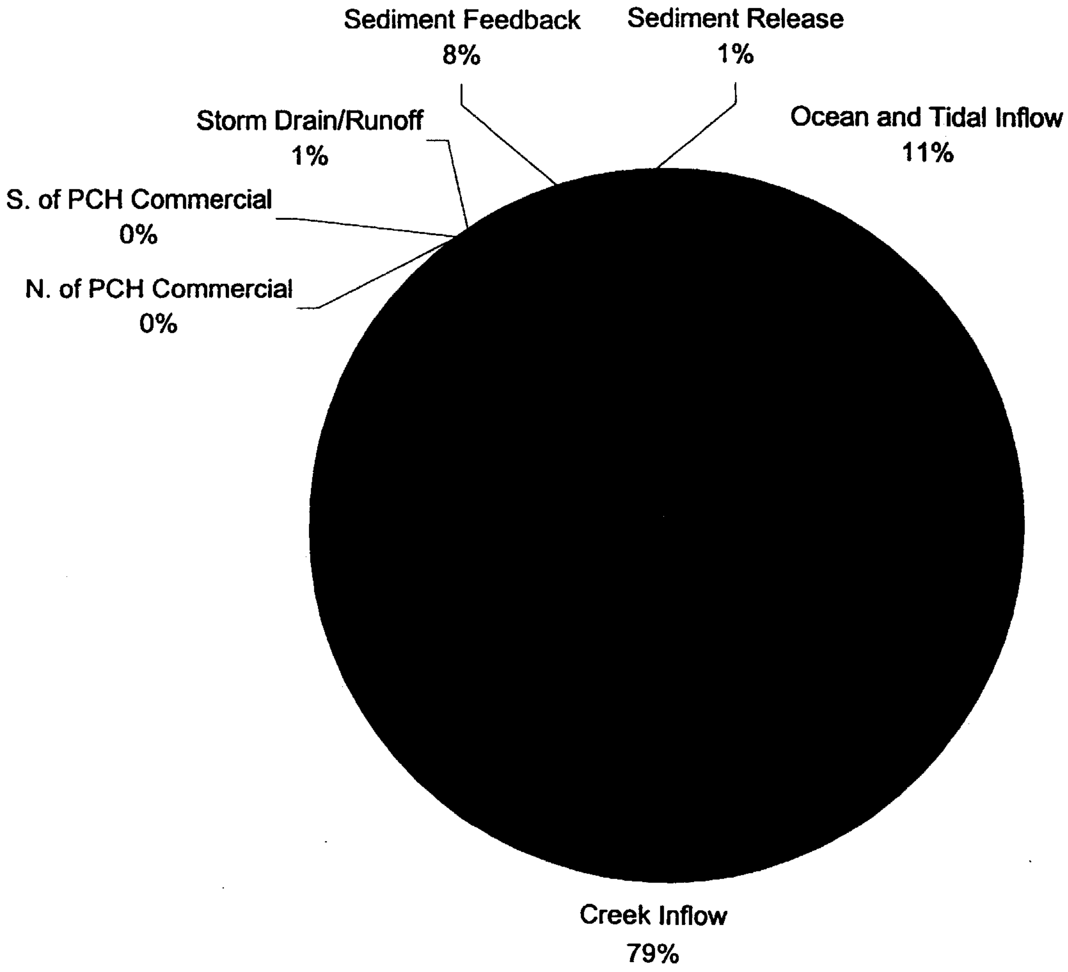
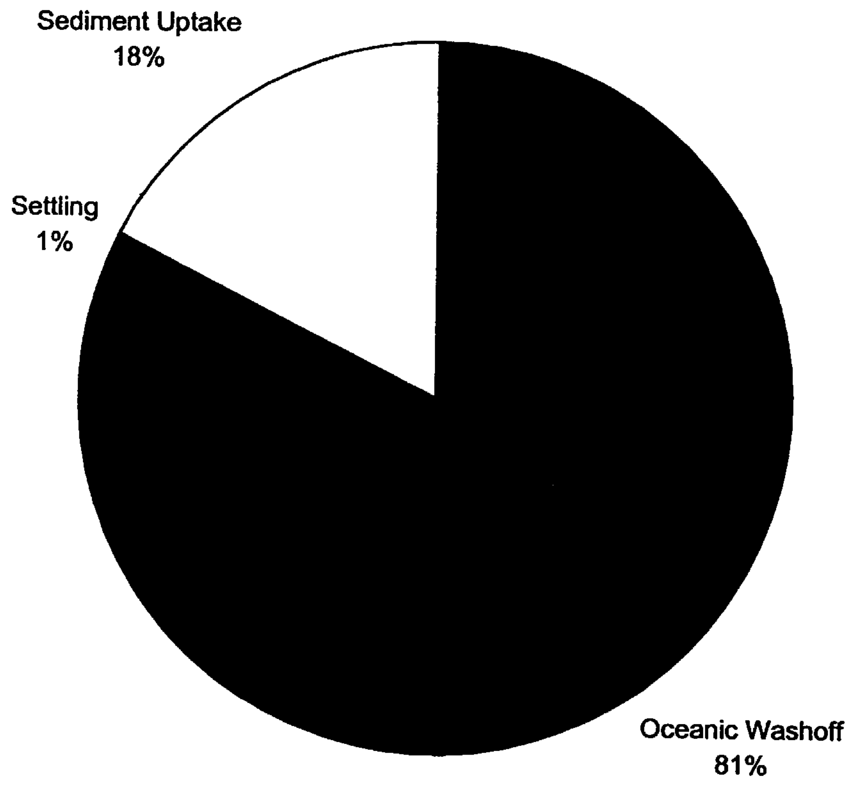


Figure 12. Seasonal P Loading - Wet, Sinks



Chapter 6: Management Pathogen Survey

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Abstract

Abstract

The purpose of this study was to assess the occurrence of pathogenic protozoan parasites and enteric viruses in Malibu Creek and the surf zone near its discharge into the ocean. Risk of infection from enteroviruses appears not to be significant in Malibu Creek and the surf zone. The Tapia plant appears to be the source of *Cryptosporidium* and increased levels of *Giardia* observed in Malibu Creek. Infectious enteroviruses were only detected in one sample-the wastewater from the discharge of the Tapia plant. These viruses were detected by the animal cell culture method where the polymerase chain reaction is used to detect viruses growing in the cell culture. *Giardia* was detected at all sample locations (before the discharge, in the discharge of the Tapia plant, in Malibu Creek below the discharge, and in the ocean surf zone) while *Cryptosporidium* was detected only below the discharge of Tapia plant. However, average concentrations of *Giardia* were greater below the discharge of the Tapia plant. Both parasites were detected in the ocean surf near the discharge of Malibu Creek. Recreational risks of *Giardia* and *Cryptosporidium* infection appear to be greater below the discharge of the Tapia plant, but are at levels which may present acceptable levels of risk. *Giardia* appears to pose the greater risk of infection to bathers because it was found in greater average concentration than *Cryptosporidium*. To better quantify the risks it is recommended that monthly sampling for the protozoa be conducted for at least a year at the same sites and that the effectiveness of disinfection against *Giardia* cysts at the Tapia plant be assessed.

6.1 Introduction

The purpose of the pathogen study was to determine the occurrence of enteric pathogens and identify potential sources in the Malibu Creek and Lagoon. To achieve this goal several sampling locations were identified to be monitored on a regular basis for enteric viruses (enteroviruses, hepatitis A, and rotavirus), *Giardia* cysts, and *Cryptosporidium* oocysts. The presence of enteric viruses was to be determined (in the concentrates of the water samples) by the use of polymerase chain reaction (PCR) which can identify the presence of viral nucleic acid, but cannot assess infectivity, we refer to this as direct PCR. If viral nucleic acid was found then conventional cell culture assays (virus detection by production of cytophathogenic affects or CPE) would be conducted to assess the presence of infectious virus. The protozoan parasites were to be detected by visualization under a ultra-violet light microscope after staining with fluorescence labeled specific (monoclonal) antibodies to aid in their detection. This standard technique does not assess viability of the parasites. No standard method is currently available to assess the viability of protozoan parasites in field samples.

There are more than 140 enteric viruses transmitted by water. Enteroviruses (polio, coxsackie, echo) cause a wide range of illnesses including meningitis, diarrhea, fever, rash, hand-foot-and-mouth disease, heart disease, etc. They usually only originate from humans and are transmitted by direct contact, aerosols, and food and water (both ingestion and bathing). They are more resistant to disinfectants than bacteria (coliforms, *Salmonella*), but can be inactivated by significant contact time with doses applied during drinking and wastewater treatment. *Giardia* and *Cryptosporidium* are protozoan parasites which cause diarrhea in both man and animals. They are one celled animals that have an environmentally resistant stage that are excreted in the feces of infected individuals. These stages are referred to as cysts in *Giardia* and oocysts in *Cryptosporidium*. Both cysts and oocysts are very resistant to in activiation (death) by disinfectants such as chlorine. Chlorination as normally practiced at drinking water and wastewater treatment plants does not kill oocysts. However, *Giardia* cysts can be killed by prolonged exposure to chlorine. Both *Giardia* and *Cryptosporidium* can be transmitted by drinking water and swimming in contaminated water (Gerba and Gerba, 1995).

Most of the samples for virus analyses proved to contain high concentrations of substances which interfered with direct PCR analyses. Several methods were evaluated to reduce this problem but all the methods resulted in substantial loss of virus during the clean-up process. Usually 99 to 99.9% of the virus were lost (using poliovirus as a model). With some samples no method proved capable of removing interfering substances. All of the samples tested by direct PCR in this study were negative. To overcome these problems it was decided to use integrated cell culture PCR (Reynolds et al., 1996). In this PCR technique is used to detect viruses growing within the cell culture. Only infectious virus are detected by this method. This method is referred of as ICC-PCR. Semi-nested PCR was used in this study since it serves as a confirmation that viral nucleic acid has been detected.

6.3 Experimental Designs

6.3.1 Collection of Samples

The general procedures used for collection of enteric viruses and protozoan parasites are described in Standard Methods for the Examination of Water and Wastewater, 19th Ed (APHA, 1995).

6.3.1.1 Enteric Viruses

Enteric viruses were collected from fresh water samples by adsorption onto 1 MDS Virozorb filters (CUNO, Meriden, CT) and from marine waters using Filterite filters (Timmorium, MD) (see Figure 6.1). Protozoan parasites are entrapped onto DPPY filters (CUNO, Meriden, CT). Water was passed through the filters with the aid of a gasoline powered pump. The system was flushed with water from the site for approximately 5 minutes and then filters were placed in the filter housing. Between samples 50 mg/liter chlorine (sodium hypochlorite) was passed through the equipment for 10 minutes. At each site measurements for pH and turbidity were obtained using procedures described in Standard Methods (APHA, 1995).

Approximately 100 gallons (378 liters) were processed at each site for enteric viruses, however the size of the sample varied from site to site depending upon the turbidity of the water at the time of collection. Samples with high turbidity tend to clog the filters faster than less turbid water reducing the sample which can be collected. Samples were shipped to the University of Arizona to be eluted and concentrated within 48 hours. Surf zone samples collected using Filterite filters were eluted in the field and brought to pH 7-7.5 by addition of 1 N HCl according to procedures described in Standard Methods (APHA, 1995).

The following is the list of the sites selected for sampling:

1) Malibu Creek before Tapia's Wastewater Treatment Plant (WWTP) (approximately 1 mile upstream from the discharge pipe)
2) Tapia's WWTP (Tertiary effluent after dechlorination and filtration before discharge)
3) Malibu Creek after Tapia's WWTP (approximately 1/2 mile downstream from discharge pipe)
4) Above Ridge Dam (approximately 3 miles downstream from discharge pipe)
5) Arizona Crossing (approximately 7 miles downstream from the discharge pipe)
6) Terminus of Malibu Lagoon (approximately 9 miles downstream from the discharge pipe and1/2 mile from beach)
7) Surf zone 100 meters down-current of lagoon breach

Because of major storm events during the winter sampling, not all locations could be sampled. Thus, not all sites were sampled with the same frequency. Mr. J. Naranjo, from the University of Arizona, collected or was present for the collection of all samples, except those in July of 1998. Mr. Naranjo, a research specialist at the University of Arizona, has 14 years of experience conducting field studies on microbial water quality. Shelby Sheehan and Joseph Moregrega (both from the University of California Los Angeles) were trained by Mr. Naranjo in the collection of the virus and parasite samples. They were present during most of the collection periods. They collected the samples in July, 1998.

6.3.1.2 Protozoan Parasites

As for enteric viruses a 378 liter sample was collected if possible. Only four sites were sampled for parasites.

1) Malibu Creek before Tapia's WWTP (approximately 1 mile upstream from the discharge pipe)
2) Tapia's WWTP (Tertiary effluent after dechlorination and filtration) before discharge
3) Malibu Creek after Tapia's WWTP (approximately ½ mile downstream from discharge pipe)
4) Arizona Crossing (approximately 7 miles downstream from the discharge pipe)

6.3.2 Laboratory Analysis

6.3.2.1 Enteric Virus

Viruses were eluted off the filters by passing 1.5% beef extract V (Becton Dickinson, Cockeysville, MD) with 0.05M glycine under pressure with nitrogen gas. The eluent was flocculated by the addition of 1N HCL to a pH of 3.5 and reconcentrated by centrifugation for 4000xg for 30 minutes. After discarding the supernatant, the final pellet was resuspended in 0.15M sodium phosphate and the pH was adjusted to 7.0 to 7.4 for storage at -80°C. Future analysis of the beef extract concentrates included cell culture assays and PCR analysis.

6.3.2.2 ICC-PCR Assays

Because of problems with substances interfering with direct PCR of the filter concentrates, cell culture assays were performed on all of the samples. In addition to eliminating problems with the interfering substances, it is also a measure viral infectivity. The cell culture was then tested for enteroviruses using the polymerase chain reaction (PCR). This technique can detect viruses which do not produce cytopathogenic effects. The combined cell culture – PCR technique is called ICC-PCR (Reynolds et al., 1996).

Cell culture assays were performed on Buffalo Green Monkey Kidney (BGM) cells. BGM cells were grown to confluent monolayers in 75cm^2 and 25cm^2 flasks using Eagle's minimum essential media with Earle's salts (Irvine Scientific, Santa Ana, CA) containing 5% fetal bovine serum (HyClone, Logan, Utah). Before inoculating the sample, the media was poured off and the monolayer was washed with Tris buffer saline solution (Sigma Chemical Co., St. Louis, MO). At least 12 ml of sample was inoculated onto the cell monolayers (3ml per flask). A negative control with sterile water and positive control with one ml of ten plaque forming units (PFU) poliovirus type1 were also included with each round of cell assays. The flasks were incubated for 60 minutes at room temperature for virus absorption to cells. After incubation, maintenance media containing 2% fetal calf serg. was added to each flask. The flasks were placed at 37°C for

14 days and examined daily for viral cytopathic effect (CPE). The cell culture lysates were then removed from the flasks and stored at -80°C. The cell culture assays did not detect any viable enteric viruses (i.e. no CPE) in any of the surface water samples after 14 days incubation.

RT-PCR (reverse transcriptase-PCR) amplification and seminested PCR were performed on the cell culture lysates after the incubation period. The purpose of the reverse transcriptase is to convert the RNA of the virus genome to DNA, which is then amplied by the PCR. The selection of primers were based upon the conserved regions in the 5' end of the enterovirus genome. They represent sequences shared with several other enteroviruses: upstream primer, 5'-cct ccg gcc cct gaa tg-3', downstream primer, 5'-acc gga tgg cca atc caa-3' and the internal primer, 5' ccc aaa gta gtc ggt tcc cgc-3'. The internal primer was used in seminested PCR with the upstream primer to give a 104 base pair product and to confirm primary PCR products. The sensitivity of RT-PCR was determined by using a ten-fold dilution of polioviruses type 1 and subjecting it to the same procedure as the cell culture lysates. The poliovirus as determined by ethidium bromide staining could detect as few as 2 PFU (plaque forming units). Plaques are the clear zones that occur in a monolayer of animals because of the destruction of the cells by the growth of a virus. Each plaque is equal to one cell infectious virus.

A total of 19µl of RT extraction mixture (10µl of cell lysates done in duplicate, 1.5µl 10X buffer, 3.5µl MgC12 (2.5mM) and 4µl dNTP mix (10mM each dNTP) was heated for 5 minutes at 99°C and placed on ice. Then 1.5µl (0.5µl each of Rnase Inhibitor) (20 units/µl), MuLV Reverse Transcriptase (50 units/µl) and 50µM random hexamers) of the RT reaction mix was added to each RT extraction and incubated at 24°C for 10 minutes, 44°C for 50 minutes and heated to 99°C for 5 minutes to denature the reverse transcriptase. The PCR amplification was performed by adding 34.5 µl of a master mix (29µl Rnase free water, 3.5µl 10X Buffer, 1.5µl $MgC1_2$ (2.5mM) and 0.25µl each of upstream primer, downstream primer and Taq DNA polymerase) to each RT reaction with a temperature profile of 80°C for 2 minutes and then 30 cycles of 95°C for 20 seconds, 60°C for 25 seconds and 72°C for 20 seconds. A final annealing phase was performed for 10 minutes at 72°C and the reaction was stored at 4°C until the seminested PCR could be completed.

For seminested PCR, 5µl of the first PCR reaction was added to 45µl of the following master mix: 31µl Rnase free water, 5µl 10X Buffer, 4µl dNTP (10mM), 5µl $MgC1_2$ (2.5mM) and 0.25µl each of the upstream primer, internal primer and AmpliTaq Gold. The thermocycler was set for 95°C for 10 minutes and 30 cycles of 95°C for 20 minutes, 60°C for 25 seconds and 72°C for 20 seconds. Then 72°C for 10 minutes and storage at 4°C until the final products could be analyzed by gel electrophoresis with an ethidium bromide stain. PCR equivalent volumes are equal to the cell culture equivalent volumes, i.e. if a cell culture flask is positive by PCR the equivalent volume of concentrate is positive. Seminested PCR is done as a control to ensure that only viral nucleic acid is amplified.

6.3.2.3 Calculations for ICC-PCR Assays

For sensitivity of the seminested PCR: 100 PFU/100μl dilution X 2μl seeded sample = 2 PFU per reaction from cell culture lysates.

Equivalent volume for cell culture: Liters filtered/milliliters concentrated X milliliters placed on cells = equivalent volume on cell culture. Example: 378 1 filtered/30 ml concentrated X 12 ml in cell culture = 151 1 equivalent volume in cell culture

6.3.2.4 Direct PCR

Direct PCR was done as described in Abbaszadegan et al., (1993). The selection of the primers and the probe was based on alignments of poliovirus 1, 2 and 3, Coxsackie virus B, B3, and B4 by a multiple alignment computer program and computer-assisted analysis of the genomic RNA sequence of the six enterovirus type. For primers amplifying a 196-bp segment for enteroviruses the sequences are: 5'-cct ccg gcc cct gaa tg -3', 5'acc gga tgg cca atc caa -3' and the internal primer is 5'-ccc aaa gta ggt tcc cgc -3'. The internal primer are used in the seminested with the upstream primers to give 104-bp product and to confirm primary PCR products or further amplification several partial or further amplification of weakly positive samples. The same internal primer used in the seminested PCR reaction can be used as a DNA probe in dot blot hybridization (Figure 6.2).

The methods described by Gouvea et al., 1994 and Schwab et al., 1995 were also evaluated to reduce substances present in the samples which interfered with the PCR reaction. Poliovirus type 1 was added to the water concentrations and the amount of loss of virus was assessed by dilution of the sample and PCR testing. The results suggested that from 99 to 99.9% of the virus was lost during these clean-up procedures. This meant that the minimum number of viruses which could be defected by direct PCR was 200 to 2,000 PFU (assuming that 2 PFU/100μl could be detected by PCR) in 100μl of sample treated to remove interfering substances. Thus, a 378 liter sample would have to contain 60,000 to 600,000 PFU. In addition, some samples no matter how treated, still contained substances which interfered with the PCR.

Ten samples were also sent to the laboratory of Dr. Morteza Abbazadegan, Head Research Microbiologist, American Water Works Service Company in Bellville, IL. He also was unable to remove all of the interfering substances from the samples. All of the samples tested by direct PCR proved to be negative, but this may have been due to the poor sensitivity of the PCR detection method used with these samples.

6.3.2.4 Giardia and Cryptosporidum

The filters used for parasite collection were processed according to the ICR (Information Collection Rule) method (EPA, 1996) summarized in the laboratory protocol below. This method is only capable of determining the presence of cysts and oocysts and not their infectivity.

6.3.2.4.1 Protozoan Filter Elution

1. Filter processed within 96 hours of collection
2. Eluated divided into three liters of eluting solution into two, four liter beakers
3. Remove filter from bag, pour residual into one of the beakers, rinse bag with eluting solution and pour rinse solution into one beaker.
4. Cut the filter fibers lengthwise and divide them between the two beakers, keeping the dirtier outer fibers in the same beaker. Rise the inner plastic core into one of the beakers and discard the core in the biohazard bag.
5. Wash fiber by hand kneading them for 15 minutes in the eluting solution for a total washing time of 30 minutes.
6. Remove fibers, wringing out liquid and discard into biohazard bag.
7. Pour eluting solution into four, 750 mL centrifuge bottles, balance and centrifuge at 1,050 xg for 10 minutes.
8. Aspirate and discard supernatant and combine pellets. Rinse bottles well with eluting solution.
9. Repeat steps 7-8 until pellet can be combined into a 50 mL centrifuge tube. Then centrifuge at 3500 rpm for 10 minutes.
10. Discard supernatant and resuspend in equal volume of 10% formalin solution.
11. Store in a 4°C until floatation.

6.3.2.4.2 Flotation

1. In a clear plastic 50 mL conical centrifuge tube(s), vortex a volume of resuspended pellet equivalent to no more than 0.5 mL of packet pellet volume with a sufficient volume of eluting solution to make a final volume of 20 mL.
2. Using a 50 mL syringe and a 14 gauge cannula underlay the 20 mL vortexed suspension of particulate with 30 mL Percoll-sucrose flotation solution.
3. Without disturbing the pellet suspension/Percoll-sucrose interface, centrifuge the preparation at 1,050 xg for 10 minutes using a

swinging bucket rotor. Slowly accelerate the centrifuge over a 30-sec interval up to speed where the tubes are horizontal to avoid disrupting the interface. Similarly, at the end of centrifugation, decelerate slowly.

4. Using a polystyrene 25 mL pipet rinsed with eluting solution, draw off the top 20 mL particulate suspension layer, the interface, and 5 mL of the Percoll-sucrose below the interface. Place all these volumes in a plastic 50 mL conical centrifuge tube.
5. Add additional eluting solution to the plastic conical centrifuge tube (step 4) to a final volume of 50 mL. Centrifuge at 1,050 xg for 10 min.
6. Aspirate and discard the supernatant fluid down to 5 mL (plus pellet). Resuspend the pellet by vortexing and save this suspension for further processing with flourescent antibody reagents.

6.3.2.4.3 Staining of cysts and oocysts

The samples were then passed through 1.2 μm cellulose acetate membranes (Schaefer, 1997) and stained with fluorescent monoclonal antibodies (Hydroflur™ Combo Kit, Strategic Diagnostics Inc., Newark, DE), which are specific for both *Giardia* cysts and *Cryptosporidium* oocysts. Positive and negative controls were done with every sample set to assure reagent performance. The filters were then placed on glass slides and examined by epifluorescence microscopically at 200-400 magnification (Olympus, Lake Sucares, NY). Cysts and oocysts were identified on the basis of size, shape, and immunofluorescence. They were also examined with DIC (Differential Interference Contrast) microscope for internal features and to preclude the presence of algae. To observe internal features magnification up to 1000x are used.

6.3.2.4.4. Sample locations

Sampling sites were selected above and below the discharge of the Tapia plant, and of the plant effluent before discharge. This was done to assess the potential impact of the plant on water quality. Samples were also collected near the lagoon and in the surf zone near where the lagoon discharge occurs. This was done to assess contamination near the lagoon and surf zone used for contact recreation. Sampling was limited at the surf zone because storm events made sampling difficult at this location.

For those samples for which no cysts or oocysts were detected, the detection limit was calculated as follows.

$<X/1L = [<1(1)] \div FVR$ where:

F = volume of concentrate floated/total concentrate volume (mL)

V= volume of original sample in liters
R = volume of suspension filtered/interface volume (mL)
L = volume in liters
</X = detection limit

6.4 Results

The results for the ICC-PCR assays for the samples are shown in Table 6.1. None of the samples were positive (i.e. no enteroviruses detected) by direct PCR (30 µl samples tested) (Table 6.1). Only one sample was positive by ICC-PCR. That sample was collected from the wastewater at the Tapia plant on July 7, 1998 before discharge (after chlorination, filtration, and disinfection).

The results for the parasite analyses are shown in Table 6.2. *Giardia* was detected in all of the samples from the discharge of the Tapia plant except on May 14, 1998. The highest concentration detected (222 cysts/liter) was also detected in the discharge of the Tapia plant. *Giardia* was detected in 2 out of 5 samples above the plant and at all sample locations below the plant. All the samples collected during February were negative, except the discharge of the Tapia plant. This may have been due to dilution caused by the very heavy rainfall during this period. *Giardia* was found at all sampling locations during July, 1998. *Cryptosporidum* were less frequently detected. They were never detected above the Tapia plant discharge. They were detected twice (2/5) in the Tapia discharge and on one occasion each at sampling locations below the Tapia discharge. *Giardia* and *Cryptosporidium* were detected in ½ surf zone samples.

A great deal of difficulty was encountered with the direct PCR of the beef extract concentrates for viruses. The samples contained much higher concentrations of substances that interfere with PCR assays than we have previously encountered. Many different methods were evaluated for removing these substances (Abbaszadegan et al., 1993; Gouva et al., 1994; Schwab et al., 1995), but none proved ideal. The greatest sensitivity which could be achieved was 2000 pfu per ml of concentrate, which would mean viruses would have to be at a concentration of 160 or more per liter in the water. These are levels approaching what is found in non-disinfected secondary sewage (Rose et al., 1984). Thus, ICC-PCR was used for the detection of virus. This method combines traditional cell culture and PCR for virus detection. It has the advantage of being 1) more rapid than traditional cell culture, 2) allows us to assay a larger volume concentrate than direct PCR, 3) allows us to determine the viability of viruses detected by PCR, and 4) detects viruses which do not produce cytopathogenic effects (CPE) - i.e. destruction of the cell culture because of the growth of the virus. Only enteroviruses were tested for by this method.

Infectious enterovirus was detectable in only one sample. This sample was from the Tapia discharge on July 7, 1998. The presence of infectious virus in only one sample is be expected because of the filtration and extended disinfection practiced at the plant. Previous studies conducted at wastewater reclamation plants in California and Arizona using conventional cell culture methods to detect infectious virus (i.e., CPE Method) only rarely detected enteric viruses after two hour contact times with free residual chlorine (Asano et al., 1992; Gerba, unpublished).

6.5 Discussion

During the last year we have employed the ICC-PCR method to study the occurrence of enteroviruses in reclaimed wastewater in California and Arizona. The ICC-PCR has proved much more sensitive in detecting infectious enteroviruses than the traditional CPE (cytopathogenic effects) methodology. Enteroviruses have been detected in numerous samples by this method in which no enteroviruses have been detected by CPE even after three passages on cell culture (C.P. Gerba and Bill Yanko, unpublished results). These results have been confirmed by sequencing the nucleotide of the PCR product, (Reynolds et al., 1996) providing additional proof that the PCR was detecting enteroviruses. In addition, semi-nested PCR was used, which is additional confirmation of enterovirus detection. The increased sensitivity of ICC-PCR is probably due to its ability to detect viruses which are not capable of producing CPE in cell culture. Many enteric viruses are capable of growing in cell culture without producing CPE, i.e. human rotavirus (Smith and Gerba, 1982) and hepatitis A (Bloch et al., 1990). Since enteroviruses will usually produce CPE in BGM cells, it is possible that these viruses are mutants not capable of producing CPE (Schlegel and Kirkegard, 1995). Recent research in our laboratory suggest such mutants may be induced by exposure to chlorine (Blackmeer et al., 1999). The detection of infectious viruses in the effluent in only one sample, and no positive samples downstream, suggests that risks of infection to bathers from the Tapia discharge are probably low.

A previous study of the Tapia effluent discharge was conducted in 1993 and 1994 (Ambrose et al., 1995). In this study, both conventional cell culture and direct PCR of sample concentrates were used to determine the presence of enteric viruses. Positive PCR results were confirmed by southern blotting. This PCR methodology did not allow assessment of the viability of the viruses detected. Samples were collected of the effluent before filtration. Samples were only positive in the first three samples collected July through September 1993. Infectious virus was detected in only one sample, the rest being positive by direct PCR. The remaining eight samples collected from November 1993 through June 1994 were negative. The present study differs in that samples of the Tapia effluent were collected after filtration and dechlorination, larger volumes of the effluent were assayed, both direct PCR and ICC-PCR were used, and semi-nested PCR was used to confirm the PCR detected viral nucleic acid. From the previous study and the present study, it appears that the operation of the plant has improved from that of late 1993 so that infectious virus is rarely, or seldom, detected in the Tapia effluent.

Giardia and *Cryptosporidium* are almost always present in domestic wastewater. *Giardia* typically occurs in higher concentrations than *Cryptosporidium* in domestic wastewater (Enriquez et al., 1995). In general, *Giardia* occurs in higher concentrations than *Cryptosporidium* in surface waters when human wastes are the major source, of contamination (Rose et al., 1991). When animals, such as cattle, are the major source, greater concentrations of *Cryptosporidium* are observed. These organisms are more resistant to disinfection than enteric viruses, and levels normally applied during waste treatment do not inactivate them (Korich et al., 1990). Thus we would expect at least some of the *Giardia,* and most of the *Cryptosporidium* oocysts, to survive disinfection. Although only a limited number of samples were collected, the data suggests that the Tapia plant may be the source of *Cryptosporidum* in Malibu Creek, as *Cryptosporidum* were only detected in discharge of the plant and in Malibu Creek downstream of the plant. In contrast to the Tapia plant discharge, humans and animals in the watershed appear to be potential sources of *Giardia.*

The understanding of appropriate action levels for decision making is still developing, with respect to the occurrence of pathogenic enteric protoza and viruses. In the case of drinking water, an annual risk of infection (not illness) is considered appropriate for drinking water (Regli et al., 1991). In the case of contact recreation, correlations between highly credible gastroenteritis rates during epidemiological surveys in which indicator bacteria were assessed may be used, along with the presumption that recommended indicator standards (200 fecal coliforms/100mL) are an acceptable level of risk (Haas, 1995). Using this approach, the acceptable risk for a one-time exposure is 19/1000 in marine waters and 12/0000 in fresh waters (Haas, 1995; Dufour, 1984). For marine water bathers, that means 19 persons will likely develop gastrointestinal illness, out of 1000 person bathing in the water, assuming 100 ml is ingested. Haas (1995) estimated that 30 rotavirus and 86 *Giardia* per 10 liters would have a risk of infection of 17/1000 (1.7x 10^{-2}). The one positive sample found in the discharge of the Tapia plant was no greater than 5 enteroviruses/71 liters (based on the number of positive flasks used for the assay). Viruses were not detected in any of the other samples (assay volumes of 19 to 156 liters). The absence of viruses in Malibu Creek and the surf zone indicate risks are not significant to bathers or surfers. The highest concentration of *Giardia* cysts was observed at Arizona Crossing on 7/7/98 when 31 cysts/100 liters were detected, which would cause a risk of infection to the bathers of about $4\text{x}10^{-3}$ or 4/1000 (Regli et al., 1991). *Cryptosporidium* oocysts are somewhat less infectious (Haas et al., 1996) and risks to bathers would be less than *Giardia*. A factor which would tend to underestimate the risk is that methods for the concentration of *Giardia* and *Cryptosporidium* usually detect less than 10-30% of the cysts or oocysts present in the water. However, it is also possible that all of the cysts are not viable, which could estimate over the risk.

The peak concentration of cysts above and below the Tapia plant were not very different (24.7 vs. 31 per 100 liters). However, average concentrations below the Tapia plant were double that above (7.6/100 liters before the Tapia plant, 15.5/100 liters after the Tapia plant, and 19.9/100 liters at Arizona Crossing). Thus, the risk of infection from *Giardia* increases after the plant discharge. The same statement also appear to be true for *Cryptosporidum.* Average values are probably more important in assessing potential risks than individual values (Haas and Rose, 1996).

Both *Cryptosporidium* and *Giardia* were detected in the ocean water at the beach front (surf zone) on 7/8/98. However, the concentration of *Giardia* was generally less than that observed in Malibu Creek. The concentrations observed for both parasites would present a risk less than that considered acceptable for recreational marine beaches as recommended by Cabelli (Haas, 1995). *Giardia* does not survive for very long periods of time in marine water, so potentially, *Cryptosporidium* may present a greater risk than *Giardia* to marine bathers (Johnson et al., 1997).

In a study of effluents from activated sludge plants in Arizona, the concentration of *Giardia* and *Cryptosporidium* averaged from 42.5 to 2.5/100 liters using the methods employed in this study (Enriquez et al., 1995). In a tertiary reclaimation plant after filtration, *Giardia* averaged 6.75/100 liters and *Cryptosporidium* 1.75/100 liters. The levels of both parasites in the discharge from the plant was somewhat higher than these values, i.e. 70.1 cysts/100 liters and 6.2 oocysts/100 liters. However, only five samples were collected in the present study, vs. 130 in the Enriquez et al., 1995 study.

It should be emphasized that these risk estimates for the parasites are based on a very limited data set. Collection of additional data would better quantify the risk and better assess the contribution of the Tapia plant discharge on Malibu Creek.

6.6 Conclusions

- Risk of infection from enteroviruses appears not to be significant in Malibu Creek.
- The greatest risk of infection to bathers appears to be from *Giardia* cysts.
- Risks from *Giardia* and *Cryptosporidium* infection appear to be greater below the Tapia plant discharge.
- The Tapia plant appears to be the source of *Cryptosporidum,* and increased levels of *Giardia* were observed below the discharge point.
- *Giardia* and *Cryptosporidium* were detected in the surf zone of the beach near the Malibu Creek discharge.
- Based on the limited data set, risks of *Giardia* and *Cryptosporidium* infections to bathers and surfers are below levels which have been considered acceptable.

6.7 Recommendations

- To better determine the risks and the impact of the Tapia plant discharge on Malibu Creek, monthly monitoring of the plant and sample locations along Malibu Creek and surf zone for *Giardia* and *Cryptosporidium,* at least 12 months are needed.
- Since some inactivation of *Giardia* cysts may occur from disinfection practiced at the Tapia plant, contact time and disinfectant concentration (C.T values) should be determined for the operational conditions at the plant. This would allow a better assessment of the viability of the cysts which could be used in a risk assessment.

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Table 1. Results of cell culture ICC-PCR

LOCATION	DATE	VOLUME COLLECTED (liters)	DIRECT PCR	CELL CULTURE (CPE)	CELL CULTURE Equivalent Volume (liters)	PCR ENTERO-VIRUS	PCR EQUIL VOLUME (liters)
Above Tapia	10/28/97	302	neg	neg	110	neg	110
After Tapia	10/28/97	378	neg	neg	252	neg	252
Tapia Effluent	11/5/97	298	neg	neg	99	neg	99
Terminus	11/4/97	378	neg	neg	113	neg	113
Ridge Dam	11/5/97	378	neg	neg	151	neg	151
Arizona Crossing	11/9/97	378	neg	neg	151	neg	151
Tapia Effluent	2/27/98	219	neg	neg	97	neg	97
Ridge Dam	2/27/98	159	neg	neg	32	neg	32
Above Tapia	2/27/98	102	neg	neg	20	neg	20
After Tapia	2/27/98	95	neg	neg	19	neg	19

nes = no viruses detected
pos = pos for enterovirus. ICC-PCR only detects infectious virus growing in cell culture. See material and methods for location of sampling sites.
*Volume which was assayed depends upon the volume collected and the cell culture toxicity of the sample. Volume collected depends upon the turbidity of the water at the time of collection.

Table 6.1 (Con't)

LOCATION	DATE	VOLUME COLLECTED (liters)	DIRECT PCR	CELL CULTURE (CPE)	CELL CULTURE Equivalent Volume (liters)	PCR ENTERO-VIRUS	PCR EQUIL VOLUME (liters)
Arizona Crossing	2/27/98	163	neg	neg	33	neg	33
Terminus	2/27/98	302	neg	neg	60	neg	60
Above Tapia	5/14/98	756	neg	neg	156	neg	156
Treatment Plant	5/14/98	348	neg	neg	67	neg	67
Below Tapia	5/14/98	340	neg	neg	66	neg	66
Terminus	5/14/98	246	neg	neg	53	neg	53
Above Ridge Dam	5/14/98	340	neg	neg	68	neg	68
Arizona Crossing	5/14/98	378	neg	neg	81	neg	81
Ocean-Surf zone	5/14/98	227	neg	neg	45	neg	45

nes = no viruses detected
pos = pos for enterovirus. ICC-PCR only detects infectious virus growing in cell culture. See material and methods for location of sampling sites.
*Volume which was assayed depends upon the volume collected and the cell culture toxicity of the sample. Volume collected depends upon the turbidity of the water at the time of collection.

Table 6.1 (Con't)

LOCATION	DATE	VOLUME COLLECTED (liters)	DIRECT PCR	CELL CULTURE (CPE)	CELL CULTURE Equivalent Volume (liters)	PCR ENTERO-VIRUS	PCR EQUIL VOLUME (liters)
Arizona Crossing	6/18/98	378	neg	neg	76	neg	76
Terminus	6/18/98	132	neg	neg	27	neg	27
Above Tapia	6/17/98	378	neg	neg	73	neg	73
Tapia	6/17/98	378	neg	neg	71	neg	71
Above Ridge	6/17/98	378	neg	neg	76	neg	76
Below Tapia	6/17/98	378	neg	neg	76	neg	76
Ocean-surf zone	6/17/98	378	neg	neg	71	neg	71
Terminus	7/08/98	189	neg	neg	38	neg	38
Ocean-surf zone	7/08/98	189	neg	neg	38	neg	38

nes = no viruses detected
pos = pos for enterovirus. ICC-PCR only detects infectious virus growing in cell culture. See material and methods for location of sampling sites.
*Volume which was assayed depends upon the volume collected and the cell culture toxicity of the sample. Volume collected depends upon the turbidity of the water at the time of collection.

Table 6.1 (Con't)

LOCATION	**DATE**	**VOLUME COLLECTED (liters)**	**DIRECT PCR**	**CELL CULTURE (CPE)**	**CELL CULTURE Equivalent Volume (liters)**	**PCR ENTERO-VIRUS**	**PCR EQUIL VOLUME (liters)**
Arizona Crossing	7/07/98	378	neg	neg	76	neg	76
Above Ridge	7/07/98	378	neg	neg	76	neg	76
Tapia effluent	7/07/98	378	neg	neg	76	**pos**	71
Below Tapia	7/07/98	378	neg	neg	71	neg	69
Before Tapia	7/07/98	378	neg	neg	76	neg	76

nes = no viruses detected

pos = pos for enterovirus. ICC-PCR only detects infectious virus growing in cell culture. See material and methods for location of sampling sites.

*Volume which was assayed depends upon the volume collected and the cell culture toxicity of the sample. Volume collected depends upon the turbidity of the water at the time of collection.

Table 2. Results of Protozoan Assays

Site	Date Collected	Giardia Cysts	Cryptosporidium Oocysts (Per 100 liters)
Before Tapia WWTP	10/28/97	<6.3*	<6.3
	02/27/98	<40	<40
	03/14/98	<44	<8.8
	06/17/98	3.3	<3.3
	07/07/98	24.7	<1.9
Tapia WWTP Discharge	11/05/97	3.0	3.0
	02/27/98	222	28
	05/14/98	<44	<2.6
	06/17/98	114	<3.8
	07/07/98	11.6	<2.9
After Tapia WWTP	10/28/97	22.5	15.0
	02/27/98	<76.9	<76.9
	05/14/98	NS	NS
	06/17/98	<9.1	<9.1
	07/07/98	8.5	<1.7
Arizona Crossing	11/04/97	<1.0	3.0
	02/27/98	<3.0	<3.0
	03/14/98	27	<9.0
	06/18/98	1.8	<2.2
	07/07/98	31	<2.2
Ocean Beach	06/18/98	<11	<11
	07/08/98	7.7	15

<Values represent the detection limit for the particular sample: The amount of turbidity in a sample limits the volume which can be assayed.

NS = no sample

Figure 6.1

Procedure for the Concentration and Detection of Enteric Viruses in Water

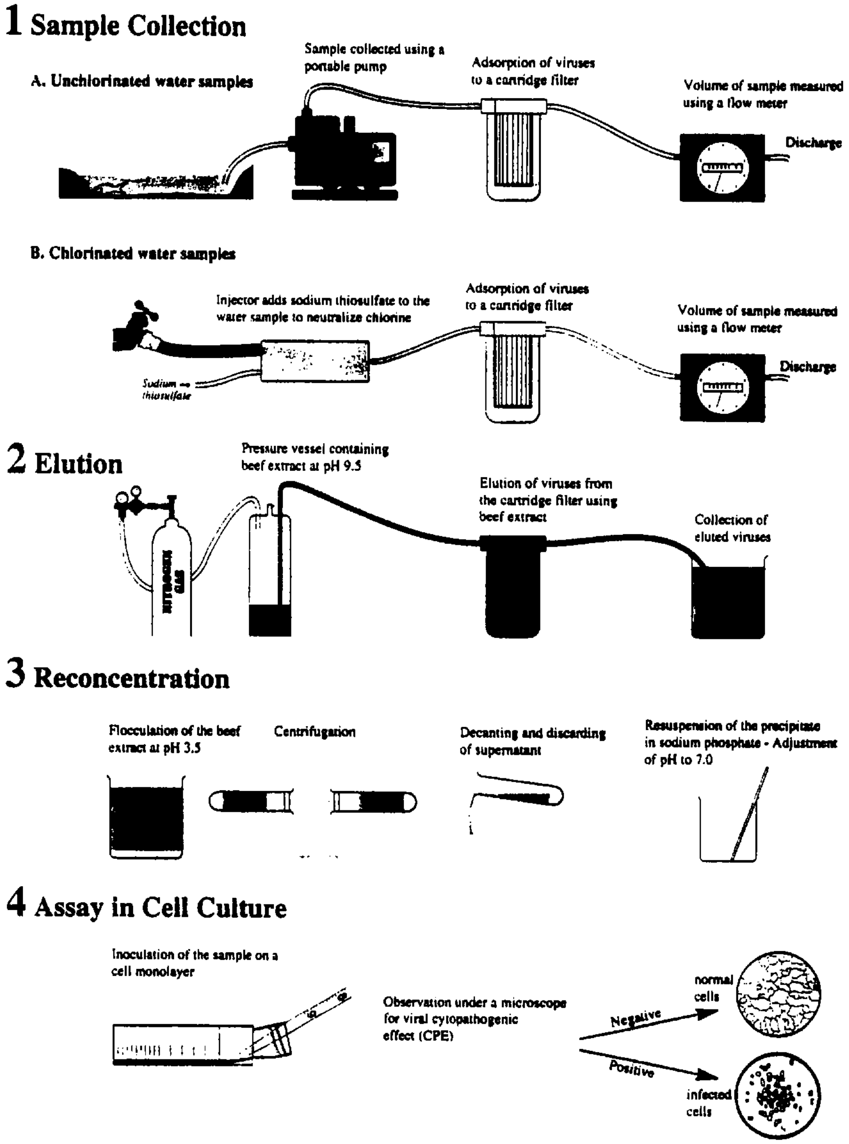
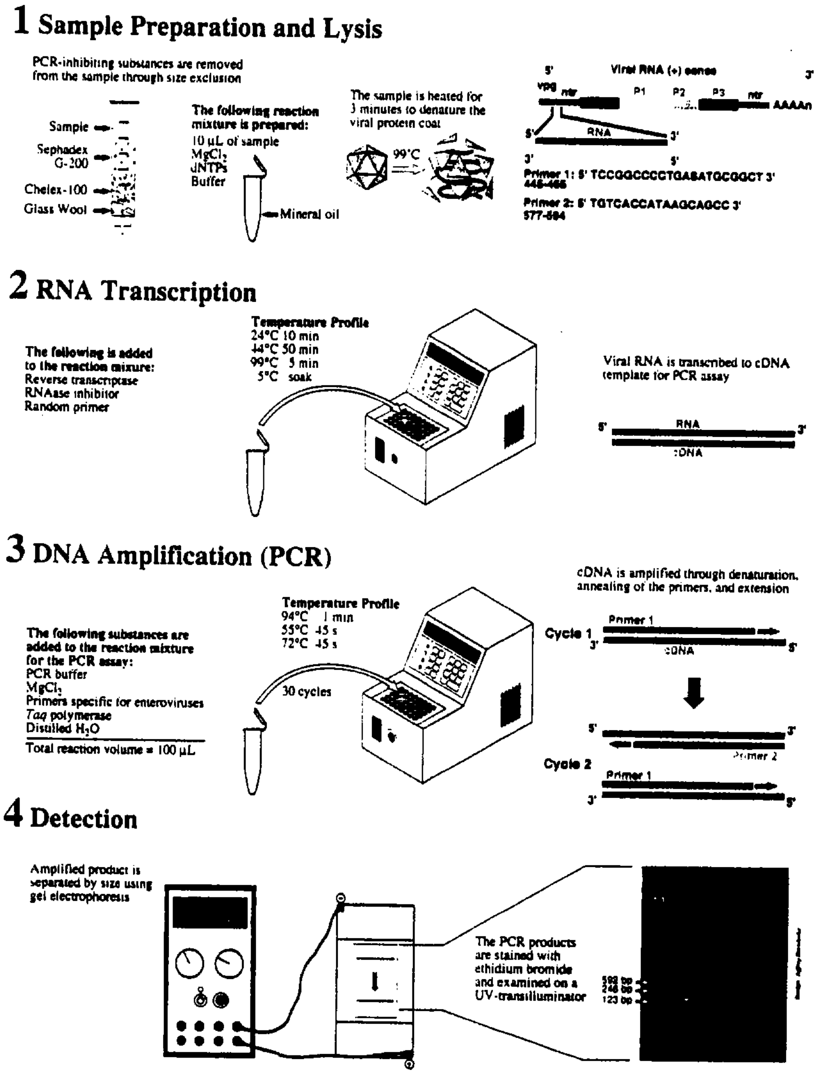


Figure 6.2

Detection of Enteroviruses by the Polymerase Chain Reaction (PCR)



1 Sample Preparation and Lysis

PCR-inhibiting substances are removed from the sample through size exclusion

The following reaction mixture is prepared:
10 µL of sample
$MgCl_2$
dNTPs
Buffer

The sample is heated for 3 minutes to denature the viral protein coat

Primer 1: 5' TCCGGCCCCTGAATGCGGCT 3'
446-465

Primer 2: 5' TGTCACCATAAGCAGCC 3'
577-594

2 RNA Transcription

The following is added to the reaction mixture:
Reverse transcriptase
RNAase inhibitor
Random primer

Temperature Profile
24°C 10 min
44°C 50 min
99°C 5 min
5°C soak

Viral RNA is transcribed to cDNA template for PCR assay

3 DNA Amplification (PCR)

The following substances are added to the reaction mixture for the PCR assay:
PCR buffer
$MgCl_2$
Primers specific for enteroviruses
Taq polymerase
Distilled H_2O

Total reaction volume = 100 µL

Temperature Profile
94°C 1 min
55°C 45 s
72°C 45 s

30 cycles

cDNA is amplified through denaturation, annealing of the primers, and extension

4 Detection

Amplified product is separated by size using gel electrophoresis

The PCR products are stained with ethidium bromide and examined on a UV-transilluminator

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Chapter7: Hydrologic Alteration and Human Disturbance

M. I. Venkatesan

7.1. Introduction

The Malibu Creek and Lagoon waters were analyzed for linear alkylbenzenes (LABs) and fecal sterols, which are markers of household laundry detergents and sewage carbon respectively (Eganhouse et al. 1983; Takada and Ishiwatari 1991a; Walker et al., 1982; Venkatesan and Kaplan 1990). The presence of these compounds will indicate the possible hydrological connection to the storm drains and septic systems. Coprostanol and other fecal sterols could also be considered as innovative chemical tracers (Venkatesan 1995) for human pathogens. Both classes of compounds were, therefore, measured in all the samples.

7.2. Methods

7.2.1. Samples Studied:

Two sets of water samples from the following locations were obtained in Nov. of 1997:

P1-well by SCE

P6-Plaza Well

P7-Parking lot well

C1 and C2- Wells near Malibu Colony and the Creek

Creek at the Arizona crossing

The third set of water samples including from the above locations and also the following locations were collected between June and August of 1998:

1. Malibu Colony Drain (Mystery Drain)
2. Above Tapia at the Salvation Army Camp
3. At Tapia after treatment and before release into the Creek
4. Just below Tapia
5. Just above Rindge Dam
6. In the Lagoon near the side arm (near the wells)
7. Ocean water

All of the above samples collected by Shelby Sheehan are from the same location as for the virus study by Dr. Gerba and Figures 7-1 and 7-2 illustrate the general sampling locations. However, unfortunately, the samples were not an aliquot from the same lot collected for viral study since they were sampled at different time.

The sample collection from the wells in August of 1998 was coordinated with Dr. Eric Fordham of Woodward Clyde when field measurements were made on water level, total depth etc. The total depth of the wells was between 12' and 14' and the water level in the wells was in the range between 5' and 8'. The lagoon level and the level of the well water appeared to be correlated.

7.2.2. Analytical procedures

7.2.2.1. Sample Preservation

The water samples were collected in gallon solvent bottles and were preserved with hydorchloric acid (~5 ml of conc. HCl), transported cold and stored in the cold room at 4°C. Samples were processed within the same week.

7.2.2.2. Analysis

Two liter of the water sample was extracted in a separatory funnel with 3X 80 ml of methylene chloride after spiking with surrogates (5α-androstanol and phenyldodecane). The solvent extract was concentrated, treated with Sodium Sulfate, again concentrated and subjected to silica gel column chromatography to separate the aromatic and sterol compound classes. The aromatic fraction was run on a gas chromatograph (GC) equipped with flame ionization detector to qulitatively identify the LABs. The sterol fractions were derivatized to their silyl ethers to quantitate the various sterols including fecal sterols by the GC under different temperature program. Quantitation of LABs was performed by GC/Mass Spectrometry. Identification of sterols was confirmed by GC/MS after rederivatization of a new aliquot of the sterol fraction. Target compounds were spiked to water samples and were analyzed the same way to establish percentage recovery after workup to correct for recovery loss. Procedure blank analyses were carried out simultaneously with the samples. Identical column and temperature programs were employed in the GC/MS as the GC runs. The detailed analytical protocols can be found in Venkatesan et al. (1986) and Phillips et al. (1997).

7.3. Results and discussion

7.3.1. 1997 Samples

The GC and GC/MS data showed that none of the two sets of samples collected in 1997 contained measurable linear alkylbenzenes or fecal sterols. They did contain some sterols, derived from higher plant material, such as campesterol and β-sitosterol in small amounts. Further, at the time of sample collection from the wells, no other field data such as well depth, conductivity of water, etc. were gathered.

7.3.2. 1998 Samples

7.3.2.1. Sterols

The distribution of biogenic and fecal sterols quantitated are listed in Table 7-1. None of the target analytes were detected in the procedure blanks. The fecal sterols, coprostanol, is present in high amounts in samples from Tapia, Malibu Colony, C2 and the Lagoon while waters from Arizona Crossing contain the least amounts. However, the level measured from Tapia is much less than the coprostanol concentrations previously observed in effluents from Los Angeles City and County Sanitation Districts (Venkatesan and Kaplan, 1990). Samples from other Malibu locations contain either trace or no coprostanol. None of the samples except Lagoon (75 ng/l) and C2 (trace) contained the other isomer (epicoprostanol). Coprostanone, an oxidative degradation product of coprostanol was found in significant amounts in most of the samples with the Lagoon and Malibu Colony Drain samples containing the highest amounts.

In addition to the absolute amounts of various sterols, specific diagnostic parameters included in Table 7-1 can be used in assessing the input of fecal contamination in the locations investigated. For example, although the presence of coprostanol and epicoprostanol would indicate inputs from fecal waste, the relative percentage of these sterols in total sterols have been found to be more useful in assessing the degree of sewage contamination in marine sediments to eliminate the effect of grain size on coprostanol and other effects in waters (Venkatesan and Kaplan 1990). Similarly, the relative percentages and ratios of other specific compounds help document the presence of fecal waste and in some instances also distinguish the source as to whether they originate from humans, land or aquatic mammals etc. (Venkatesan and Santiago 1989; Leeming et al., 1997 and Venkatesan 1995). The relative percentages of coprostanol and coprostanone indicate the contribution from fecal matter in waters from P6, P7, C2, Malibu Colony Drain, Arizona Crossing, S.A.Camp, Tapia, Lagoon and the ocean. A consideration of the absolute amounts as well as the various parameters listed in the Table which are comparable to those reported from human fecal specimen, influent and effluent waste waters from the Hyperion Plant (Ferezou et al., 1978; Venkatesan 1995) suggests that besides the sample from Tapia (as expected), sample C2 contains the highest human waste contamination. Water from P7, Malibu Colony Drain and the Lagoon exhibit significant human fecal contamination. The Salvation Army Camp contain lower levels and the waters from the Arizona Crossing, P6 and the ocean, the least of fecal wastes and the available data does not indicate if they are of human origin. The other three locations, P1, C1 and below Tapia are pristine.

Coprostanone can be formed by the oxidation of coprostanol both within and exterior to the body or as an intermediate in the reduction of cholesterol to coprostanol and has been suggested as a possible sewage indicator (Dougan and Tan 1973; Parmentier and Eyssen 1974). It has, however, not been exploited as a sewage tracer by others. Human feces was found to contain only twice as much %coprostanone in total sterols as many other animals ie., cat, horse,rat, cow (Ferezou et al., 1978; Venkatesan 1995). Coprostanone, unlike coprostanol, can therefore, probably not be used as an absolute indicator of human waste. However, if it is assumed that most of the coprostanone was derived from the oxidation of the precursor, coprostanol, then the presence of coprostanone (despite the absence of coprostanol itself) in samples, P6, S.A.Camp and ocean, would point to mammalian waste inputs as discussed above. Available limited data is insufficient to indicate if it is of human or animal origin.

Apparently the fecal contamination was sporadically detected and no clear gradient was observed in the distribution of fecal sterols in the locations studied. This precludes tagging the septic system as the single major origin of contaminants in all the polluted locations. For the same reason, the data establishes the hydrologic connection of the Creek and the Lagoon to the storm drains only in some locations. However, these conclusions have to be viewed with great caution, since they are based on one time sampling from a single location from a given site due to limited resources available to this aspect of the project. It is possible that hydrological connection between the septic systems and the locations sampled are episodically and preferentially established under optimum environmental conditions. Our sampling might not have been carried out under those conditions. Further, ideally, several samples should have been collected in an intensive sampling program- from different points in a given location at different seasons coinciding with different water table levels of the lagoon, and at least once before and after a major storm.

Although coprostanol was found at relatively higher levels than the other sterols at Tapia (and also the highest amount of all the samples studied), it appears that sewage sterols get quickly buried into the Creek sediments within a short distance from the treatment plant. This is evident from the observation that a sample from below Tapia was relatively pristine containing only biogenic sterols such as cholesterol, campesterol and β-sitosterol which originate from vascular plants and/or algae (Venkatesan et al., 1987).

7.3.2.2. Linear alkylbenzenes (LABs)

Table 7-2 contains data on the distribution of LABs. Only five of the thirteen samples analyzed contained LABs. Salvation Army Camp sample is the only one which contains a suite of LABs comparable to those found in wastewater influents, effluents and nearshore contaminated marine sediments (Takada and Ishiwatari 1991b; Phillips et al., 1997). The total amount of LABs at this location is comparable to those found in water and suspended particles from some of the Tokyo Rivers (Takada and Ishiwatari 1991b). Except for the absence of first four LAB isomers, the composition of LABs isomers at this location is also comparable to the Tokyo River waters and appears to have originated primarily from untreated domestic waste water (rather than from treated waste water effluents). The very low I/E ratio (0.43) is consistent with this origin. Since coprostanol was not found in this sample, it would indicate that grey water containing only laundry detergents near the site has contributed to LABs detected here rather than sewer waste. Incidentally this sample also contained hydrocarbons (normal alkanes and polycyclic aromatic hydrocarbons) characteristic of freshpetroleum origin (data not shown). Tapia sample contains only very few LABs at low levels similar to Malibu Colony Drain, Lagoon and P7 samples. The very low levels in the Tapia sample is consistent with the low amounts of coprostanol measured in contrast to that normally found from effluent samples as discussed above. This would indicate that the treatment at Tapia Plant is very effective in the removal of particles containing these contaminants. Procedure blanks did not contain any of the target analytes. Therefore, the presence of very low amounts of only selected isomers in the other three samples do not warrant any discussion as to their specific origin.

7.4. Conclusion

Tapia sample as expected contains human fecal waste. Water from C2, P7, Malibu Colony Drain and the Lagoon exhibit significant human fecal contamination. The waters from the Salvation Army Camp contain low levels and those from the Arizona

Crossing and the ocean the least of fecal wastes and the available data does not indicate if they are of human origin. The other three locations, P1, C1 and below Tapia are pristine. In addition, a suite of linear alkylbenzenes was detected in high amounts in the Salvation Army Camp sample that must have originated from untreated domestic wastewater. This sample also contained petroleum hydrocarbons. The very limited available data establishes hydrologic connection of the Creek and the Lagoon to the storm drains and septic systems only in some locations. Perhaps a more intensive sampling would be required to address this issue in greater detail.

7.5. Acknowledgement

Shelby Sheehan did the field sampling. Eric Fordham helped to collect water samples from wells. T. Northrup, O. Merino and J. Hao provided technical assistance and E.Ruth performed GC/MS analyses.

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Table 7-1. Sterols in the waters from the Malibu Creek, Lagoon and the vicinity (ng/L)

UCLA sample ID *	P1(8/14)	P6(8/14)	P7(8/14)	C1(8/14)	C2(8/14)	.Colony Drai	AZ Xing	S.A.Camp	Tapia	Below Tapia	indge Da	Lagoon	Ocean
Sterols (ng/l) †													
Coprostanol	tr	nd	72.1	tr	199.8	498.6	94	tr	987	tr	nd	800.5	nd
Epicoprostanol	nd	nd	nd	nd	tr	nd	nd	nd	nd	nd	nd	75	nd
Coprostanone	nd	154.4	97.5	tr	186.2	579.9	nd	101.5	114.6	nd	nd	617.5	97.7
Cholesterol	35.5	50.6	101.7	tr	66.5	1171	1296	581.2	330.4	721	332.1	3748.3	194.6
Cholestanol	nd	tr	nd	nd	nd	214.1	158.4	44.5	210	131.5	nd	427.1	nd
Campesterol	tr	nd	126.6	nd	nd	1920.3	1210.4	122.3	249.8	205.9	98.9	2655.4	93.9
β-Sitosterol	tr	82.1	273.9	tr	65.6	1131.4	760.4	520.4	105.4	955.7	103.3	1836.8	37.9
5α-Androstanol (Surrogate) % recovered	80.5	83.5	73.9	74.9	90.2	89.9	88.5	92.9	81.1	80.7	90.4	81.7	89.3
Total sterols (ng/l)	36	133	574	tr	332	4935	3519	1268	1883	2014	534	10,086	326
%Coprostanol in total sterols	tr	nd	12.6	tr	60.2	10.1	2.7	tr	52.4	nd	nd	5.8	23
%Coprostanone in tot.sterols+ Coprostanone	nd	11.6	16.9	tr	5.6	11.8	nd	8.0	6.09	nd	nd	6.12	29.9
%Cholesterol in tot.sterols	100	38.0	17.7	tr	20.0	23.7	36.8	45.8	17.5	35.8	62.2	37.2	59.7

* All samples except from Tapia, Lagoon and Ocean are from the Malibu Creek at designated locations. Tapia sample is from Tapia Plant after treatment, but before release into the creek.

† Data not corrected for surrogate recovery.

Table 7-2. Linear alkylbenzenes (LABs) in the waters from the Malibu Creek, Lagoon and the vicinity (ng/L)

UCLA sample ID	P7(8/14)	.Colony Dra	S.A. CAMP	Tapia	LAGOON
LABs (ng/l)					
55-11	nd	nd	nd	nd	nd
64-11	nd	nd	nd	nd	nd
73-11	nd	nd	nd	nd	nd
82-11	nd	nd	nd	nd	nd
91-11	nd	3.58	7.64	3.12	nd
65-12	4.17	2.95	13.40	2.98	nd
74-12	nd	nd	14.77	nd	nd
83-12	nd	nd	14.42	nd	nd
92-12	6.28	nd	14.32	nd	nd
101-12	3.01	5.89	36.16	5.39	3.71
66/75-13	nd	4.79	25.04	4.18	nd
84-13	nd	nd	13.68	nd	nd
93-13	nd	nd	15.26	nd	nd
102-13	nd	4.01	12.01	nd	nd
111-13	nd	5.12	28.01	4.95	5.37
76-14	nd	nd	10.88	nd	nd
85-14	nd	nd	6.43	nd	nd
94-14	nd	nd	15.67	4.19	nd
103-14	3.14	3.97	16.67	3.56	nd
112-14	nd	nd	nd	nd	nd
121-14	nd	nd	3.47	nd	nd
Total LABs (ng/l)	16.60	30.31	247.83	28.37	9.08
I/E*	0.45	0.50	0.43	0.55	nd

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nd - Not detected

* Ratio of (6-C12 + 5-C12) to (4-C12 + 3-C12 + 2-C12)

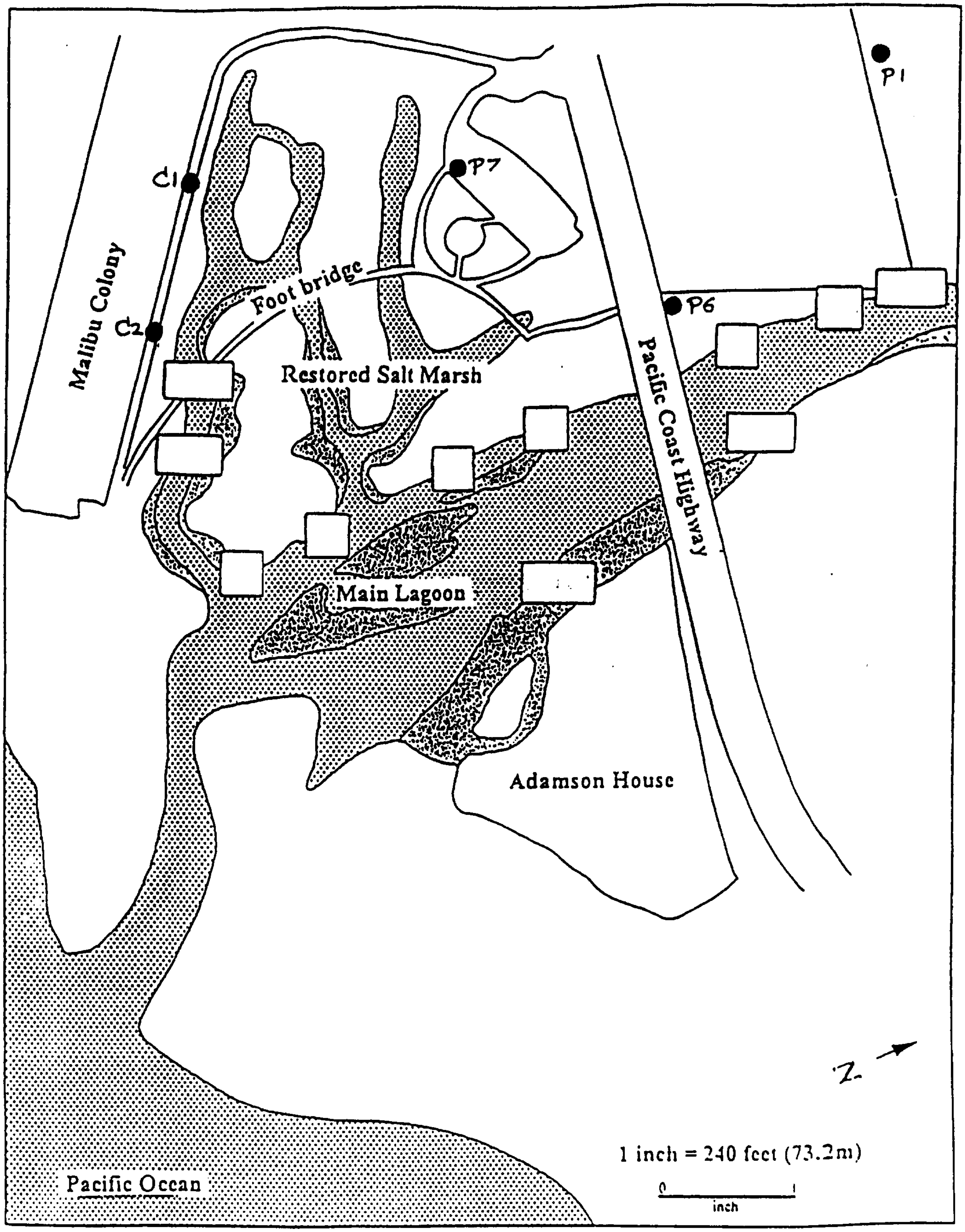

Figure 7-1. General water sampling locations from the Wells for LABs and sterols study.

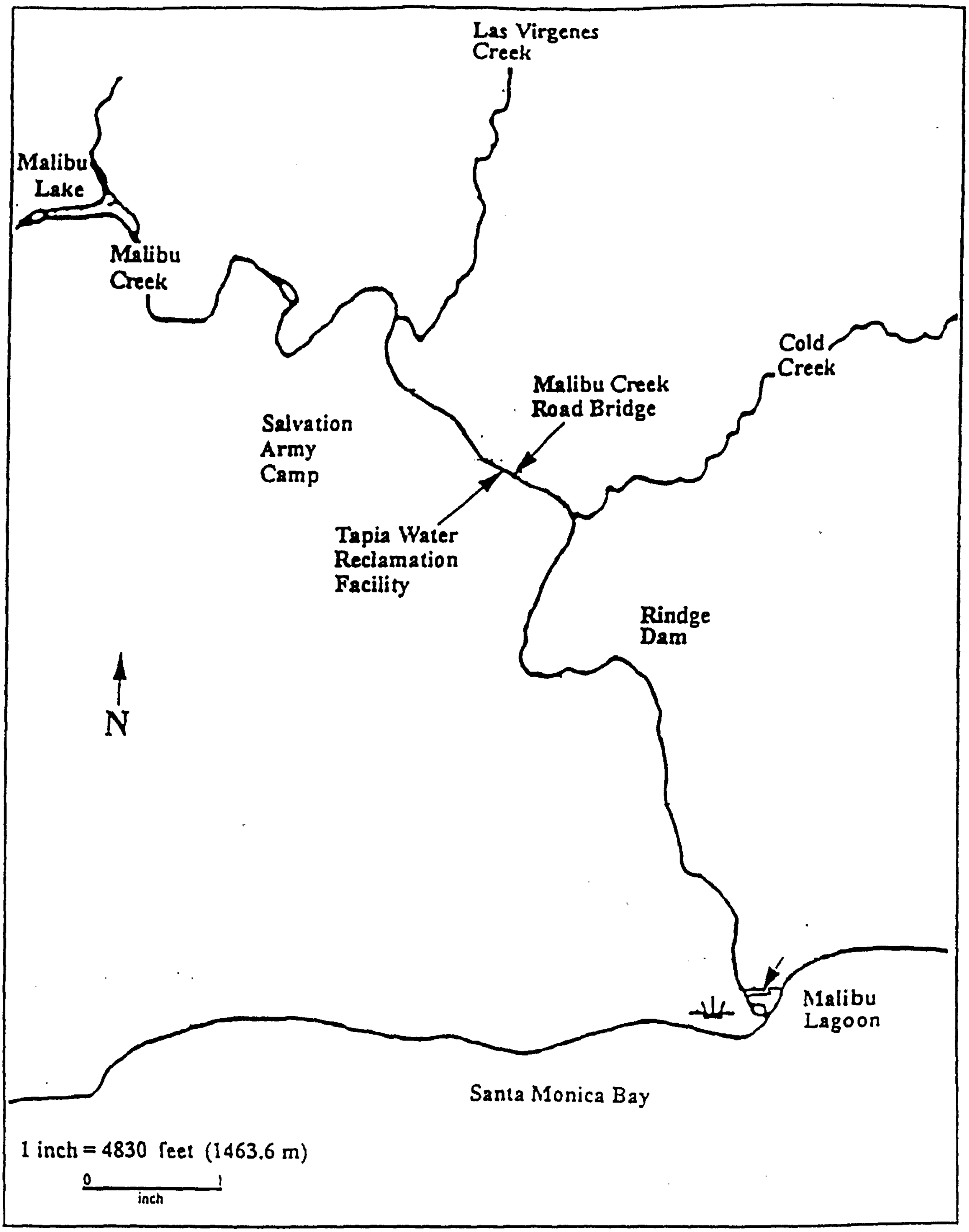

Figure 7-2. General water sampling locations for LABs and sterols study. Samples were collected from above Tapia at the Salvation Army Camp, at Tapia after treatment and before release into the Creek, just below Tapia, just above Rindge Dam, at Arizona crossing, in the Lagoon in the side arm (near the wells) and in the ocean.

Chapter 8: Management Alternatives

Richard F. Ambrose
Jonathan Lilien

8.1. Management and Restoration History

8.1.1. Introduction

A number of agencies and municipalities have been and continue to be involved in managing and restoring aquatic ecosystems in the lower Malibu Creek watershed. These include the California Department of Parks and Recreation, Resource Conservation District of the Santa Monica Mountains, Las Virgenes Municipal Water District, and City of Malibu. The U.S. Army Corps of Engineers is also considering undertaking a restoration project in the lower creek. This section briefly outlines relevant activities carried out by each of these entities.

8.1.2. California Department of Parks and Recreation

8.1.2.1. Water Level Management

Since 1984, the California Department of Parks and Recreation (DPR) has conducted a water level management program that involves breaching the barrier beach at the mouth of lagoon to allow rising waters to drain to Santa Monica Bay. Although their plan calls for breaching within 48 hours when lagoon water levels reach 3.7 feet and are rising at a rate of greater than 6 inches per day, DPR typically waits until lagoon waters are extremely high before initiating a breach. In order to minimize impacts to the adjacent surf break and ensure adequate public access, DPR typically breaches between the so-called "second" and "third" points of the beach (DPR 1984).

The primary purpose of mechanical breaching is to alleviate flooding and prevent septic system failures in Malibu Colony and the Civic Center area. Mechanical breaching provides a number of ancillary benefits, such as improving lagoon water quality, facilitating mosquito control, and increasing shorebird habitat (Capelli 1997). DPR prefers mechanical breaching to other breaching methods because it is simple and inexpensive. For this reason, it has become common practice in lagoons throughout the state (Taylor 1991; Capelli 1997).

Although it generally requires agencies to acquire a coastal development permit to breach barrier beaches artificially, the California Coastal Commission (CCC) did not interfere with DPR's water level management program during the first 12 years of its implementation. At the urging of state and federal resource agencies concerned about the potential effects of mechanical breaching on the tidewater goby, CCC recently reversed its informal policy of allowing DPR to mechanically breach the barrier beach. DPR has subsequently suspended mechanical breaching except for one occasion (June 20, 1997). On this occasion, widespread complaints about septic system backups and the Los Angeles County Health Department's closure of a local restaurant due to a flooded restroom prompted DPR officials to invoke their privileges under emergency provisions outlined in the California Coastal Zone Management Act.

DPR is in the process of studying alternative water level management strategies for the lagoon. Such alternatives include (1) a spillway across the barrier to allow lagoon waters to drain to the ocean when they reach a certain height, or (2) a pump and pipeline over the top of the beach to siphon lagoon waters to Santa Monica Bay.

8.1.2.2. Salt Marsh Restoration

As a result of modern development, Malibu Lagoon had experienced extensive habitat loss by the late 1970s. In an effort to reverse this trend, DPR initiated a salt marsh restoration project. A parcel of land south of the Pacific Coast Highway (PCH) bridge on the western flank of the lagoon was selected for the project. Under the direction of a group of biologists and landscape architects, three 30-foot wide channels were excavated, flooded, and seeded with salt marsh plants in 1983. The restored salt marsh has the same basic configuration today.

8.1.2.3. Other Projects

In addition to managing lagoon water levels and restoring salt marsh habitat, DPR is attempting to control the spread of non-native plants in the lower watershed. Since the local district does not allocate funds for non-native plant control in its budget, the program takes place on an ad hoc basis when DPR officials secure funds from external sources. DPR ecologists, maintenance personnel, and volunteers carry out the work, which usually involves manual plant removal and light herbicide applications (S. Goode, personal communication).

DPR also has an ongoing sand dune restoration project in the southwestern portion of Malibu Lagoon State Beach. Unfortunately, the project has had limited success because exotic weeds have invaded the site, and the restored dunes are sheltered from prevailing sand-bearing winds by beachfront homes in Malibu Colony (S. Goode, personal communication).

In addition to these projects, DPR is considering undertaking a number of small projects on the eastern flank of the lagoon. These include (1) excavating a waterway to provide access between the lagoon and the Adamson boathouse, (2) removing rock rip-rap under the PCH bridge to improve access between the northern and southern portions of the lagoon, and (3) restoring a ramada and historic picnic area in the "riparian forest" on the eastern bank of Malibu Creek north of PCH (S. Goode, personal communication).

8.1.3. Resource Conservation District of the Santa Monica Mountains

8.1.3.1. Tidewater Goby Reintroduction and Habitat Enhancement

Tidewater goby (*Eucyclogobius newberryi*) populations were extirpated from Malibu Lagoon in the late 1960s. In 1991, the Resource Conservation District of the Santa Monica Mountains (RCD) reintroduced 52 individuals to the lagoon. Malibu tidewater goby populations have thrived ever since; by 1993, they numbered around 500 (Manion 1993).

In 1995, intense creek flows associated with a large winter storm washed out the PCH bridge. In compliance with its reconstruction permits, the California Department of Transportation contributed funds to mitigate the negative impacts of the bridge reconstruction. RCD acquired a portion of these funds and launched a project to enhance tidewater goby habitat in the lagoon (S. Manion, personal communication).

The project, initiated in 1996, comprised the removal of fill material, formation of a narrow peninsula and island, and installation of a cobble spine. Its primary goal is to encourage the deposition of coarse-grained sediment (i.e. sands and gravel) to improve substrate conditions for tidewater goby breeding. Secondary goals include diverting creek flows toward the barrier at the mouth of the lagoon to alleviate flooding problems in Malibu Colony and increasing available mudflat habitat for local bird populations (S. Manion, personal communication).

8.1.3.2. Streambank Restoration

RCD has also restored a 200 linear foot stretch of streambank in the upper watershed near Lost Hills Road in the city of Calabasas. The project involved widening the creek channel, stabilizing the streambank with a geotextile fabric, and revegetating with native plants. Its goal is to prevent further streambank erosion and the subsequent release of suspended sediment to Malibu Creek. The project was supported by the U.S. Environmental Protection Agency, Los Angeles County, and the City of Calabasas (K. Bullard, personal communication).

8.1.4. City of Malibu

8.1.4.1. Groundwater Cutoff Wall

The City of Malibu recently proposed to construct a groundwater cutoff wall along the access road between the lagoon and Malibu Colony. The purpose of the cutoff wall would be to lower groundwater levels in the Colony area, expanding the vertical distance between septic system leachfields and the water table. This separation would increase septic system effluent travel in the unsaturated zone which, in turn, would reduce nutrient and pathogen loads to the lagoon during the summer months (R. Morgan, personal communication).

8.1.4.2. Disinfection/Water Level Management Facility

The City of Malibu and State Parks recently received a $1.2 million Proposition A grant from Los Angeles County for the construction of a disinfection/water level management facility in the lagoon area. The primarily goal of the proposed facility is to remove human pathogens from lagoon waters before they enter Santa Monica Bay, reducing health risks associated with surfing and swimming at Malibu Surfrider Beach. The project would also allow for the management of lagoon water levels, thus eliminating the need for mechanical breaching (City of Malibu 1996).

Basic components of the proposed system would include a small treatment facility in the grassy area adjacent to the parking lot in Malibu Lagoon State Beach, a pump capable of handling 2.5 million gallons per day, spreading basins and screens to remove debris and prevent the ingestion of biota, and an outlet structure to discharge treated lagoon waters offshore. Treatment options include ozonation, microfiltration, and ultraviolet light. Additional components that could be added to the system include a pump and pipeline to increase tidal flushing in the lagoon, and an extensive intake system with multiple pick up locations to enhance circulation within the lower creek and lagoon (City of Malibu 1996).

8.1.4.3. Other Projects

The City of Malibu recently received a $1 million grant from the County of Los Angeles to develop a multi-purpose park in the Civic Center area. Components of the proposed park include a public plaza for recreation and open air events, 3 miles of walkways and riding trails, and a series of wetlands and polishing ponds to treat urban runoff or treated effluent from a local wastewater treatment facility (City of Malibu 1997).

The city is contemplating modifications to its storm drain system to reduce pollutant loads to Malibu Lagoon. Alternatives under consideration include a small treatment wetland and a conveyance system to re-route urban runoff offshore. The Civic Center Specific Plan contains plans to construct a state-of-the-art water reclamation facility in Malibu. The city is also considering a number of flood control projects in the lower creek, including construction of a raised levee near the Arizona crossing and installation of flap-gates on box culverts entering the creek (City of Malibu 1997).

8.1.5. Las Virgenes Municipal Water District

8.1.5.1. Percolation Ponds

In the late 1970s, the Las Virgenes Municipal Water District (LVMWD) reached an informal agreement with DPR to develop a series of "percolation ponds" on 10 acres of land adjacent to the Tapia Water Reclamation Facility (Tapia) in Malibu Creek State Park. The ponds, comprising a series of ditches that serve as infiltration basins for tertiary treated effluent, were completed in the late 1970s. Rather than discharging directly into Malibu Creek, the ponds allow Tapia to polish their effluent before it enters the creek (R. Orton, personal communication).

In 1995, floods associated with a large winter storm event washed out a portion of the percolation ponds. LVMWD's request to repair damaged portions of ditches was denied because local interest groups have been pressuring DPR to allocate the site to recreational use. LVMWD has since developed a proposal to construct a subsurface constructed wetland at the site to filter pollutants from Tapia effluent and creek flows. Its goal would be to achieve relatively modest reductions in pathogens, heavy metals, and nutrients. LVMWD recently won a Los Angeles County Proposition A grant to pursue the project (R. Orton, personal communication).

8.1.6. Army Corps of Engineers

8.1.6.1. Rindge Dam Reconnaissance Study

In the 1920s, the Rindge family commissioned the construction of a dam 2.5 miles north of the mouth of the creek in Malibu Canyon to supply water to their ranching operations. The 100-foot concrete arch dam and reservoir were completed in 1928 with a storage capacity of 574 acre-feet (Doyle et al. 1985). Sediment from Malibu Creek began to accumulate in the reservoir immediately after its inauguration. By the 1950s, the reservoir was completely filled with sediment, rendering it functionally useless (Bureau of Reclamation 1995).

The dam serves as a barrier to anadromous fish such as the steelhead trout (*Onchorhyncus mykiss*), preventing access to historic spawning and rearing habitat in the upper watershed (Franklin and Dobush 1989). Local environmentalists have called for the removal Rindge Dam (Slack 1998) and Congress recently allocated $100,000 to the U.S. Army Corps of Engineers (USACE) to conduct a reconnaissance study to explore this possibility. The primary goals of the 6-month expedited study are to conduct an preliminary assessment of the feasibility of removing the dam, and identify a local governmental agency willing to fund half of a more detailed feasibility study and environmental impact statement. If removal is feasible and a local sponsor is identified, the proposal will go back to Congress for funding consideration.

The USACE study follows a 1995 Bureau of Reclamation (BR) study on the possibility of removing the dam and disposing of the one million cubic yards or so of sediment that have accumulated in the reservoir. The report evaluates three alternatives: (1) hauling sediment to an undetermined disposal site out of Malibu Canyon (estimated cost: $17.5 million, estimated duration: 2 years); (2) using a conveyor belt system to move sediment to an engineered landfill site along Malibu Creek (estimated total cost: $12.8 million, estimated duration: 1 year); and (3) mechanically removing the dam in segments and allowing natural fluvial process to move sediment downstream (estimated total cost: $4 million, estimated duration: 8-18 years). Other options discussed in BR's report include constructing structures to allow anadromous fish to circumvent Rindge Dam, allowing creek flows to erode sediments through a V-notch in top of dam or a hole at base of dam, and adding water to sediments to create a slurry which could be removed hydraulically (Bureau of Reclamation 1995).

8.2. Environmental Problems and Causes

8.2.1. Introduction

This section identifies major environmental problems in the lower Malibu Creek watershed and their primary anthropogenic causes. The goal is to develop an understanding of what problems exist, why they exist, and how they might be solved. This information will be used to develop management objectives and identify potential intervention strategies.

A number of scientific studies have been conducted in Lower Malibu Creek and Lagoon over the past decade, including general environmental assessments (e.g., Manion and Dillingham 1989; Ambrose et al. 1995; National Resource Conservation Service 1995) and detailed studies of resident species (e.g., Franklin and Dobush 1989; Manion 1993, Ambrose and Meffert 1999). By reviewing these and other studies, it is possible to identify a number of environmental problems currently afflicting the lower watershed. For the sake of convenience, these problems can be divided into two "problem categories:" (1) biota and habitat, and (2) water resources.

Table 8-1 identifies these problems and their primary anthropogenic causes. Figure 8-1 presents this information graphically as a problem-cause diagram. The following sections discuss each of the problems in detail.

8.2.2. Biota and Habitat Problems

8.2.2.1. Loss of Aquatic and Riparian Habitat

Loss of aquatic and riparian habitat is one of the most visible aspects of human-induced environmental change in the lower Malibu Creek watershed. This loss is especially pronounced below the base of Malibu Canyon. With the exception of a few areas, the portion of the lower watershed in and above Malibu Canyon has not experienced extensive habitat loss. This section briefly reviews changes in the Lagoon area; more detailed information is provided in Section 1.4.

Although our knowledge of historical conditions in Malibu is incomplete, evidence suggests aquatic and riparian habitat below the base of Malibu Canyon was much more extensive than it is today. Before urban development and channelization within the floodplain constrained its lateral movement, the lower creek occupied a wider floodplain and experienced greater meandering. This combination of a large area and dynamic geomorphic regime allowed for the existence of variety of aquatic and riparian habitat types. Most of this habitat is still present, although it is not as extensive as it was in the past.

Habitat loss in Malibu Lagoon is more dramatic. Prior to modern human occupation, the lagoon area was considerably larger than it is today and contained a rich mixture of aquatic and riparian habitat types. Some of this habitat is present in the lagoon area today, although it is not nearly as extensive as it was in the past. Certain habitat types that occurred in the lagoon during historic times are no longer present. For example, early maps show an arm of Malibu Lagoon extending far to the west of the present lagoon (Section 1.4.2). No similar expanse of open water habitat is encountered in the lagoon area today.

Infilling and urbanization have been the primary anthropogenic driving forces behind habitat loss in the lagoon area, initially through ranching, later through housing development, railroad and highway construction, and more recently by commercial development. These activities have greatly reduced the amount of aquatic and riparian habitat in the lagoon area. In order to prevent flooding, a large portion of the western bank of the creek was reinforced with rip-rap and other materials, destroying riparian habitat and inhibiting the delivery of water to permanent and seasonal wetlands in the Civic Center area (Manion 1993).

8.2.2.2. Proliferation of Exotic Species

Proliferation of exotic species is another serious problem afflicting the lower creek and lagoon. According to recent ecological surveys, fish and plants are the taxa most affected by non-native invasions. Of the five fish species commonly found in the lower creek, four are non-native (Ambrose et al. 1995). In addition to shaping species composition, non-native fish dominate the overall distribution of fish in the lower creek, accounting for 87.6% of the total catch (Ambrose et al. 1995). The spread of non-native fish is not as dramatic in Malibu Lagoon; only one of the thirteen species commonly found in the lagoon is non-native (Ambrose et al. 1995).

Like exotic fish, non-native plants have become common in the lower creek. A number of exotic species are encountered regularly in the riparian zone, including giant reed (*Arundo donax*) and castor bean (*Ricinus communis*) (see Section 4.1). Although both species are undesirable, *Arundo* is especially problematic since it is highly invasive, forms monotypic stands with little habitat value, and may allow fire to encroach into the riparian zone (Bell 1995). *Arundo* reproduces vegetatively; invasions typically commence in the upper reaches of watersheds and spread downstream as flood flows deposit severed roots and shoots downstream (Bell 1995). Non-native plants are also common in the lagoon area. According to Manion and Dillingham (1989), sixty-five percent of the vascular plants in the lagoon area are of non-native origin.

Elevated freshwater and nutrient inputs have contributed to the proliferation of exotic species in the lower creek and lagoon. Over the last fifty years or so, human populations in the Malibu Creek watershed have grown substantially. Since local supplies are insufficient to meet demand, water authorities have imported water into the catchment from outside sources. After it is used, most of this water finds its way to Malibu Creek.

These inputs have altered the natural hydrologic regime in the lower watershed dramatically. Total creek flows have increased and the seasonal pattern of creek flows has changed from a regime characterized by very low or nonexistent dry season flows to one of constant background flows (Manion 1993; Natural Resources Conservation Service 1995). As a result, organisms in the lower creek and lagoon are subject to year-round freshwater inputs and low salinity levels.

As an estuarine ecosystem, Malibu Lagoon experiences fluctuating salinity levels. When creek discharges are high or the barrier beach closes, the lagoon experiences low salinity levels. When creek discharges are low but the lagoon is open to the ocean, the lagoon experiences the higher salinity levels associated with ocean water (Manion and Dillingham 1989; Ambrose et al. 1995). As a consequence of these salinity variations, Malibu Lagoon is dominated by organisms tolerant of a wide range of salinity levels. This has also been the case for many natural wetland systems in California (Swift et al. 1989).

Human-induced water inputs lessen these salinity fluctuations, promoting freshwater conditions in the lagoon and allowing non-estuarine species to persist in the lagoon. These conditions provide an opportunity for non-native fish and plant species, most of which prefer freshwater environments, to invade Malibu Lagoon (Manion 1993).

Elevated nutrient inputs have also contributed to the proliferation of exotic species in the lower creek and lagoon. As a result of human population growth and anthropogenic activities, the Malibu Creek watershed receives unnaturally high nutrient loads (Ambrose et al. 1995). The lower creek and lagoon serve as sinks for nutrients generated within the watershed and, consequently, experience high nutrient concentrations. It is hypothesized that this increased nutrient availability allows opportunistic, non-native species to invade Lower Malibu Creek and Lagoon.

8.2.2.3. Reduced Benthic Invertebrate Populations

Benthic invertebrates (e.g., clams, crabs, shrimp, and worms) play an important role in wetland ecosystems; they serve as food for fish and birds and increase the availability of nutrients and organic matter for other aquatic organisms (Ambrose et al. 1995). Since they perform vital ecosystem functions and are sensitive to disturbance, it has been suggested that benthic invertebrates be used as indicators of overall ecological health and integrity (Karr 1991).

Southern California coastal wetlands are generally rich in benthic invertebrates, supporting as many as 200 species in some cases (Zedler et al. 1992). Recent ecological surveys conducted in Malibu Lagoon suggest local benthic invertebrate communities are impoverished. Manion and Dillingham (1989) encountered only two infauna species in the lagoon. Ambrose et al. (1995) identified a total of 17 benthic invertebrate species, but found a number of taxa to be impoverished, including bivalves (only one species) and polychaetes (only two families). These figures are low compared to data obtained in other southern California coastal wetlands (Zedler 1982; Ambrose et al. 1995).

Attenuated tidal flushing represents one of the factors that contribute to this phenomenon. According to Nordby and Covin (1988), benthic invertebrate richness is often reduced in coastal wetlands that do not experience good tidal flushing. Malibu Lagoon constitutes one such system. During the wet season, high creek flows breach the barrier at the mouth of the lagoon, opening the lagoon to Santa Monica Bay. Under these conditions, the lagoon generally experiences good tidal flushing. During the dry season, creek flows drop allowing marine sands to form a barrier that inhibits tidal flow. Under these conditions, the lagoon experiences little or no tidal flushing.

Since historical data are lacking, it is unclear whether the frequency and duration of barrier closure in Malibu Lagoon have increased or decreased as a result of human activity. Certainly, a number of anthropogenic forces have interfered with tidal movement into and out of Malibu Lagoon, including infilling, which has reduced the water-holding capacity of the lagoon, and road-building, which has inhibited natural lagoon hydrodynamics. As a result, it is reasonable to assume tidal prism has decreased over time, promoting more frequent and longer-lasting barrier beach closure. However, elevated freshwater flows have increased total creek discharges and flood control projects along the lower creek have concentrated flows toward the mouth of the lagoon. Together, these forces may have increased the scouring effect of creek flows, leading to more frequent and prolonged breaching of the barrier beach. Since there are no historical data available, we cannot say whether tidal flushing in Malibu Lagoon has increased or decreased compared to its pre-development state.

There are other human factors that have clearly played a role in the impoverishment of Malibu Lagoon's benthic invertebrate community, including loss of aquatic habitat and elevated freshwater flows. In the past, Malibu Lagoon was much larger and had a greater expanse and diversity of aquatic habitat. Accordingly, the lagoon contained a wide variety of microhabitats for benthic invertebrates. Over the last hundred years or so, infilling and urbanization have greatly reduced aquatic habitat in the lagoon area. Some microhabitats have been reduced in size; others have been eliminated entirely. As a result, the lagoon cannot accommodate as many benthic invertebrate species as in the past.

Elevated freshwater flows have probably played a large role in contributing to the decline of Malibu Lagoon's benthic invertebrate community as well. As described earlier, human population growth has increased freshwater flows to the lagoon. As a result, the lagoon is subject to lower salinity levels than in historic times. This phenomenon has probably had a negative impact on lagoon benthic invertebrate communities. Some of the more halophilic benthic invertebrate species are unable to persist in freshwater environments; others survive in low numbers. Manion (1993) attributes recent declines in Malibu jackknife clam populations (*Tagelus californicus*) to low lagoon salinity levels.

Eutrophication is another human factor that may have contributed to the decline of benthic invertebrate populations in Malibu Lagoon. Eutrophication promotes declines in dissolved oxygen concentrations, particularly in the depths of the water column. In some cases, anoxic conditions at the sediment surface. Many benthic invertebrates are unable to persist in these conditions.

Finally, it is possible that elevated contaminant inputs have adversely affected invertebrates in Malibu Lagoon. Although the Malibu Creek watershed is not highly urbanized, there are a variety of sources of contaminants in the watershed. Ambrose et al. (1995) and Cohen et al. (in press) report elevated levels of metals in invertebrates. Body burdens of several metals were high enough to suggest that some impairment might be occurring.

8.2.2.4. Reduced Native Bird Populations

Since they contain abundant food supplies and a variety of habitats, coastal wetlands are important resources for birds. For this reason, coastal wetlands typically accommodate rich native avian faunas. Southern California coastal wetlands are no different, hosting as many as 300 bird species in some instances (Zedler 1982).

Since it contains one of the last remaining coastal wetlands in Los Angeles County and is located on the Pacific flyway, Malibu Lagoon is an important regional center for birds. Two major groups of birds are typically found in the lagoon area: (1) waterbirds (e.g., gulls, shorebirds, ducks, divers, coots, rails, herons, and egrets) which occupy open water and intertidal habitat in the lagoon, and (2) landbirds (e.g., starlings, bushtits, and finches) which occur in scrub habitat in the flanks of the lagoon (Ambrose et al. 1995).

Recent bird surveys have confirmed Malibu Lagoon's importance to birds, with up to 262 bird species observed in the lagoon area (Kiff and Nakamura 1979; Manion and Dillingham 1989; Ambrose et al. 1995). These numbers compare favorably to other southern California coastal wetlands which is impressive given Malibu Lagoon's small size. Including both aquatic and terrestrial components, the lagoon covers 35.1 acres (14.7 hectares). Other southern California coastal wetlands known for their rich avian faunas (200-300 species) occupy areas 30-70 times larger than Malibu Lagoon (Ambrose et al. 1995).

Although the lagoon has high avian species richness, there are undoubtedly fewer birds using the Lagoon area than in historic times. A number of anthropogenic forces may have contributed to this decline, including loss of aquatic and riparian habitat. Prior to the modern human occupation of Malibu, the lagoon area was much larger, contained a more diverse mixture of habitat types, and presumably supported more birds than today.

Persistent high lagoon waters during the dry season also may have played a role in the decline of native bird populations in Malibu. When the barrier beach closes during the dry season, the lagoon serves as a sink for elevated freshwater flows, leading to persistent high water levels. This condition poses a problem for shorebirds, terns, herons, egrets, and other birds that forage in intertidal flats. When lagoon water levels are low, intertidal flats are exposed, making foraging resources readily available. When lagoon water levels are high, intertidal flats are submerged and unavailable. For this reason, bird densities in Malibu Lagoon typically parallel intertidal flat availability (Ambrose et al. 1995).

8.2.2.5. Endangered Bird Populations

A number of endangered bird species regularly visit Malibu Lagoon. Snowy plovers (*Charadrius alexandrinus*) nested on the barrier beach until the late 1950s or early 60s. Although they no longer nest at Malibu, snowy plovers commonly visit sandy beach habitat along the southern edge of Malibu Lagoon, excavating small hollows in the sand and feeding at the water's edge. Persistent high water levels in the lagoon inhibit snowy plovers' use of the lagoon (S. Wolcott, personal communication).

Although they do not currently nest in the lagoon area, California least terns (*Sterna antillarum browni*) probably nested on the barrier beach in the past (S. Wolcott, personal communication). They continue to use the lagoon for roosting and can often be seen diving for fish.

Brown pelicans (*Pelicanus occidentalis*) also use the lagoon (Ambrose et al. 1995), primarily as a roosting area.

8.2.2.6. Reduced Native Fish Populations

Southern California coastal wetlands play an important role in the life cycle of native fish species. For some, they serve as primary habitat; for others, southern California coastal wetlands serve as breeding grounds, nurseries, or feeding areas. As one of the last remaining coastal wetlands in Los Angeles County, Malibu Lagoon is an especially important resource for local wetland fish populations. Recent fish surveys indicate fish species richness in Malibu Lagoon is low compared to other southern California coastal wetlands. Manion and Dillingham (1989) identified 13 species in the lagoon with a distribution dominated by a few prevalent species that accounted for over 99% of total catch. Ambrose et al. (1995) found similar results.

Barrier beach closure exerts a strong influence on fish composition in Malibu Lagoon. Other southern California wetlands that experience frequent and prolonged barrier closure have similar numbers of fish species as Malibu; wetlands that are continuously open to the ocean or are only occasionally closed have considerably more species, especially marine species (Ambrose et al. 1995; Swift et al. 1993). As described earlier, determining whether barrier beach closure was more or less common in the past is difficult. Thus, prolonged barrier beach closure is not necessarily an anthropogenic phenomenon that has led directly to a decreased native fish abundance.

There are, on the other hand, a number of anthropogenic factors that have clearly played a role in the decline of native fish populations in Lower Malibu Creek and Lagoon. The loss of quality fish habitat is one such factor. The larger lagoon that appears on early maps could have supported large fish populations. The lower creek and lagoon now have far less total habitat and a less diverse pool of microhabitats available and, consequently, are not capable of supporting as large fish populations as in the past.

Proliferation of exotic species also might have contributed to the decline of native fish populations in Lower Malibu Creek and Lagoon. Swift et al. (1993) have noted the large number of non-native fish species in California as well as their devastating effects on native fish faunas. As described earlier, non-native fish have become increasingly common in Malibu Creek, particularly in the lower creek. Many exotics compete with natives for critical resources. Others such as the green sunfish (*Lepomis cyanellus*), large-mouth bass (*Micropterus salmoides*), and bluegill (*Lepomis macrochirus*) prey on native fish (Manion 1993). Both of these interactions, competition and predation, have probably had a negative impact on native fish populations in the lower Malibu Creek watershed. Effects of the abundant introduced mosquitofish are not known, but may be significant (Hurlbert et al. 1972, Gamradt and Katz 1997).

Barriers to fish migration have negatively impacted native anadromous fish populations in the lower Malibu Creek watershed, particularly the Pacific lamprey (*Lamptetra tridentata*) and endangered steelhead trout (*Onchorhyncus mykiss*). A number of artificial structures have been constructed to regulate flows down Malibu Creek, notably Rindge Dam. These and other natural barriers such as tunnel falls inhibit the upstream movement of anadromous fish, denying them access to spawning and rearing habitat in the upper watershed. As a consequence, 86% of the total potential spawning habitat and 65% of the total potential rearing habitat in the watershed is inaccessible to steelhead and lamprey (Franklin and Dobush 1989).

In addition to factors that have played a direct role in their declines, there are a number of anthropogenic forces that potentially threaten native fish populations. The first is fine sediment deposition. By nature, the Malibu Creek watershed is highly erosive. Human activity has augmented natural erosion rates in the watershed, at least during the development phase, by exposing soil surfaces and increasing the scouring power of runoff. As a consequence, the lower creek and lagoon are subject to high rates of fine sediment deposition (Manion 1993).

Fine sediment may negatively impact native fish populations in a number of ways. When it is deposited on the coarse sand and gravel substrates used for spawning by native fish populations, fine sediment may damage the physical integrity of spawning burrows or inhibit oxygen delivery to developing embryos (McEwan and Jackson 1996). Fine sediment may also harm fish populations by impacting primary producers and invertebrates (Wood and Armitage 1997).

Mechanical breaching represents another potential threat to native fish populations in the lower Malibu Creek watershed, particularly the endangered tidewater goby (*Eucyclogobius newberryi*). In the past, the California Department of Parks and Recreation typically breaches the barrier beach when lagoon water levels become problematic. When the barrier beach is closed, tidewater goby populations congregate near the mouth of the lagoon (Manion 1993). If a mechanical breach is initiated under these conditions, as it often is, gobies can be swept out to the ocean (Manion and Ambrose, unpub. data). Mechanical breaching could also negatively impact the tidewater goby and other native fish by rapidly increasing salinity levels. In some instances, such rapid increases can cause fish to die from osmotic shock (Capelli 1997). Precipitous drops in lagoon water levels can expose juvenile fish and incubating eggs in breeding burrows to desiccation and death and greatly decreases the amount of suitable fish habitat in the lagoon (Manion 1993; Capelli 1997). Although it primarily threatens the tidewater goby and other lagoon species, mechanical breaching can also have detrimental impacts on the survival of juvenile steelhead who use the lagoon as a nursery before migrating to the ocean (McEwan and Jackson 1996).

Finally, it is possible that elevated contaminant inputs have adversely affected fish in Malibu Lagoon. Although the Malibu Creek watershed is not highly urbanized, there are a variety of sources of contaminants in the watershed. Ambrose et al. (1995) and Cohen et al. (in press) report elevated levels of metals in fish. Body burdens of several metals were high enough to suggest that some impairment might be occurring.

8.2.2.7. Endangered Fish Populations

Two endangered fish species are known to occur in the lower Malibu Creek watershed. The tidewater goby, a member of the family Gobiidae, is endemic to California coastal lagoons and estuaries between Agua Hedionda in San Diego County to Tillas Slough in Del Norte County (Capelli 1997). Since the turn of the century, human activities have caused the extirpation of around half of all tidewater goby populations (Swift et al. 1989). In 1994, the U.S. Fish and Wildlife Service responded to this decline by designating the tidewater goby as an endangered species. Scientists consider southern California populations the most endangered of all tidewater goby populations (Swift et al. 1989). The tidewater goby was extirpated in Malibu Lagoon, but was re-introduced in 1991.

The steelhead trout is an anadromous form of the rainbow trout. Although they are abundant in the Pacific Northwest, southern steelhead populations are scarce, especially those south of the Santa Maria River in San Luis Obispo County. Based on this pattern, the National Marine Fisheries Services added southern coast steelhead populations to the national endangered species list in 1997. Although there has not been a steelhead sighting in Malibu for over three years (Slack 1998), Malibu Creek is considered the southernmost stream containing known spawning populations.

8.2.2.8. Reduced Native Plant Populations

Aquatic and riparian plants serve a variety of important ecological functions; they stabilize sediment, filter pollutants from runoff, and provide habitat for aquatic and terrestrial organisms. Recent botanical inventories reveal some cause for concern about the native plant communities of the lower Malibu Creek watershed. As described earlier, there has been an alarming increase in non-native plants in the riparian zone, particularly *Arundo donax* (Chapter 4). Plant species richness in Malibu Lagoon is low compared to other southern California coastal wetlands (Ambrose et al. 1995). Pickleweed (*Salicornia virginica*), abundant in most southern California salt marshes, is surprisingly sparse in Malibu Lagoon (Ambrose et al. 1995). Although they identified a total of 133 species of vascular plants, Manion and Dillingham (1989) found only 35% of all lagoon plants to be native.

A number of anthropogenic factors have contributed to the decline of native plant populations in the lower watershed. Habitat loss is the first and most obvious. Prior to modern human occupation, aquatic and riparian habitat in the Lagoon area was much more extensive and plant communities were more diverse than today. Proliferation of exotic species has also contributed to the decline of native plant populations in the lower watershed. As described earlier, non-native plants have become common in the lower creek and lagoon, undoubtedly at the expense of native plants.

Plant populations in the restored salt marsh have also been affected by other anthropogenic factors. Excess freshwater flows have lowered salinity levels, preventing halophytes from outcompeting their less salt-tolerant counterparts. The increased presence of California bulrush (*Scirpus californicus*) in one channel of the restored salt marsh serves as testimony to this phenomenon. Persistent high water levels in the lagoon during the dry season have also played a role in the decline of native salt marsh plant populations. Many salt marsh plants require extended drawdown periods to germinate; persistent high lagoon water levels probably interfere with their regeneration (Zedler 1995). Such water levels also cause plant mortality, as evidenced by the ring of dead vegetation in channels of the restored salt marsh caused by the prolonged high water during the summer of 1997.

8.2.3. Water Resource Problems

8.2.3.1. Eutrophication

Eutrophication is the process by which water bodies become enriched in dissolved nutrients, leading to elevated aquatic plant growth. Eutrophic (high nutrient) conditions can occur naturally, but eutrophication is commonly linked to the release of unnaturally large quantities of nutrients into water bodies associated with human activities. If nutrients are high enough, aquatic plant growth will be exceedingly high. This in itself can be perceived as undesirable due to visual impacts (e.g., algal mats floating on the water surface), clogging of waterways, and nuisance odors. The most important biological impacts are the indirect effects of algal and plant growth. Large amounts of dissolved oxygen in the water are used for respiration by the aquatic plants and algae. At night, when oxygen produced during photosynthesis cannot balance oxygen used in respiration, dissolved oxygen levels in the water column can drop to very low levels. In addition, when the plants and algae die, their decomposition likewise results in low water-column oxygen levels. When eutrophication is severe, the dissolved oxygen in the water can be reduced to levels that result in the death of fish and aquatic invertebrates. In addition to acute effects, eutrophication can promote changes in species composition, favoring taxa that are adapted to high nutrient and low dissolved oxygen concentrations (Vollenweider 1992).

Although anecdotal accounts of excessive algal growth and unpleasant odors abound, eutrophication in the lower Malibu Creek watershed is not well documented. Between 1993 and 1994, Ambrose et al. (1995) attempted to evaluate eutrophication in Malibu Lagoon. Their efforts were thwarted, however, by unusual conditions in which the lagoon remained open to the ocean throughout the dry season. Eutrophication is likely to be most extensive when the lagoon is closed to the ocean, which leads to an accumulation of nutrient-laden waters, increased water temperatures, and low salinity levels. Such conditions generally occur during the dry season, but did not occur during 1994. Consequently, the researchers were unable to document the full extent of eutrophication in the lagoon. Nevertheless, they did observe a number of conditions indicative of eutrophication including (1) nutrient concentrations greater than 10 mg/L, (2) dense floating algal mats, and (3) dissolved oxygen concentrations below 5 mg/L (Ambrose et al. 1995). Manion and Dillingham (1989) also documented dissolved oxygen concentrations below 5 mg/L at several locations in the lagoon. Although they do not document the full range of eutrophication that can occur in the Lagoon, these observations show that some eutrophication occurs in Malibu Lagoon. Some of the secondary effects of eutrophication were also observed, including mortality of fish captured overnight in minnow traps. However, extensive fish kills were not observed (Ambrose et al.1995).

Elevated nutrient and freshwater inputs are the primary anthropogenic causes of eutrophication. As described earlier, the lower creek and lagoon receive unnaturally high nutrient inputs from point and nonpoint sources within the watershed. Coupled with elevated freshwater flows and resulting low salinity levels, these nutrients promote conditions favorable to the growth of algae and other macrophytes. When these organisms die and decay, they consume dissolved oxygen in the lower creek and lagoon, completing the eutrophication cycle.

Eutrophication issues are discussed in more detail in Chapter 5.

8.2.3.2. High Contaminant Concentrations

Although the Malibu Creek watershed is not highly urbanized, there are a variety of sources of contaminants in the watershed. Ambrose et al. (1995) reported elevated levels of some organic compounds, such as PAHs, in the creek system. Ambrose et al. (1995) and Cohen et al. (in press) report elevated levels of metals in invertebrates and fish, the only two taxa examined. Body burdens of several metals were high enough to suggest that some impairment might be occurring. No studies have been conducted on contaminant levels in plants, but it is possible that plants are affected by contaminants at Malibu. Similarly, no studies have been conducted on contaminant levels in birds occurring at Malibu. Most birds are transients at Malibu, but because some feed in the lagoon, it is possible that there is a transfer of contaminants up the food chain from invertebrates and fish to birds.

8.2.3.3. High Pathogen Concentrations

High pathogen concentrations in Lower Malibu Creek and Lagoon are well documented. Gold et al. (1992) sampled for bacterial indicators (total coliforms, fecal coliforms, enterococci) and enteric viruses at three locations in the lower creek and lagoon during the summer months. The authors encountered mean bacterial densities one to twenty times higher than the objectives outlined in the California Ocean Plan and detected coxsackie B virus, which can cause gastroenteritis, pericarditis, and meningitis.

Subsequent studies have substantiated these findings. Ambrose et al. (1995) and NPDES reports submitted to the Los Angeles Regional Water Quality Control District by the Las Virgenes Municipal Water District have detected total coliform, fecal coliform, and enterococcus concentrations in excess of state and federal water quality standards on multiple occasions. Particularly high bacterial densities were observed during the summer months and after rainfall events. Ambrose et al. (1995) also detected viruses in samples of Tapia effluent using polymerase chain reaction (PCR) and traditional tissue culture for enteroviruses. (The significance of these positives is not clear, however, because PCR does not differentiate "live" from "dead" viruses, or whole viruses vs. fragments of virus nucleic acid, nor quantify the amount of virus in a sample.) Pathogen results reported in Chapter 6 indicate that pathogenic protozoan parasites (*Giardia* and *Cryptosporidium*) are found in Malibu Creek and the surf zone.

Unfortunately, the pathogen problem is not limited to the Lower Creek and Lagoon. High pathogen concentrations are also encountered at Malibu Surfrider Beach, one of the most popular surfing spots in southern California. In their semi-annual beach report cards, Heal the Bay consistently rates Malibu Surfrider Beach as one of the worst places to swim in Santa Monica Bay. During the summer, water quality at Surfrider Beach typically receives D or F grades; during the rainy season, Surfrider Beach almost inevitably receives F (Fleischli et al. 1998).

High pathogen concentrations in the lower creek, lagoon, and surf zone potentially have adverse health effects on swimmers and surfers. In a recent study, Haile et al. (1996) documented an increased incidence of illness among individuals who swam immediately adjacent to the mouth of Malibu Lagoon. Positive correlations were detected between swimmers' illness, distance from lagoon mouth, bacterial indicator density, and presence of enteric viruses.

Elevated pathogen inputs are the primary anthropogenic cause of high pathogen concentrations in the lower creek and lagoon. Elevated freshwater flows also contribute to the problem. Bacterial indicators and viruses survive better in freshwater than brackish or marine environments (Valiela et al. 1991; Gersberg et al. 1995). By lowering salinity levels, elevated freshwater flows allow pathogens to persist longer than they would under more natural conditions. Bacterial concentrations in the lower Malibu Creek watershed lend support to this notion; Gold et al. (1992) found higher bacterial concentrations upstream than near the ocean.

Human-induced nutrient inputs and eutrophication also promote high pathogen concentrations in Lower Malibu Creek and Lagoon. Nutrients increase the growth rate of pathogenic microorganisms. Eutrophication lowers dissolved oxygen concentrations, creating conditions conducive to the survival of human pathogens (Harris 1995).

8.2.3.4. Persistent High Lagoon Water Levels During the Dry Season

During the wet season, precipitation promotes high creek flows that displace all or part of the barrier beach, opening Malibu Lagoon to the ocean (Chapter 2). As long as the lagoon remains open, discharges from the creek flow directly into Santa Monica Bay. Lagoon water levels fluctuate with the tides, but are generally low under these conditions. During the dry season, creek discharge diminishes, allowing wave processes to reconstruct the barrier beach, sealing the lagoon off from the ocean. While the barrier beach is closed, the lagoon serves as a sink for creek flows, and lagoon water levels rise.

Elevated dry season freshwater flows are a major anthropogenic cause of high lagoon water levels. As described earlier, the introduction of imported freshwater into the Malibu Creek watershed has changed the natural hydrologic regime of the lower creek and lagoon dramatically. Whereas they were typically low in historic times, dry season flows now constitute a sizeable input to the lagoon. Since they are not strong enough to breach the barrier beach, dry season freshwater flows accumulate in the lagoon, raising water levels. Unless evaporative losses are exceptionally high, elevated water levels persist in the lagoon until the barrier beach is breached.

Persistent high lagoon water levels lead to secondary problems. By raising groundwater levels beneath Malibu Colony and the Civic Center area, high water levels prompt septic system failures and unhealthful pathogen concentrations in the lagoon. Persistent high lagoon water levels also negatively impact bird populations by making intertidal flats inaccessible. Prolonged inundation also causes mortality of the salt marsh plants fringing tidal creeks in the restored salt marsh.

Development in Malibu has aggravated lagoon water quantity problems. Infilling associated with urban and residential growth has reduced the water holding capacity of the lagoon. Consequently, the lagoon is less able to accommodate human-augmented freshwater inputs without water levels becoming problematic.

8.3. Biota and Habitat Management Alternatives

8.3.1. Introduction

This section identifies and evaluates biota and habitat management alternatives for Lower Malibu Creek and Lagoon. As described previously, biota and habitat problems in the lower creek and lagoon include loss of aquatic and riparian habitat, proliferation of exotic species, and reduced native species populations. Infilling and urbanization, elevated freshwater flows, eutrophication, persistent high lagoon water levels, and barriers to anadromous fish migration are the primary anthropogenic causes of these problems.

8.3.2. Procedure

The analysis of alternatives began with a compilation of potential alternatives. In identifying these alternatives, we referred to previous work done at Malibu, including the facilitated watershed meetings, watershed conferences, and previous studies (e.g., Manion and Dillingham 1989, Keegan 1990, Manion 1993, Ambrose et al. 1995). We also considered management actions taken elsewhere. Our goal in this stage was to be inclusive, even though particular alternatives might not be feasible or have undesirable consequences. We presented the Malibu Lagoon Task Force with a preliminary list of alternatives and solicited comments and suggestions for additional alternatives.

Once our list of alternatives was determined, we evaluated each alternative based on feasibility, cost, effectiveness, environmental impacts, and potential controversy. We did not assign an explicit weighting to each of these factors; instead, we relied on our judgement in weighing the importance of each factor for a particular alternative. However, there is a logical sequence for evaluating a technique. Feasibility is of fundamental importance; if a technique is not feasible, there is no point in considering it further. Next, effectiveness and environmental impacts are considered. Clearly, the best alternatives would have great effectiveness with no adverse environmental impacts; most alternatives are not so clear cut. Our analyses were completed as a screening tool within the short time frame of this project, and cannot substitute for a more detailed technical analysis. In most cases, a more detailed analysis would be required before implementing an alternative. We also considered cost in a general way. We did not conduct detailed cost analysis for any alternative; particularly for the alternatives involving engineering, this means that our cost assessment is very rough and there is a great deal of uncertainty about what the actual cost would be. However, we wanted to include a rough cost assessment to help us distinguish between alternatives. For example, an alternative with a moderate effectiveness might be given a high priority if it was inexpensive, but a low priority if it was very expensive. In the extremes, cost was considered in the ranking of alternatives, but it was not used to make fine distinctions because there is so much uncertainty in the assessments. Finally, we also felt it was important to consider potential controversy, since the management alternatives will be implemented in the public arena and there are many active stakeholders. However, potential controversy *per se* had little influence on the ultimate ranking of an alternative.

Following internal evaluation of each alternative, we consulted with the Malibu Lagoon Task Force. We presented the Task Force with a summary of the alternatives and our evaluations. Initial discussions focused on the "viability" of each alternative, with an alternative being considered "not viable" if it (a) is not capable of being implemented (e.g., not technically feasible) in Malibu Creek/Lagoon, (b) would not work or function properly in Malibu Creek/Lagoon, or (c) has unacceptable attributes (e.g., significant negative environmental impacts). For each viable measure, we discussed the priority for implementation ("high," "medium," or "low"). We attempted to reach a consensus among the Task Force members, but of course that was often not possible.

The analyses presented in this report reflect our consideration of all the factors known to us concerning the alternatives, including discussion with the Task Force and comments on the draft final report. In virtually every case, there are significant uncertainties. Nonetheless, we have attempted to provide a definitive judgement about each alternative, although the degree of uncertainty was so great for several alternatives that it precluded defining a priority level. We did not assess the alternatives relating to Rindge Dam because a more extensive study is currently being conducted by the U.S. Army Corps of Engineers.

8.3.3. Analysis of Alternatives

Table 8-2 identifies biota and habitat management objectives for Lower Malibu Creek and Lagoon based on this list of problems and causes. Table 8-3 evaluates management alternatives that could potentially be employed to achieve these objectives. The following sections discuss each of the alternatives in detail.

8.3.3.1. Non-native Species

As described previously, exotic species have become increasingly more common in the lower Malibu Creek watershed. Factors responsible for this phenomenon include nutrient inputs and elevated freshwater flows (especially in summer). Decreasing freshwater flows and nutrient inputs thus represents one means of reducing non-native populations in the lower creek and lagoon. Alternatives for accomplishing this goal are discussed in Section 8.4 of this report.

Exotic populations in the lagoon could be reduced by increasing tidal flushing, which would raise lagoon salinity levels and allow native fish and plants to outcompete their non-native, freshwater counterparts. Alternative means of increasing tidal flushing in Malibu Lagoon are discussed in Section 8.4. Salt application might also help reduce exotic plant species in the lagoon. According to Kuhn and Zedler (1997), this might be an effective non-native plant control strategy in areas receiving unnaturally high freshwater inputs.

There are limited options for removing native fish from a system by direct manipulation (as opposed to modifying physical processes). In extreme cases, sections of a stream or a lake is poisoned to remove all species, then re-stocked with native species. A recent, well publicized example of this is Davis Lake in the western Sierra foothills, where rotenone was used to kill fish in the lake in an attempt to control introduced pike. This decision by the California Department of Fish and Game caused a great deal of controversy, and even after the rotenone treatment, pike were later found in the lake again. We have not considered this type of manipulation for Malibu Creek or Malibu Lagoon. Instead, we have considered alternatives that involve less drastic manipulations, either through addition of biocontrol species or mechanical removal.

8.3.3.1.1. Alternative #1: Biomanipulation to reduce non-native fish populations

Biomanipulation (#1, Table 8-3) could be employed to limit the spread of non-native fish populations in the lower creek and lagoon. There is a great deal of uncertainty associated with this alternative (Table 8-3). In most cases, research would be needed to identify a suitable control agent. There is considerable uncertainty about the outcome of such research, and it could be many years before a potential agent was suitably tested and approved by state and federal resource agencies. Extensive testing would be needed to avoid impacts to non-target organisms. Furthermore, it is unclear whether biomanipulation would actually reduce non-native fish populations in the lower creek and lagoon. For these reasons, Management Alternative 1 is considered impractical at this time (although it might be appropriate in the future if a suitable control agent is identified and proven both effective and safe).

8.3.3.1.2. Alternative #2: Remove non-native invasive plants and revegetate with native species

Removing exotic species and revegetating with native species could control exotic plants (#2). This could be accomplished in phases with motorized equipment to remove large colonies, manual removal of small colonies or individual plants, and herbicide application (Wetlands Research Associates 1994). Suitable native candidates for revegetation include willow (*Salix spp.*) and sycamore (*Platanus racemosa*) in the riparian zone and salt grass (*Distichlis spicata*) and fleshy jaumea (*Jaumea carnosa*) in wetlands. Alternative 2 would be relatively inexpensive on a small scale; one estimate put the cost at $12,000 per acre (Wetlands Research Associates 1994). It is unclear how successful it might be unless there was a continuous monitoring and maintenance effort. Since many non-native, invasive species resist treatment, removal would likely have to be repeated on a regular basis. Despite this drawback, Management Alternative 2 is considered high priority given the ongoing explosion of exotic plants in the lower creek and lagoon.

8.3.3.2. Reduced Bird Populations

Because of the extensive loss of wetland habitat in the Malibu Lagoon area, there are undoubtedly fewer birds using the Lagoon. This problem could be addressed by restoring aquatic and riparian habitat. Local bird populations would benefit from increased tidal flushing, which would provide a more abundant supply of benthic invertebrates for foraging. Wetland restoration and enhancement would also enhance bird populations by increasing overall habitat availability and providing a greater diversity of microhabitats for birds, thereby allowing more species to persist in the lagoon area. Potential means of achieving this objective are discussed in Chapter 9.

By inhibiting access to intertidal flats, persistent high water levels also negatively impact some bird populations, particularly shorebirds. This problem could be mitigated by reducing freshwater flows and managing lagoon water levels so that intertidal mudflats are exposed. Alternatives for achieving these goals are discussed in Section 8.4. No alternatives are proposed specifically for bird populations.

8.3.3.3. Endangered Birds

Although they still occur in Malibu Lagoon, snowy plover and California least tern populations are constrained by a lack of suitable nesting habitat and human and predator encroachment. These endangered bird populations might be re-established if these problems were alleviated. This could be accomplished by constructing a bird nesting island in the lagoon (#3) or erecting signs and fences in critical areas (#4).

Brown pelicans typically use the central area of the Lagoon as a roosting site. Unlike the least tern or snowy plover, which have limited nesting areas remaining along the California coast and hence could benefit from nesting sites at Malibu, it is unlikely that roosting sites limit brown pelican populations.

8.3.3.3.1. Alternative #3: Construct a bird nesting island in the lagoon

A composite island would provide nesting habitat for snowy plovers and least terns, restoring one of Malibu Lagoon's lost habitat functions. Nesting habitat could also be constructed on an existing island on the eastern side of the lagoon; this option is evaluated as a restoration alternative in Chapter 9. The nesting island in the middle of the lagoon has one important advantage over the eastern island; it would be more isolated from the surrounding upland areas. Consequently, nesting birds would be better protected from predators and humans. However, a central location would put the island in the direct path of high creek flows; protecting the island from the force of floods (e.g., by armoring with rip-rap) would increase the expense of building the island. An island in the middle of the lagoon would also alter lagoon hydrodynamics. This alternative is considered impractical because a central island would not be consistent with the natural hydrodynamics of the lagoon system and would not survive winter stream flows.

8.3.3.3.2. Alternative #4: Erect signs and fences to prevent human and domestic animal encroachment

Erecting signs and fences would reduce human and predator encroachment in areas that are frequented by endangered birds. Fences have been used to set aside areas for endangered bird species in other areas, such as in Venice Beach. The lagoon side of the barrier beach, an area used extensively by snowy plovers, is a strong candidate for this alternative.

Although they might help re-establish endangered bird populations in Malibu, signs and fences would negatively impact the aesthetic quality of the lagoon, both from their presence and from the trash and debris they would collect. Appropriate design and maintenance could potentially mitigate these impacts, and perhaps local community or environmental groups could collect trash. More importantly, fences would be difficult to maintain in the dynamic barrier beach environment. Because the barrier beach is normally removed each year, fences would need to be erected and removed annually or more frequently as the barrier beach morphology changes.

Erecting signs (#4a) to warn against disturbing birds would be relatively simple and inexpensive. Although the effectiveness of signs alone is not known, their minimal costs mean they are considered high priority. Fences, on the other hand, involve a greater commitment of resources, and it is not certain that any agency could commit these resources. Fences (#4b) could collect trash and debris and require regular maintenance. Depending on their location, they could be regularly damaged or removed by the dynamic natural physical processes in the lagoon area (e.g., flood and scour). Furthermore, we have not conducted a detailed biological study to confirm that a fenced area would actually benefit snowy plovers or least terns. Consequently, we consider them to be medium priority.

8.3.3.4. Reduced Fish Populations

Habitat loss and degradation have played a central role in the decline of fish populations in Malibu Lagoon. This problem could be addressed by restoring aquatic and riparian habitat, especially salt marsh habitat. Potential means of achieving this objective are discussed in Chapter 9.

Changes in species composition, particularly the high abundance of the introduced mosquitofish, have been caused by the reduced salinity in the lagoon. Reducing freshwater flows in the creek could mitigate this problem. Actively managing the barrier beach to increase tidal flushing would also benefit native fish populations in the lagoon. Alternatives for achieving this goal are discussed in Section 8.4. However, no specific alternatives are proposed for fish populations.

8.3.3.5. Endangered Fish

Tidewater goby populations in Malibu Lagoon have undoubtedly been impacted by habitat loss, hydrologic change in Malibu Creek, and modifications to barrier beach dynamics. However, tidewater gobies have flourished in Malibu Lagoon since their reintroduction in 1991 (Manion 1993). Based on this resurgence and the Resource Conservation District's recent completion of a habitat enhancement project, this report assumes sufficient tidewater goby habitat exists in Malibu Lagoon and that adopting additional habitat enhancement measures specifically for the tidewater goby is not a high priority at this time.

On the other hand, there is reason to believe Malibu steelhead trout populations are not thriving. The last confirmed steelhead siting in Malibu occurred in 1995 (Slack 1998). As a means of re-establishing local populations, it may be desirable to enhance steelhead habitat in the lower creek. This could be accomplished by installing instream structures (#5) or modifying channel geometry and/or substrate conditions (#6).

8.3.3.5.1. Alternative #5: Install instream structures to enhance steelhead habitat

Although they might help reestablish steelhead populations in the short term, instream habitat enhancement structures would be subject to physical failure during high flow events. Frissell and Nawa (1992) document common failure among instream habitat enhancement structures in flood events of modest recurrence interval (i.e. 2-10 years). Instream habitat enhancement structures are often inappropriate and counterproductive in streams with elevated sediment loads, high peak flows, and erodible bank materials such as Malibu Creek (Frissell and Nawa 1992).

8.3.3.5.2. Alternative #6: Modify channel geometry or substrate conditions to enhance steelhead habitat

Like instream structures, modifications to channel geometry and substrate conditions may also fail in the high-energy creek environment.

Furthermore, steelhead habitat enhancement may not be necessary in Lower Malibu Creek. Habitat enhancement techniques are only effective where the existing habitat is somehow unsuitable for a species. According to Franklin and Dobush (1989), the lower creek already contains abundant suitable steelhead habitat. For these reasons, Management Alternatives 5 and 6 are considered low priority.

8.3.3.6. Barriers to Anadromous Fish Migration

As described previously, Rindge Dam and other barriers to fish migration may have played an important role in the decline of steelhead trout and other anadromous fish populations in Malibu Creek. Constructing structures to allow fish to circumvent barriers

(#7) or removing the barriers altogether (#8) could eliminate this problem. If successful, these measures would allow steelhead and other anadromous fish (e.g., the Pacific lamprey, *Lamptetra tridentata*) to reach the upper watershed, increasing spawning and rearing habitat by 590% and 180%, respectively (Franklin and Dobush 1989).

8.3.3.6.1. Alternative #7: Construct structures to allow anadromous fish to circumvent Rindge Dam and other barriers (e.g., tunnel falls, County-operated gage station)

The feasibility of Management Alternative 7 is uncertain. Since Rindge Dam stands over 100 feet tall and occupies a narrow riparian corridor, fish bypass structures would have to be mechanically complex to bridge the sections of the creek above and below the dam. It is unclear whether anadromous fish would actually use the structures for this reason. Given the powerful flows that roll through this portion of the creek, fish bypass structures might fail during high flow events; consequently, they could have considerable operation and maintenance costs. Moreover, if Rindge Dam is removed, there would be no need for bypass structures. For these reasons, the priority for Management Alternative 7 is uncertain.

8.3.3.6.2. Alternative #8: Remove Rindge Dam and other barriers (e.g., tunnel falls, County-operated gage station) to allow anadromous fish to move directly upstream

The U.S. Army Corps of Engineers has conducted a reconnaissance study on the possibility of removing Rindge Dam. If the feasibility study is undertaken, it will provide important information with respect to the feasibility, cost, and environmental impacts of Management Alternative 8. The viability and priority level of removing Rindge Dam and other barriers is uncertain pending the outcome of this study. For this reason, Alternative 8 is given a priority of "uncertain."

The uncertainty associated with this alternative should not be taken as a low priority. On the contrary, removal of barriers to anadromous fish is a very important goal for restoring the biotic integrity of the Malibu Creek system. When the outcome of the Rindge Dam feasibility study is known, we believe that some management alternative that would allow the movement of anadromous fish up and down the watershed should be given a high priority.

8.3.3.7. Reduced Benthic Invertebrate Populations

Direct management measures to enhance Malibu infauna populations (e.g., modifying lagoon substrate conditions) are unlikely to be effective in the highly dynamic lagoon environment. Reductions in benthic invertebrate communities are best addressed indirectly by improving the overall condition of the aquatic environment and attempting to eliminate some of the major environmental problems currently afflicting the lagoon.

Habitat loss and degradation have played a central role in the decline of benthic invertebrate populations in Malibu Lagoon. This problem could be addressed by restoring aquatic and riparian habitat. Wetland restoration and enhancement would not only increase overall habitat availability, but also provide a greater diversity of microhabitats for benthic invertebrates. Potential means for achieving this restoration objective are discussed in Chapter 9.

Changes in the natural lagoon hydrodynamics due to reduced tidal flushing, increased freshwater flows, and change in the barrier beach dynamics have affected benthic invertebrates. Also, eutrophication has likely impacted benthic invertebrate populations. These problems could be addressed by reducing freshwater and nutrient inputs to the lagoon and managing the lagoon water levels. Increased tidal flushing would also benefit benthic invertebrate populations in Malibu Lagoon by providing an abundant source of propagules, as well as, reducing the effects of eutrophication. Alternatives for achieving these goals are discussed in Section 8.4. No alternatives are proposed specifically for benthic invertebrate populations.

8.3.4. Summary of Management Alternative Prioritization

Eight alternative strategies were identified for addressing the biota and habitat problems in the lower Malibu Creek Watershed and Malibu Lagoon. The assessments of these alternatives are summarized in Table 8-4. Two alternatives (installing fish bypass structures, #7, and removing barriers to anadromous fish migration, #8) were placed in the uncertain category because of the pending outcome of current studies concerning Rindge Dam (and questions about feasibility for #7). Two alternatives were judged not feasible, meaning they (a) are not capable of being implemented (e.g., not technically feasible) in Malibu Creek/Lagoon, (b) would not work or function properly in Malibu Creek/Lagoon, or (c) have unacceptable attributes (e.g., significant negative environmental impacts). Two alternatives were assigned a low priority and one was assigned a medium priority. Finally, two alternatives were assigned a high priority:

- Remove non-native plants and revegetate with natives (#2).
- Erect signs to protect birds (#4a)

It should be noted that the management alternatives discussed in this section do not directly address the most important cause of the biota and habitat problems, the loss and degradation of natural habitats. This cause is addressed by proposed wetland restoration, creation and enhancement alternatives (Chapter 9).

8.4. Water Resource Management Alternatives

8.4.1. Introduction

This section identifies and evaluates water resource management alternatives for Lower Malibu Creek and Lagoon. As described previously, water resource problems in the lower watershed include eutrophication, high pathogen concentrations, and persistent high lagoon water levels during the dry season. Elevated freshwater flows, elevated nutrient inputs, elevated pathogen inputs, infilling, and urbanization are the primary anthropogenic causes of these problems.

8.4.2. Procedure

As in the previous section, the analysis of alternatives began with a compilation of potential alternatives. In identifying these alternatives, we referred to previous work done at Malibu, including the facilitated watershed meetings, watershed conferences, and previous studies (e.g., Manion and Dillingham 1989, Keegan 1990, Manion 1993, Ambrose et al. 1995). We also considered management actions taken elsewhere. Our goal was to be inclusive at this stage, even though particular alternatives might not be feasible or may have undesirable consequences. We presented the Malibu Lagoon Task Force with a preliminary list of alternatives and solicited comments and suggestions for additional alternatives.

Once our list of alternatives was determined, we evaluated each alternative based on feasibility, cost, effectiveness, environmental impacts, and potential controversy. We did not assign an explicit weighting to each of these factors; instead, we relied on our judgement in weighing the importance of each factor for a particular alternative. However, there is a logical sequence for evaluating a technique. Feasibility is of fundamental importance; if a technique is not feasible, there is no point in considering it further. Next, effectiveness and environmental impacts are considered. Clearly, the best alternatives would have great effectiveness with no adverse environmental impacts; most alternatives are not so clear cut. Our analyses were completed as a screening tool within the short time frame of this project, and cannot substitute for a more detailed technical analysis. In most cases, a more detailed analysis would be required before implementing an alternative. We also considered cost in a general way. We did not conduct detailed cost analysis for any alternative; particularly for the alternatives involving engineering, this means that our cost assessment is very rough and there is a great deal of uncertainty about what the actual cost would be. However, we wanted to include a rough cost assessment to help us distinguish between alternatives. For example, an alternative with a moderate effectiveness might be given a high priority if it was inexpensive, but a low priority if it was very expensive. In the extremes, cost was considered in the ranking of alternatives, but it was not used to make fine distinctions because there is so much uncertainty in the assessments. Finally, we also felt it was important to consider potential controversy, since the management alternatives will be implemented in the public arena and there are many active stakeholders. However, potential controversy *per se* had little influence on the ultimate ranking of an alternative.

Following internal evaluation of each alternative, we consulted with the Malibu Lagoon Task Force. We presented the Task Force with a summary of the alternatives and our evaluations. Initial discussions focused on the "viability" of each alternative, with an alternative being considered "not viable" if it (a) is not capable of being implemented (e.g., not technically feasible) in Malibu Creek/Lagoon, (b) would not work or function properly in Malibu Creek/Lagoon, or (c) has unacceptable attributes (e.g., significant negative environmental impacts). For each viable measure, we discussed the priority for implementation ("high," "medium," or "low"). We attempted to reach a consensus among the Task Force members, but of course that was often not possible.

The analyses presented in this report reflect our consideration of all the factors known to us concerning the alternatives, including discussions with the Task Force and comments on the draft final report. In virtually every case, there are significant uncertainties. Nonetheless, we have attempted to provide a definite judgement about each alternative, although the degree of uncertainty was so great for several alternatives that we cannot define a priority level.

8.4.3. Analysis of Alternatives

Table 8-5 identifies water resource management objectives for Lower Malibu Creek and Lagoon based on this list of problems and causes. Table 8-6 evaluates possible methods of achieving these objectives. The following sections discuss each of the alternatives in detail.

8.4.3.1. Nutrient and Pathogen Inputs

Eutrophication and high pathogen concentrations are the primary water quality problems currently afflicting the lower creek and lagoon. The effects of eutrophication are generally most pronounced during the summer months; pathogen concentrations are high during summer and after rain events (Ambrose et al. 1995).

Both nutrients and pathogens enter the lagoon primarily through creek flows. For the purposes of this analysis, it is useful to divide creek flows into wet season and dry season flows. Because of their high volume, intermittent nature, and variable pollutant loads, treating wet weather flows is extremely difficult (O'Shea and Field 1992). Nitrogen inputs during the wet season are roughly four times higher than during the dry season. However, the lagoon is often open to the ocean during the wet season, at which time water quality problems are less serious. During the dry season, when the barrier beach usually separates the lagoon from the ocean, nutrients and pathogens can accumulate within the lagoon. Furthermore, dry season flows, with lower volumes, are easier to treat. For these reasons, this report focuses on the reduction of dry season nutrient and pathogen inputs to the lagoon.

Since they originate from many of the same sources (e.g., animal feces, domestic wastewater) and enter the lagoon through the same pathways (e.g., creek flows, urban runoff, contaminated groundwater), nutrient, contaminant and pathogen inputs can be simultaneously reduced in three basic ways: by diverting pollutant-laden inflows to alternative receiving waters or locations, by treating incoming flows before they reach the lagoon, or by reducing pollutants at their source of origin. Diversion alternatives include constructing a groundwater cutoff wall between Malibu Colony and the lagoon (#9), diverting urban runoff offshore or elsewhere (#12), and eliminating septic systems (#3). Treatment alternatives include filtering creek flows (#10), removing pollutants from urban runoff (#11), and retrofitting Malibu's storm drain system (#16). Source reduction alternatives include eliminating illicit connections and discharges (#14), implementing best management practices (#15), retrofitting septic systems (#17), and requiring Tapia to reduce nutrient concentrations in their effluent (#18). As noted in Section 8.4.4, the ideal suite of management actions would focus on source reduction. Source reduction techniques prevent problems before they occur, are frequently relatively inexpensive, and in the long term may be the most effective approach for resolving water problems in the Malibu Creek watershed and Malibu Lagoon.

8.4.3.1.1. Alternative #9: Construct a groundwater cutoff wall between Malibu Colony and the Lagoon

As described earlier, the City of Malibu has proposed the construction of a groundwater cutoff wall between Malibu Colony and the lagoon (R. Morgan, personal communication). Although such a wall might temporarily reduce nutrient and pathogen inputs to the lagoon, its long-term effectiveness is questionable. It is likely that pollutant-laden groundwater from Malibu Colony would eventually make its way beneath or around the cutoff wall, and groundwater input to the Lagoon would be re-established. For this reason, Management Alternative 9 is considered low priority.

8.4.3.1.2. Alternative #10: Develop a system to treat creek flows before they reach the Lagoon

Creek flows could be treated with an advanced wastewater treatment facility or constructed wetlands. Chapter 9 discusses treatment wetland alternatives in detail. Both these facilities would be very expensive to construct and maintain, but would reduce dry season nutrient and pathogen inputs to the lagoon. There are also a number of constraints on treatment wetlands based on site limitations. Restoration sites identified adjacent to the creek have limited potential for constructing treatment wetlands (see Chapter 9). Thus, significant obstacles must be overcome in order to implement this alternative. Nonetheless, the input of excess nutrients is one of the most important contributions to water quality problems, and Alternative 10 could be an effective way to address this problem. Since current estimates of nitrogen loading indicate that the vast majority of nitrogen is transported into the lagoon via the creek, this alternative is given a high priority.

8.4.3.1.3. Alternative #11: Develop a system to treat urban runoff before it reaches the Lagoon

Urban runoff could also be treated in a variety of ways, including constructed wetlands, detention ponds, infiltration basins, and end-of-the pipe disinfection devices (Ferguson 1991; O'Shea and Field 1992; Bingham 1994). Any of these options would reduce dry season nutrient and pathogen inputs to the lagoon. Because current estimates of nitrogen loading indicate that urban runoff is a major source of nitrogen loading to the Lagoon, and dry-season discharges into the Lagoon are likely to have local effects due to constituents besides nitrogen, Management Alternative 11 is considered a high priority for nutrient removal.

8.4.3.1.4. Alternative #12: Divert urban runoff offshore

Diverting urban runoff offshore represents another strategy for reducing nutrient and pathogen inputs to the lagoon. Since it would constitute a new point source of pollutants, an offshore outlet would have to be approved by the Los Angeles Regional Water Quality Control Board.

This alternative would reduce nutrient and pathogen inputs to the lagoon and partially alleviate lagoon water quantity problems. Rather than eliminating pollutants outright, diverting urban runoff would transfer pollutants from one receiving water to another. Since it has a greater assimilative capacity than Malibu Lagoon does, Santa Monica Bay in theory might be viewed as a more logical destination for locally generated urban runoff. Of course, Santa Monica Bay itself is impacted by urban runoff.

Since it would require the construction of complex conveyance system to the ocean and offshore outfall, this alternative would be expensive. Moreover, the Surfrider Foundation representatives have expressed an opposition to an ocean outfall. To the extent that an offshore outfall would alter the surf break, this opposition has a valid foundation, and the outfall would need to be designed to avoid such an impact (perhaps by discharging a considerable distance from shore, which would increase expense). On the other hand, there is less justification for objecting to the outfall because it would discharge polluted water directly into the ocean, since runoff ultimately enters the ocean in any event. The outfall could be placed far enough offshore that the discharge would not present a human health risk. Nonetheless, it is true that this alternative simply bypasses the lagoon rather than solving the root source of the problem. The expense of constructing a bypass system is not justified if the runoff is released untreated into the Bay.

Unlike Alternative 11, however, Alternative 12 would not remove the contaminants from urban runoff, but would simply release them into Santa Monica Bay. Therefore, Management Alternative 12 is judged to be a low priority.

8.4.3.1.5. Alternative #13: Eliminate septic systems in the Malibu Colony and the Civic Center area and divert wastewater to a treatment facility

Current estimates of nitrogen loading indicate that a substantial fraction of nitrogen transported into the lagoon comes from lagoon-area septic systems. Eliminating septic systems in Malibu Colony and the Civic Center area and diverting wastewater to a treatment facility could reduce dry season nutrient and pathogen inputs to the lagoon. If treated effluent were reused, this alternative would have minimal environmental impacts (City of Malibu 1997).

Elimination of septic systems would be expensive and thus may elicit objections from local residents, at least initially. These objections (if they in fact exist) could make implementation of this alternative difficult. Attitudes about septic system replacement might change, however, if the effects of septic systems around the Lagoon become better known, perhaps with an appropriate outreach/public education program.

The significance of Lagoon-area septic systems to nutrient inputs to the Lagoon, coupled with the fact that this is a source reduction technique, means this alternative is currently given a medium priority.

Information on the importance of Malibu Colony and Civic Center area septic systems to the *pathogen* loading in the Lagoon was not available at the time of this report. If the septic systems are found to be an important source of pathogens in the Lagoon, the priority ranking of this alternative could be revised upwards to a high priority.

8.4.3.1.6. Alternative #14: Identify and eliminate illicit connections and discharges (IC/ID) in the lower watershed

Eliminating illicit connections and discharges (IC/ID) would also reduce dry season nutrient and pathogen inputs to the lagoon. There is no estimate of how common illicit connections and discharges are, so there is no estimate of how important their input into the Lagoon is. However, its implementation is mandatory under the terms of Los Angeles County municipal storm water permit (CRWQCB 1996), so Management Alternative 14 is considered high priority.

8.4.3.1.7. Alternative #15: Implement non-point source pollution Best Management Practices

Implementing best management practices (BMPs) represents another means of improving water quality in the lower creek and lagoon. BMPs that could be employed include an enhanced street sweeping and catch basin cleaning program, horse corral management measures, and public education and outreach on fertilizer reduction, proper disposal of pet feces, and septic system monitoring/maintenance (McCarthy and Mercer

1995; RCD 1997). In addition to reducing nutrients and pathogens, Management Alternative 15 would reduce trash and debris inputs to the lagoon. This alternative is considered a high priority. However, its overall effectiveness depends on people's willingness to participate, and so there are some questions about how effective it will be in reducing contaminant and nutrient inputs into the lower Creek and Lagoon.

Although the scope of this project was restricted to the lower Malibu Creek and Lagoon, the majority of the population in the watershed lives in the upper watershed. To be effective, BMPs would have to be implemented in the upper watershed as well as the lower watershed.

8.4.3.1.8. Alternative #16: Retrofit Malibu's storm drain system

Retrofitting Malibu's storm drain system could be accomplished with baffle boxes, disinfection devices, fiberglass inlet weirs, sediment sumps, and/or trash and debris screens (O'Shea and Field 1992, England 1995). Other than expense, Management Alternative 16 has no negative attributes; it would reduce nutrient, pathogen, trash, and debris inputs to the lagoon. Because current estimates of nitrogen loading indicate that urban runoff is a major source of nitrogen loading to the Lagoon, and dry-season discharges into the Lagoon are likely to have local effects due to constituents besides nitrogen, Management Alternative 16 is considered a high priority.

8.4.3.1.9. Alternative #17: Retrofit septic systems in Malibu Colony and the Civic Center area

Retrofitting septic systems in Malibu Colony and the Civic Center area could be accomplished by installing pollution prevention equipment or re-locating systems immediately adjacent to the lower creek and lagoon. It is not clear that this alternative could be implemented everywhere, since many septic systems cannot be modified due to spatial constraints. Furthermore, retrofitting septic systems might be unpopular with local residents and merchants. Despite these drawbacks, this alternative would reduce nutrient and pathogen inputs to the lagoon. Because current estimates of nitrogen loading indicate that the septic systems around the lagoon are a significant contributor to overall loading, Management Alternative 17 is considered a medium priority.

8.4.3.1.10. Alternative #18: Reduce nutrients in Tapia discharge

Reducing nutrient concentrations in Tapia's effluent represents another means of reducing nutrient inputs to the lagoon. Results presented in Chapter 5 indicate that Tapia contributes significantly to the nutrient input to the Lagoon.

Because nutrient inputs from wastewater treatment plants has been a general concern, a variety of treatment alternatives have been developed, including advanced biological or chemical treatments. Implementing these treatments at Tapia is probably feasible, although it may be complex and we have not conducted engineering studies to confirm the feasibility or identify the details of how they would be implemented. Although likely to be feasible, they are also likely to be expensive. An alternative to in-plant modifications would be to use constructed wetlands to reduce nutrient concentrations of effluent. Constructed wetlands have been widely used to treat wastewater effluent, and appear to be feasible at Tapia.

Because Tapia is a significant source of nutrients in the Lagoon, especially during the dry season when eutrophication is most likely to be a problem, and this is a source-reduction alternative, Management Alternative 18 is considered high priority. In addition, compliance with this standard is mandatory based on current NPDES permit requirements. Whereas it did not have a nutrient effluent limit in the past, Tapia's new NPDES permit prohibits effluent nutrient concentrations from exceeding 13 mg/L on an interim basis and 10 mg/L in the long-term (R. Orton, personal communication).

8.4.3.2. Nutrient Concentrations

Reducing nutrient inputs ultimately represents the best strategy for eliminating eutrophication in Malibu Lagoon. Since this goal may take a long time and prove difficult to achieve, reducing nutrient concentrations in the lagoon itself might constitute a practical short-term solution to the Malibu eutrophication problem. Such a task could be accomplished by removing nutrients from the water column or preventing their release from sediments.

Alternative methods of removing nutrients from lagoon waters include application of a multivalent cation salt (#19), biomanipulation (#20), and biological treatment devices (#23).

8.4.3.2.1. Alternative #19: Apply multivalent cation salt to precipitate phosphorus from lagoon waters

Multivalent cation salts such as lime or alum react with soluble phosphorus to form a precipitate that decreases phosphorus availability in the water column (McComb 1995). Since phosphorus is not limiting in Malibu Lagoon (Ambrose et al. 1995), such a strategy probably would not be effective. Hence, Management Alternative 19 is considered not viable.

8.4.3.2.2. Alternative #20: Biomanipulation to reduce nutrient concentrations in the lagoon

Management Alternative 20, biomanipulation, would employ nutrient-degrading microorganisms. Similar to Management Alternative 1 (biomanipulation to reduce non-native fish populations), there is a great deal of uncertainty associated with this alternative. It is unclear whether nutrient-degrading microorganisms would function in the highly-dynamic lagoon environment and if they would negatively impact native species populations. For these reasons, Management Alternative 20 is considered not viable.

8.4.3.2.3. Alternative #21: Cover lagoon sediments to interfere with the sediment-water exchange process

Internal nutrient desorption could be controlled by covering lagoon sediments with a fabric or grid (#21) to interfere with the sediment-water exchange process. Such a strategy has been successful in eutrophic lakes and reservoirs (Cooke et al. 1986). Although their use has been advocated in coastal lagoons and estuaries (McComb 1995), sediment covers probably would not function in Malibu Lagoon because lagoon sediments experience a great deal of movement, thereby necessitating frequent fabric replacement. Altering substrate conditions would also have a negative impact on benthic organisms, including the federally-protected tidewater goby. For these reasons, Management Alternative 21 is considered not viable.

8.4.3.2.4. Alternative #22: Inject nitrate into lagoon sediments

Nitrate injection (#22) could also be employed to reduce dry season nutrient concentrations in the lagoon. Under anaerobic conditions, nitrate acts as an electron receptor, preventing reduction of iron and subsequent release of phosphorus to the water column (Cooke et al. 1986). Although it has been successful in eutrophic lakes and reservoirs, nitrate injection probably would not function in the highly dynamic lagoon environment. Since phosphorus appears to be limiting at Malibu, nitrate injections would have little effect on eutrophication. Moreover, the Los Angeles Regional Water Quality Control Board probably would not allow nitrate injection since it prohibits ambient nitrate concentrations greater than 10 mg/L in local water bodies (CRWQCB 1994). For these reasons, Management Alternative 22 is considered impractical.

8.4.3.2.5. Alternative #23: Install biological treatment devices in the lagoon

"Eco-rafts" and "living machines" are biological treatment devices that float along the surface of eutrophic water bodies, filter nutrients from the water column, and incorporate them into plant biomass. Such devices could be used to reduce dry season nutrient concentrations in the lagoon. In the absence of well-documented case history, it is unclear whether they would function properly in the highly dynamic lagoon environment. Additional research would have to be conducted to predict performance and environmental impacts before such devices could be implemented in Malibu Lagoon. Until then, the priority level of Management Alternative 23 is considered uncertain.

8.4.3.3. Pathogen Concentrations

8.4.3.3.1. Alternative #24: Construct a disinfection facility and water level management system in the lagoon area

The City of Malibu recently received a $1.2 million grant to construct a disinfection facility and water level management system in the lagoon area (#24). If implemented successfully, this system would reduce dry season pathogen concentrations and prevent lagoon water levels from becoming problematic. If intake lines and a pump and pipeline were added, the system would improve water circulation and increasing tidal flushing in the lagoon. Despite these advantages, the disinfection/water level management system has a number of drawbacks; it might negatively impact lagoon organisms and would be unpopular with surfers and environmentalists.

The City of Malibu is no longer interested in pursuing the original project (R. Morgan, personal communication). However, State Parks is continuing to pursue the possibility of using the grant money to construct a project in the lagoon area. The State Parks project may not include the disinfection facility.

This project is a significant engineering project, and a detailed engineering study should be conducted before a decision is made about its desirability. Further research should also be conducted to predict the environmental impacts of Management Alternative 24, which will depend on the specific design. Until then, it is considered medium priority.

8.4.3.4. Algal Growth

Eliminating algal mats represents another strategy of managing eutrophication in Malibu Lagoon. Such a goal could be accomplished via algicide application (#25), biomanipulation (#26), or physical removal (#27). Although this approach focuses on the symptoms rather than the root cause of eutrophication, it could be a valuable approach. High algal abundance and the consequent low oxygen concentrations cause fish kills, the most serious consequence of eutrophication. Controlling algae should eliminate the potential occurrence of eutrophication.

8.4.3.4.1. Alternative #25: Apply algicides to lagoon waters

Algicide application would temporarily reduce algae populations in the lagoon. Algicides would have to be applied on a regular basis, would negatively impact lagoon organisms, and would be unpopular with surfers and environmentalists. Algicide application would also likely encounter regulatory hurdles before it could be implemented. For these reasons, Management Alternative 25 is considered not viable.

8.4.3.4.2. Alternative #26: Biomanipulation to reduce algae populations in the lagoon

The addition of algae grazers or phytophagous fish/insects is similar to the other biomanipulation management alternatives in having a great deal of uncertainty associated with its implementation. Although it partially reduces the growth of algae, recent research has shown biomanipulation does not eliminate eutrophication altogether and is more effective in freshwater systems than brackish waters such as Malibu Lagoon (Carpenter et al. 1995; Jeppesen et al. 1994). For these reasons, Management Alternative 26 is considered not viable.

8.4.3.4.3. Alternative #27: Physically remove algae from lagoon waters

Physical removal has been advocated as a effective means of reducing algal growth in coastal lagoons and estuaries (Atkins et al. 1993; McComb 1995). At $12.50 per cubic meter (Atkins et al. 1993), physical algae removal is inexpensive. Since it would have to be repeated on a regular basis and might negatively impact lagoon organisms (e.g., young fish occurring within algal mats), however, Management Alternative 27 is considered low priority.

8.4.3.5. Water Circulation

Although the fundamental cause of algal growth in the lagoon is the presence of nutrients, there are other contributing factors. Ambrose et al. (1995) noted that extensive algal mats were less common in the lagoon after the sand barrier had been breached and the lagoon was open to tidal flushing. Two alternatives for enhancing water circulation in the lagoon are evaluated.

8.4.3.5.1. Alternative #28: Install aerators in the lagoon during the dry season

Installing aerators at the bottom of the lagoon during the dry season (#28) could alleviate the problem of poor water circulation, which contributes to Malibu Lagoon's eutrophication problem. Aerators would enhance water circulation and partially reduce algal growth in the lagoon. By increasing dissolved oxygen concentrations, aerators would also create conditions less conducive to pathogen survival and regrowth. The effect of aerators on lagoon nutrient concentrations is unclear. By preventing the development of anoxic conditions at the sediment surface, aerators might reduce nutrient release from sediments. On the other hand, aerators might facilitate nutrient desorption by stirring up sediments. Physical disturbance of sediments might also negatively impact benthic organisms. The degree to which these effects occur depends on the actual action of the specific aerators. Given these uncertainties, the priority level of Management Alternative 28 is undecided at this time.

8.4.3.5.2. Alternative #29: Redirect Creek flows to areas with poor circulation

Lagoon water circulation could also be improved by redirecting excess creek flows to areas with poor circulation (#29). By increasing water delivery, this alternative might reduce algal growth in portions of the lagoon such as the restored salt marsh. On the other hand, redirecting creek flows would lower salinity levels, which, in turn, would negatively impact halophilic organisms in the lagoon. Redirecting the creek flows would also require construction of a conveyance system, and erosion problems could occur in the areas with higher flows. For these reasons, Management Alternative 29 is considered low priority.

8.4.3.6. Freshwater Flows

As described previously, Malibu Lagoon often experiences persistent high water levels when the barrier beach forms in summer. Like eutrophication and pathogens, water levels are most problematic during the dry season. Hence this report focuses on reducing dry season freshwater flows to the lagoon. Reducing freshwater inputs to the lagoon could alleviate this problem; conceptually, this represents the simplest solution because pre-development flows were typically low in the summer. Dry season flows into the lagoon could be lowered by reducing creek flows before they reach the lagoon or by curtailing freshwater inputs at their source of origin. Creek flow reduction measures include offshore diversion (#30) or use by the City of Malibu as a non-potable water supply (#31).

8.4.3.6.1. Alternative #30: Divert excess creek flows offshore (or elsewhere)

Management Alternative 30 would reduce dry season freshwater, nutrient, and pathogen inputs; and enhance shorebird habitat in the lagoon.

This alternative would be expensive, much like the alternative to divert urban runoff offshore (#12). In one possible configuration, it would entail construction of a complex conveyance system to the ocean and an offshore outfall. The outfall could be placed far enough offshore that the discharge would not present a human health risk (certainly the risk would be smaller than currently exists when the lagoon is breached). The outfall could presumably be designed to avoid impacts to the surf break. The same objections to construction of an offshore outfall for Alternative #12 apply to this alternative.

It is possible that excess flows could be diverted somewhere else besides the ocean. For example, it might be possible to divert the excess freshwater to the upper watershed, where it might be used productively. This diversion could take place from the Lagoon area, or from somewhere farther up the watershed. Diverting the excess creek flows in this manner would eliminate the need for an ocean outfall (and the negative attributes of that feature).

Management solutions addressing root sources, such as reducing water use (#33) and implementing Best Management Practices (#15), are the preferred approach for solving environmental problems such as those experienced in Malibu Lagoon. However, these alternatives may not be effective enough to eliminate the problems associated with excess creek flows. Moreover, much of the source is in the upper Malibu Creek watershed, which is not covered by this analysis but is certain to present a challenge in terms of scope of the problem and number of jurisdictions that must be coordinated. Although it is an "end-of-the-pipe" solution, diverting creek flows around Malibu Lagoon does accomplish many of the major objectives for protecting and improving the health of the Malibu Lagoon ecosystem.

The benefits of this alternative would be extensive and cut across many of the lagoon's problems. The "costs" would be extensive, as well, particularly the logistic difficulties and high financial cost of construction. This project is a significant engineering project, and a detailed engineering study should be conducted before a decision is made about its desirability. Further research should also be conducted to predict the environmental impacts of Management Alternative 30, which will depend on the specific design. On balance, however, it provides a realistic approach to resolving many of the lagoon's problems, and thus it is considered a high priority.

Consideration of diversion projects should not be limited to the lower watershed; upper watershed diversion projects should also be considered.

8.4.3.6.2. Alternative #31: Divert creek flows to the City of Malibu for use as a non-potable water supply

Management Alternative 31 would have many of the same benefits as Management Alternative 30; it would reduce dry season freshwater, nutrient, and pathogen inputs and enhance shorebird habitat in the lagoon. This alternative would require construction of a complex conveyance system and storage facility; consequently, its implementation would be very expensive. Given the city's plans to construct a wastewater reclamation facility in the Civic Center area (City of Malibu 1997), it is unlikely Malibu would be able to find uses for the water. For this reason, Management Alternative 31 is considered not viable.

8.4.3.6.3. Alternative #32: Eliminate Tapia's discharge during the dry season

The Tapia Water Reclamation Facility is a clearly identifiable source of water in Malibu Creek. One way to reduce the flow of water in the Creek in the dry season would be to eliminate any discharge from Tapia during this period (#32). This alternative is a source-reduction alternative.

In recent years, Tapia has discharged relatively little water into Malibu Creek during the dry season. Tapia's tertiary treated wastewater is reused as much as possible, with dry-season discharges mainly occurring when demand for reuse does not meet supply. Previously, when Tapia discharged more water into the Creek in summer, Tapia's discharge constituted about one-third of the creek flow (Ambrose et al. 1995).

Eliminating Tapia's discharge during the dry season is an effective way to reduce excess freshwater flows into the Lagoon; it would also reduce nutrient inputs that would otherwise enter the Lagoon. Consequently, Management Alternative 32 is considered high priority. Under the terms of Tapia's new NPDES permit, Tapia may not discharge into the creek during the dry season, so implementation of this alternative is a foregone conclusion.

8.4.3.6.4. *Alternative #33: Reduce water use in the lower watershed*

Another source reduction measure is to reduce water use in the lower watershed[1] (#33). Installing high-efficiency faucets, showerheads, toilets, and washing machines or instituting rationing during the dry season could reduce water use. If successful, these measures would greatly reduce dry season freshwater flows and partially reduce nutrient and pathogen inputs to the lagoon.

This alternative is low in cost and, if fully implemented, would be very effective at reducing dry season freshwater flows in Malibu Creek. The only disadvantage of this technique is the uncertainty about how effectively it could be implemented. The effectiveness of this alternative depends on people's willingness to participate. During drought years, some water conservation measures have been effective, but it is not clear that people's understanding of the need to reduce water use could be communicated as effectively. Moreover, public education in the upper watershed is further complicated by the presence of sever different municipalities. However, it is possible that different programs could be developed that would lead to lower water use.

Although its success is somewhat uncertain because it depends on people's willingness to participate, Management Alternative 33 is considered high priority. It has the potential to reduce the excess freshwater (and nutrients) at the source, and it could be the most cost-effective of all the alternatives.

8.4.3.7. Water Levels

In addition to *ex situ* measures, persistent high water levels can be addressed within the lagoon itself.

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[1] Because the scope of this project does not include the upper watershed, we have not proposed management alternatives for that region. Obviously, reducing water use in the upper watershed would be even more effective at reducing freshwater flows.

8.4.3.7.1. Alternative #34: Install temporary spillway to allow lagoon waters to drain to the ocean when water levels exceed 3-5 ft.

One means of achieving the goal of managing water levels would be to install a temporary spillway to allow lagoon waters to drain to the ocean (#34).

This alternative would benefit lagoon ecology by preventing water levels from becoming problematic (a particular problem for salt marsh plants, which die if inundated for an extended period of time), enhancing shorebird habitat, and improving water quality by decreasing water residence times in the lagoon. On the other hand, a temporary spillway could negatively impact beach access by producing a consistent stream of water across the beach. However, a stream now exists across the beach during the wet season and whenever the barrier is breached, so this is not a major disadvantage. A spillway might be unpopular with surfers and other beach users. The spillway would be swept away during major floods of the rainy season, so it would have to be removed each year and re-installed in spring. Moreover, when natural processes form the barrier beach, the temporary spillway would be buried by sand. Before the water could be drained from the beach, the spillway would have to be excavated.

A temporary spillway could be implemented very quickly, unlike some other approaches to control the lagoon water level (e.g., diverting excess creek flow, #30, or constructing a permanent water exchange system, #36, or a water level management/ disinfection system, #24). Thus, it might be worth implementing this alternative as an interim measure if one of these other alternatives is chosen as the permanent solution.

The temporary spillway would perform a function similar to that of the modified mechanical breaching alternative (#38). Both would be used to prevent the lagoon from having persistent high water levels. Both would avoid the rapid, violent flushing that occurred under the past mechanical breaching procedure. The main functional difference is that the spillway would prevent the lagoon from draining completely. The ecological significance of this is not completely clear. Some species (perhaps infauna and fish) might flourish with more water in the lagoon, while others (birds using mudflats for feeding or loafing) might be negatively affected. Since the lagoon would drain completely under natural conditions, we do not see the retention of more water in the lagoon as an advantage. The need to excavate the spillway before draining water and remove it before the rainy season are extra complications not associated with the modified mechanical breaching. For these reasons, Management Alternative 34 is considered low priority.

8.4.3.7.2. Alternative #35: Construct a permanent artificial opening at the lagoon mouth

Constructing a permanent artificial opening at the lagoon mouth (#35) would eliminate persistent high water levels. Such an opening could take a variety of forms such as a channel with automated or manual tide gates, or a jettied outlet (Jenkins and

Skelly 1985; Goodwin et al. 1992). Additional designs options might include a breakwater to prevent the intrusion of marine sands and a fluidizer system to prevent sand accumulation (Jenkins and Skelly 1985).

Although it would benefit the lagoon in a number of ways, a permanent opening would have a variety of undesirable attributes, including updrift accretion, sand dune accumulation, downdrift erosion, change in foreshore geometry, loss of city and private property to state by foreshore progradation, and undermining of Adamson property, Malibu pier and other downdrift structures. It would be very expensive to construct and maintain, requiring sand bypassing and frequent dredging. Also, it might negatively impact endangered tidewater goby populations. Some design options, such as jetties, would interfere with the public's access along the beach and would cause significant changes in the shoreline. Although jetties have been constructed recently in conjunction with wetland restoration projects (e.g., Batiquitos Lagoon in San Diego County), more commonly they have not been chosen for incorporation into restoration projects due to local community opposition (e.g., San Dieguito Lagoon, also in San Diego County). For these and many other reasons, Management Alternative 35 is considered not viable.

8.4.3.7.3. Alternative #36: Construct a permanent water exchange system between the lagoon and the ocean

Constructing a permanent water exchange system between the ocean and the lagoon (#36) represents another strategy of managing lagoon water levels. Such a system would provide the same basic benefits as a temporary spillway (# 34), including lower water levels, improved water quality, and enhanced shorebird habitat. Since it would bring ocean water to the lagoon, Management Alternative 36 would provide the additional benefits of increasing tidal flushing and enhancing benthic invertebrate populations in the lagoon.

On the other hand, a permanent water exchange system would be much more expensive than a temporary spillway (#34). A permanent water exchange system would likely be unpopular with surfers since, as noted earlier for Alternative #30 (diverting excess creek flows offshore), Surfrider has expressed opposition to offshore outfalls. This alternative is similar to Alternative #30 in other ways, as well. Both require a conveyance system, construction of which would comprise a significant engineering project. The major distinction between #30 and #34 is when the excess water is transported to the ocean. In #30, the excess water is diverted before entering the lagoon, thus avoiding depostion of excess nutrients or contaminants into the lagoon, and avoiding the lowering of salinity levels by excess freshwater. In #34, Malibu Creek would continue to empty into the lagoon. Thus, nutrients, pathogens, and other pollutants would still enter the lagoon. Moreover, salinity would be regulated by the mixing of freshwater from the creek and saltwater from the ocean, rather than simply diverting excess freshwater.

Because it has more negative attributes than a temporary spillway (e.g., costly to construct, offshore outfall), Management Alternative 36 is judged inferior. Because it deals with the excess water problem after the creek water has entered the lagoon rather than before, thus allowing nutrients, contaminants and pathogens to enter the lagoon, Management Alternative 36 is judged inferior to the creek diversion Alternative (#30). Considering these issues, Management Alternative 36 is assigned a low priority.

8.4.3.7.4. Alternative #37: Resume previous mechanical breaching regime

Resuming mechanical breaching as practiced in the recent past (#37) represents another means of managing lagoon water levels.

The procedure for mechanical breaching used in the past was employed to keep the water level in the lagoon from reaching too high a level. A protocol for when and where to breach was established. Sometimes, the right combination of tidal height and timing did not occur for some time after the water in the lagoon reached the level at which breaching should occur, so the water continued to rise or stay at a high level for a prolonged period. Prolonged inundation is harmful to some of the salt marsh vegetation, and the prolonged period of low salinity is harmful to some invertebrates. The breaching was timed to coincide with a very low tide, so maximum scour effect would occur as the water rushed out of the lagoon (and hence the lagoon would stay open for as long as possible after breaching). Unfortunately, the extended period of high water levels in the lagoon coupled with the rapid draining of the lagoon could have adverse effects on the organisms in the lagoon, including tidewater gobies, who were stranded after breaching (S. Manion and R. Ambrose, unpublished data).

Since it is prohibited by the California Coastal Commission, would not effectively prevent water quantity and quality problems in the lagoon, and could negatively impact endangered tidewater goby populations, Management Alternative 37 is considered low priority.

8.4.3.7.5. Alternative #38: Implement a modified mechanical breaching regime

Lagoon water levels could also be managed by implementing a modified mechanical breaching regime (#38). The breaching regime could be modified to avoid some of the most negative features of the procedure followed in the past (#37). Such a regime might include breaching at the onset of a rising high tide to minimize the difference between lagoon and ocean water levels and beaching regularly before water levels become problematic (Capelli 1997). Minimizing the difference in water level between lagoon and ocean levels would reduce the scour resulting from breaching, so the channel connecting the lagoon to the ocean would not be as deep, but it would also lessen the change from closed to open conditions in the lagoon. If less sand was scoured with each breach, the lagoon would have to be breached more often, but this would also mean that the period of low salinity in the lagoon would be shorter before tidal flushing was reintroduced. The need for more frequent breaching might mean that the necessary equipment would have to be available more often than was the case in the past.

It is possible that a modified mechanical breach regime would still negatively impact lagoon tidewater goby populations, although we expect that the effect would be much less than the previously used breaching protocol. If the goby were to be affected, the procedure would need to be reviewed by state and federal agencies.

This technique would be relatively inexpensive and benefit the lagoon in a number of ways (i.e., prevent water levels from becoming problematic, enhance shorebird habitat, improve water quality, increase tidal flushing, and enhance invertebrate populations). Despite some potential drawbacks, Management Alternative 38 is considered high priority.

Management Alternative 38 could be implemented immediately, with no additional capital costs. As noted in the discussion for the temporary spillway (#34), even if it is not chosen for the long-term solution, interim implementation of #38 might be warranted.

8.4.4. Summary of Water Resource Management Alternative Prioritization

Our analysis of water resource management alternatives has been restricted to alternatives for the lower watershed because of the designated scope of this study. However, upper watershed activities clearly influence the water resources, including Malibu Lagoon, in the lower watershed. The much larger number of people and activities in the upper watershed mean that implementing appropriate management alternatives in the upper watershed should be a high priority. The recent requirement to implement some BMPs for new developments in Los Angeles County is a step in the right direction, but the problem of inputs from the upper watershed cannot be resolved with controls on new construction alone. Many of the management alternatives discussed in this report could be applied in the upper watershed. However, it is not possible to prioritize these alternatives for the upper watershed without more information about the relative importance of different causes of environmental problems. Any serious effort to solve the environmental problems in Malibu Creek and Malibu Lagoon must focus on the upper watershed.

Thirty different strategies have been evaluated for addressing the water resource problems in the lower Malibu Creek Watershed and Malibu Lagoon. The assessments of these alternatives are summarized in Table 8-7. Two alternatives (#23 and #28) were not prioritized because of uncertainty about their effectiveness in the Malibu system. Eight alternatives were judged not viable, meaning they (a) are not capable of being implemented (e.g., not technically feasible) in Malibu Creek/Lagoon, (b) would not work or function properly in Malibu Creek/Lagoon, or (c) have unacceptable attributes (e.g., significant negative environmental impacts). Seven alternatives were assigned a low priority, and three alternatives were assigned a medium priority[2]. Finally, these ten alternatives were given a high priority:

- Treat creek flows (#10)
- Treat urban runoff (#11)
- Eliminate illicit discharges and connections (#14)
- Implement Best Management Practices (#15)
- Retrofit storm drain system (#16)
- Reduce nutrients in Tapia's effluent (#18)
- Divert excess creek flows (#30)
- Eliminate Tapia's discharge during dry months (#32)
- Reduce water use (#33)
- Implement a modified mechanical breaching regime (#38)

It is not necessary to implement all of these management actions. The suite of actions needed depends on the particular combination chosen and the effectiveness of each action. For example, eliminating illicit discharges and connections, implementing Best Management Practices, and reducing nutrient concentrations in Tapia's effluent could, potentially, resolve the problems with nutrients, pathogens, and other pollutants in Malibu Creek water. In that case, there would be no need to implement Management Alternative 10, treating creek flows. Furthermore, if Management Alternatives 15, 32 and 33 were effective at reducing the volume of water in the creek in the dry season, there would be no need to divert excess creek flows (#30) or initiate a modified mechanical breaching regime (#38).

The ideal suite of management actions would focus on source reduction. Some treatment, diversion and breaching alternatives are included among the high-priority alternatives in recognition that source reduction alternatives alone may not be sufficient or successful enough in the short term. Some of these other alternatives, such as diverting excess creek flows offshore, would be costly to implement, but would provide the lagoon with immediate relief.

The following sections compare the alternatives for resolving water quality and water quantity problems.

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[2] Although we have separated medium and high priority alternatives, we feel that the medium prioritization should not disqualify these alternatives from further consideration. The three medium priority alternatives could potentially resolve some of the water resource problems. They were not included in the high priority ranking because of complexity and likely cost or cost-effectiveness. However, more detailed engineering and cost analyses should be conducted before some of the high priority alternatives are implemented, and the medium alternatives would also benefit from more detailed analysis.

8.4.4.1. Water Quality

Eutrophication and high pathogen levels are the most pressing water quality problems in Lower Malibu Creek and Lagoon. Since they have the same basic causes (i.e. elevated nutrient and pathogen inputs) and originate from many of the same sources (e.g., urban runoff, runoff from horse corrals, and septic seepage), the two problems are best addressed simultaneously, through a single, concerted effort.

Nutrients and pathogens can be reduced in three basic ways: by reducing pollutants at their source of origin, by diverting pollutant-laden waters to alternate receiving waters, or by removing pollutants from existing receiving waters (i.e. the lower Creek and Lagoon). As a general rule of thumb, source reduction measures are preferred over diversion and *in situ* treatment measures.

Our assessment of water resource management alternatives reflects this principle. Diversion-based management alternatives generally are not viewed favorably. Constructing a groundwater cutoff wall (#9), redirecting creek flows to areas with poor circulation (#29), and diverting urban runoff from the City of Malibu offshore (#12) are all considered low priority. The exception to this principle is the diversion of excess creek flows (#30), which was assigned a high priority. Although not a source reduction measure, the high-priority designation of this diversion alternative recognizes that it may not be possible to reduce nutrients, contaminants, pathogens, and water volume to low enough levels. In that case, it would be better to divert the creek flow before it enters the lagoon rather than allowing the excess nutrients, contaminants, pathogens, and water volume to empty into the lagoon.

In situ treatment measures receive mixed priorities. Multivalent cation salt application (#19), biomanipulation (#20 and 26), covering lagoon sediments (#21), nitrate injection (#22), and algicide application (#25) are all considered impractical. Physical removal of algae (#27) is considered low priority. Constructing a disinfection facility (#24) is given medium priority status (although the City of Malibu currently is no longer considering it). Treating creek flows (#10) is considered high priority because creek flows account for a quarter of all dry season nutrient inputs to the lagoon. Treating urban runoff (#11) is also assigned high priority because treating runoff is a relatively straightforward way to reduce contaminant inputs into the Lagoon.

Source reduction measures, on the other hand, generally receive high marks. Eliminating (#13) or retrofitting septic systems in Malibu (#17) are assigned medium priority. The mass balance model described in Chapter 5 suggests local septic seepage may be a significant dry season nutrient input to the lagoon. The ranking of these alternatives could change to high priority if future pathogen studies indicate that local septic systems are an important source of pathogens. Implementing non-point source BMPs (#15) is given high priority, despite questions about how effective it will be given its dependence on public cooperation. Eliminating illicit connections and discharges (#14) and reducing nutrients in Tapia's effluent (#18) are assigned high priority.

The priority level of the remaining water quality management measures, biological treatment devices (#23) and installing aerators (#28), is considered uncertain at this time. Further research is needed to determine whether these measures would be effective in the highly dynamic lagoon environment.

In addition to measures that are directly aimed at improving water quality, a number of management alternatives exist that, although intended to solve other problems, would also ameliorate water quality in the lower creek and lagoon. Actively managing water quantity to prevent lagoon water levels from becoming problematic during the dry season represents one such strategy. If successful, such a measure would lower groundwater levels beneath Malibu Colony and the Civic Center area, increase the vertical distance between septic system leachfields and the water table, and reduce nutrient and pathogen inputs to the lagoon. Adopting measures to increase tidal flushing would also improve lagoon water quality by creating a brackish environment less conducive to algal and pathogen growth.

8.4.4.2. Water Quantity

Malibu Lagoon's water quantity problem (i.e. persistent high lagoon water levels during the dry season) can be addressed in one of two ways: (1) reducing freshwater flows to the lagoon or (2) actively managing lagoon water levels to prevent them from becoming problematic during the dry season. Eliminating Tapia's discharge into the creek during the dry season (#32) and reducing water use in the watershed (#33) represent the best means of achieving the former; both are considered high priority. [Note that water use would have to be reduced in the entire watershed, not just the lower watershed.]

If the source-reduction approaches cannot solve the problem of persistent high lagoon water levels during the dry season (and it seems likely they will not, certainly not in the short term), then some type of active management of lagoon water levels will be necessary. Two alternatives, constructing a permanent water exchange system between the ocean and the lagoon (#36) and resuming mechanical breaching as practiced in the recent past (#37), are considered low priority for reasons outlined in the previous sections. Four other alternatives could be implemented: diverting excess creek flows (#30), modified mechanical breaching (#38), construct a water level management facility (#24), or install a temporary spillway (#34). Each of these alternatives has advantages and disadvantages, as discussed earlier in this section, but one of them must be chosen to resolve the problem of excess freshwater input into the Lagoon.

Only one of these alternatives, diverting excess creek flows offshore, would reduce pollutant (including nutrient) inputs to the lagoon as well as reducing freshwater flows and alleviating water quantity problems; for this reason, it is assigned high priority. This alternative is not a source-reduction approach, however, and it does not reduce pollutant inputs into the *ocean* (unless the water is diverted to the upper watershed for reuse). It is considered a high priority because it would work even if other management techniques do not reduce pollutant loads and water volume in the creek, and it does not allow these loads to enter the lagoon. Allowing untreated creek water to enter the ocean is not ideal, even though the ocean has a much greater assimilative capacity and the elevated nutrient levels would cause fewer problems in the ocean. However, it is important to remember that the excess water with its pollutants enters the ocean in any case when the lagoon is breached.

The remaining three alternatives focus on managing lagoon water levels after the water has entered the lagoon. Implementing a modified mechanical breaching regime (#38) is given a high priority. In addition to addressing the water quantity problem, such a measure would increase tidal flushing in the lagoon, thereby improving lagoon water quality and enhancing salt marsh development. Proactive measures should be adopted to minimize negative impacts associated with breaching as it has been practiced in the recent past. Rather than waiting for septic system failures to prompt breaching, lagoon opening should be performed on a regular basis before water levels become problematic. Furthermore, breaching should be initiated at the onset of a rising tide to reduce the hydraulic gradient between the lagoon and the ocean and prevent precipitous drops in lagoon water levels (Capelli 1997).

Installing a temporary spillway to allow lagoon waters to drain to the ocean (#34) is another strategy that could be implemented to prevent lagoon water levels from becoming problematic. Such a system would allow lagoon waters to flow to the ocean without rapid draining, thereby reducing environmental impacts associated with mechanical breaching. This strategy would result in a stream across the beach and the spillway would need to be removed before major floods; consequently, it is assigned low priority status. Since it would not increase tidal flushing to the lagoon as #38 and has added complexities, this alternative is not as desirable as Management Alternative 38.

Finally, a water level management facility could be constructed (either with or without a disinfection facility). Although this might be simpler to engineer (and less costly) than the creek bypass, it would still involve discharging excess water (and its pollutants) into the ocean, and there would be higher capital costs and ongoing maintenance costs than with modified breaching. Pending more detailed engineering feasibility studies, this alternative is given a medium priority.

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Table 8-1. Major environmental problems in Lower Malibu Creek and Lagoon and their primary anthropogenic causes.

CATEGORY	PROBLEM	CAUSES
Biota and Habitat	Loss of Aquatic and Riparian Habitat	• Infilling and Urbanization
	Proliferation of Exotic Species	• Introduction of Exotic Species • Elevated Freshwater Flows • Elevated Nutrient Inputs
	Reduced Benthic Invertebrate Populations	• Loss of Aquatic and Riparian Habitat • Eutrophication • Elevated Freshwater Flows
	Reduced Native Bird Populations	• Loss of Aquatic and Riparian Habitat • Persistent High Lagoon Water Levels During the Dry Season • Reduced Benthic Invertebrate Populations
	Reduced Native Fish Populations	• Loss of Aquatic and Riparian Habitat • Proliferation of Exotic Species • Barriers to Anadromous Fish Migration
	Reduced Native Plant Populations	• Loss of Aquatic and Riparian Habitat • Proliferation of Exotic Species
Water Resources	Eutrophication	• Elevated Nutrient Inputs • Elevated Freshwater Flows
	High Pathogen Concentrations	• Elevated Pathogen Inputs • Elevated Freshwater Flows • Elevated Nutrient Inputs
	Persistent High Lagoon Water Levels During the Dry Season	• Elevated Freshwater Flows • Infilling and Urbanization

Table 8-2. Biota and habitat problems and management objectives.

PROBLEM	MANAGEMENT OBJECTIVES
Loss of Aquatic and Riparian Habitat	• Enhance Aquatic and Riparian Habitat
Proliferation of Exotic Species	• Control the Proliferation of Exotic Species
Reduced Benthic Invertebrate Populations	• Enhance Benthic Invertebrate Populations
Reduced Native Bird Populations	• Enhance Native Bird Habitat • Enhance Endangered Bird Habitat
Reduced Native Fish Populations	• Enhance Native Fish Habitat • Enhance Endangered Fish Habitat • Eliminate Barriers to Anadromous Fish Migration
Reduced Native Plant Populations	• Enhance Native Plant Populations

Table 8-3. Assessment of biota and habitat management alternatives for Lower Malibu Creek and Lagoon.

Management Alternative	Design Options	Feasibility	Cost	Effectiveness	Environmental Impacts	Potential Controversy
OBJECTIVE: CONTROL THE PROLIFERATION OF EXOTIC SPECIES						
1. Biomanipulation to reduce non-native fish populations	Addition of host-specific diseases/pathogens, ichthyocides, natural predators, or sterile populations	Uncertain, depends on development of appropriate control; Would require state and federal resource agency approval	Inexpensive	Uncertain	Uncertain; Might negatively impact non-target organisms	High; Might be unpopular due to its potential impacts on non-target organisms
2. Remove non-native invasive plants and revegetate with native species	Removal options: Remove large colonies with motorized equipment, Manually remove small colonies, Apply herbicides (Wetlands Research Associates 1994); Revegetation options: Propagate and plant, Replant locally-collected cuttings, Seed	Feasible	Inexpensive to expensive; Would need to be repeated on a regular basis; $12,000 per acre (Wetlands Research Associates 1994)	Uncertain; Depends on how exotics would respond to treatment; Would reduce non-native plant populations and enhance habitat for native plants if successful	Minor; Widespread use of herbicides may negatively impact non-target species	Low
OBJECTIVE: ENHANCE ENDANGERED BIRD HABITAT						
3. Construct a bird nesting island in the lagoon		Feasible	Relatively inexpensive initially, but frequent recurring expenses	Would provide nesting habitat for endangered birds; Prone to physical failure during high flow events (yearly?)	Significant; artificial island would disrupt hydrological processes	Low
4. Erect signs and fences to prevent human and domestic animal encroachment		Feasible	Inexpensive	Would reduce human and domestic animal encroachment in areas that are heavily frequented by endangered birds	Minor; Would negatively impact aesthetic quality of the lagoon area; fence would collect trash and debris	Low

Table 8-3 (cont.). Assessment of biota and habitat management alternatives for Lower Malibu Creek and Lagoon.

Management Alternative	Design Options	Feasibility	Cost	Effectiveness	Environmental Impacts	Potential Controversy
OBJECTIVE 1: ENHANCE ENDANGERED FISH HABITAT						
5. Install instream structures to enhance steelhead habitat	Boulders or log weirs to collect and secure spawning gravel; Cover devices to provide hiding places; Deflectors, sills, or random rocks to induce scouring and promote the formation of spawning pools (Shields 1983)	Feasible	Inexpensive	May help re-establish populations in the short term; May not be necessary (Franklin and Dobush 1989); Prone to physical failure during high flow events (Frissell and Nawa 1992)	Uncertain; Modifying channels may destabilize the creek and promote localized flooding	Low
6. Modify channel geometry or substrate conditions to enhance steelhead habitat		Feasible	Inexpensive; Channel geometry modification: $110/linear foot, Gravel supplementation: $22/cubic yard (California Department of Fish and Game 1993)	May help re-establish populations in the short term; May not be necessary (Franklin and Dobush 1989); Prone to physical failure during high flow events (Frissell and Nawa 1992)	Uncertain; Modifying channels may destabilize the creek and promote localized flooding	Low
OBJECTIVE 2: ELIMINATE BARRIERS TO ANADROMOUS FISH MIGRATION						
7. Construct structures to allow anadromous fish to circumvent Rindge Dam and other barriers (e.g., tunnel falls, County-operated gage station)	Bypass chutes, Conduits, Ladders, Lifts, Pumps, Sluiceways (U.S. Congress Office of Technological Assessment 1995)	Probably not feasible; Structures would have to be mechanically complex and would be subject to physical failure during high flow events (McEwan and Jackson 1996)	Expensive to very expensive; $500,000 for construction (Bureau of Reclamation 1995); High operation and maintenance costs	Uncertain; Depends on whether the structures would function properly; Would increase steelhead spawning and rearing habitat by 590% and 180%, respectively, if successful (Franklin and Dobush 1989)	Insignificant	Medium; Would be unpopular with those who would prefer to see the barriers removed altogether
8. Remove Rindge Dam and other barriers (e.g., tunnel falls, County-operated gage station) to allow anadromous fish to move directly upstream	Allow natural fluvial processes to remove sediments, Remove sediments with hydraulic dredge, Transport sediments out of the canyon, Transport sediments to an engineered landfill within the canyon (Bureau of Reclamation 1995)	Uncertain; Depends on the outcome of the ongoing Army Corps study	Very expensive, $4-18 million (Bureau of Reclamation 1995)	Would increase steelhead spawning and rearing habitat by 590% and 180%, respectively (Franklin and Dobush 1989); Increased deposition of coarse sands and gravel might enhance aquatic habitat over the long term	Significant; Would cause flooding and short-term damage to aquatic and riparian habitat if fluvial processes are allowed to remove sediments (Shuman 1995); Would cause channel incision upstream of the dam and destabilize side slopes adjacent to the dam	High; Would be unpopular with some local residents who believe the dam has important historical value

Table 8-4. Assessment of biota and habitat management alternatives.

Uncertain	Not viable	Low Priority	Medium Priority	High Priority
• Install bypass structures for anadromous fish (#7) • Remove barriers to anadromous fish migration (#8)	• Biomanipulation to reduce non-native fish populations (#1) • Construct a composite island in the lagoon for birds (#3)	• Install fish habitat enhancement structures (#5) • Modify Creek channel geometry/ substrate to enhance fish habitat (#6)	• Erect fences to protect birds (#4b)	• Remove non-native plants and revegetate with natives (#2) • Erect signs to protect birds (#4a)

Table 8-5. Water resource problems and management objectives

PROBLEM	MANAGEMENT OBJECTIVES
Eutrophication	• Reduce Dry Season Nutrient Inputs to the Lagoon • Reduce Dry Season Nutrient Concentrations in the Lagoon • Reduce Dry Season Algal Growth in the Lagoon • Enhance Dry Season Water Circulation in the Lagoon
High Pathogen Concentrations	• Reduce Dry Season Pathogen Concentrations to the Lagoon • Reduce Dry Season Pathogen Concentrations in the Lagoon
Persistent High Lagoon Water Levels During the Dry Season	• Reduce Dry Season Freshwater Flows to the Lagoon • Prevent Lagoon Water Levels From Becoming Problematic During the Dry Season

Table 8-6. Assessment of water resource management alternatives for Lower Malibu Creek and Lagoon.

Management Alternative	Design Options	Feasibility	Cost	Effectiveness	Environmental Impacts	Potential Controversy
OBJECTIVE: REDUCE DRY SEASON NUTRIENT AND PATHOGEN INPUTS TO THE LAGOON						
9. Construct a groundwater cutoff wall between Malibu Colony and the Lagoon		Feasible	Expensive; $200,000 for construction (R. Morgan, pers. comm.)	Would temporarily reduce nutrient and pathogen inputs to the lagoon; Questionable long-term effectiveness	Insignificant; Temporary ground disturbance	Low
10. Develop a system to treat creek flows before they reach the Lagoon	Advanced wastewater treatment facility, Constructed wetlands (surface, subsurface)	Uncertain due to spatial constraints, land ownership issues, and the system's ability to withstand high flow events (applies only to wetlands)	Very expensive	Would partially reduce dry season nutrient and pathogen inputs to the lagoon	Minor	Low
11. Develop a system to treat urban runoff before it reaches the Lagoon	Constructed wetlands (surface, subsurface), Detention ponds, End-of-the-pipe disinfection devices, Infiltration basins (Ferguson 1991; O'Shea and Field 1992; Bingham 1994)	Feasible	Very expensive	Would reduce dry season nutrient and pathogen inputs to the lagoon	Minor; Urban runoff treatment wetland might not be suitable for wildlife due to the potential for heavy metals and other toxic compounds to bioaccumulate (Helfield and Diamond 1997)	Low
12. Divert urban runoff offshore	Outlet beyond surf zone, System to disinfect runoff before discharge (O'Shea and Field 1992)	Uncertain due to regulatory constraints	Very expensive	Would reduce nutrient and pathogen inputs to the lagoon; Would partially reduce freshwater flows to the lagoon	Significant; Would transfer pollutants from one receiving water (lagoon) to another (ocean); Might negatively impact water quality and aquatic life offshore	High; Offshore outlet would be unpopular with surfers
13. Eliminate septic systems and divert wastewater from Malibu Colony and the Civic Center area to a treatment facility	Construct small water reclamation facility in Civic Center area, Divert wastewater to existing treatment facility (e.g., Tapia, Hyperion), Expand existing "package" plants in area (J.M. Montgomery Consulting Engineers 1986; Peter Warshall and Associates 1992; City of Malibu 1997)	Feasible	Very expensive	Would reduce nutrient and pathogen inputs to the lagoon; Would partially reduce freshwater flows to the lagoon	Uncertain; Would have significant impact if discharged to the creek or offshore; Would have little impact if reused (City of Malibu 1997)	High; Unpopular with local residents due to concerns about future growth in the City of Malibu (Peter Warshall and Associates 1992)

Table 8-6 (cont.). Assessment of water resource management alternatives for Lower Malibu Creek and Lagoon.

Management Alternative	Design Options	Feasibility	Cost	Effectiveness	Environmental Impacts	Potential Controversy
OBJECTIVE: REDUCE DRY SEASON NUTRIENT AND PATHOGEN INPUTS TO THE LAGOON (cont.)						
14. Identify and eliminate illicit connections and discharges (IC/ID) in the lower watershed		Feasible	Inexpensive	Would partially reduce nutrient and pathogen inputs to the lagoon	Insignificant	Low
15. Implement non-point source pollution best management practices (BMPs)	Enhanced street sweeping and catch basin cleaning program; Horse corral management measures; Public education and outreach on fertilizer reduction, proper disposal of pet feces, and septic system maintenance (McCarthy and Mercer 1995; RCD 1997)	Feasible	Inexpensive	Depends on people's willingness to adopt measures; Would reduce nutrient, pathogen, trash, and debris inputs to the lagoon if successful	Insignificant	Low
16. Retrofit Malibu's storm drain system	Baffle boxes, Disinfection devices, Fiberglass inlet weirs, Sediment sumps, Trash and debris screens (O'Shea and Field 1992; England 1995)	Feasible	Expensive	Would reduce nutrient, pathogen, trash, and debris inputs to the lagoon	Insignificant	Low
17. Retrofit septic systems in Malibu Colony and the Civic Center area	Install denitrification units, low-pressure uniform distribution systems, mound systems, trenches/beds, or water separation systems; Re-situate systems immediately adjacent to the lagoon (Harris 1995)	Uncertain; Many systems cannot be modified due to spatial constraints; Would have to be evaluated on a case-by-case basis	Very expensive	Would reduce dry season nutrient and pathogen inputs to the lagoon	Minor; Disposing of effluent by evaporation would create nuisance odors	High; Would be unpopular with local residents and merchants
18. Reduce nutrients in Tapia's discharge	Advanced biological or chemical treatment process, Constructed wetlands	Feasible	Expensive to very expensive	Would reduce nutrient inputs to the lagoon; Constructed surface wetlands would enhance local aquatic habitat	Insignificant	Medium; Tapia might decide to discharge elsewhere if costs are prohibitive

Table 8-6. (cont.). Assessment of water resource management alternatives for Lower Malibu Creek and Lagoon.

Management Alternative	Design Options	Feasibility	Cost	Effectiveness	Environmental Impacts	Potential Controversy
OBJECTIVE: REDUCE DRY SEASON NUTRIENT CONCENTRATIONS IN THE LAGOON						
19. Apply a multivalent cation salt to precipitate phosphorus from lagoon waters	Alum, Lime	Feasible	Inexpensive	Probably would not be very effective since phosphorus is not limiting (Ambrose et al. 1995)	Significant; Lime would alter the pH of the lagoon; Alum can be toxic to aquatic organisms (Cooke et al. 1986); Both would negatively impact lagoon organisms and water quality	High; Might be unpopular with environmentalists and surfers due to its potential impacts on lagoon organisms and water quality
20. Biomanipulation to reduce nutrient concentrations in the lagoon (Addition of nutrient-degrading microorganisms)		Feasible	Inexpensive	Uncertain; Might not function in highly-dynamic lagoon environment	Uncertain; Might negatively impact lagoon organisms	Medium; Might be unpopular with environmentalists due to its potential impacts on lagoon organisms
21. Cover lagoon sediments to interfere with the sediment-water exchange process	Fabric, Grid	Feasible	Expensive, requiring renewal after every flood or, at least, every flood season	Uncertain; Might not function because lagoon sediments experience a great deal of movement	Significant; Altering substrate conditions would negatively impact benthic organisms and tidewater goby populations	High; Would be unpopular with state and federal resource agencies due to its impact on tidewater goby populations
22. Inject nitrate into lagoon sediments		Uncertain due to regulatory constraints	Inexpensive	Uncertain; Might not function in highly-dynamic lagoon environment	Minor; Physical disturbance of the lagoon bottom might negatively impact benthic organisms	Medium; Might be unpopular due to its potential impacts on benthic organisms
23. Install biological treatment devices in the lagoon	"Eco-rafts," "Living machines"	Feasible	Expensive; $120,000 for installation (R. Morgan, pers. comm.); Operation and maintenance costs unknown	Uncertain; Might not function in the highly-dynamic lagoon environment	Uncertain; Might negatively impact lagoon organisms	Uncertain

Table 8-6 (cont.). Assessment of water resource management alternatives for Lower Malibu Creek and Lagoon.

Management Alternative	Design Options	Feasibility	Cost	Effectiveness	Environmental Impacts	Potential Controversy
OBJECTIVE: REDUCE DRY SEASON PATHOGEN CONCENTRATIONS IN THE LAGOON						
24. Construct a disinfection facility and water level management system in the lagoon area	Chlorination-dechlorination, microfiltration, ozonation, ultraviolet light; Multiple pick up locations within lagoon to improve circulation; Pump and pipeline to bring ocean water to lagoon (City of Malibu 1996)	Feasible	Very expensive; $1.2 million for construction; Operation and maintenance costs unknown	Would reduce dry season pathogen concentrations in the lagoon; Would prevent lagoon water levels from becoming problematic; Intake system would enhance circulation in the lagoon; Pump and pipeline would increase tidal flushing in the lagoon	Uncertain; Might negatively impact lagoon organisms	High; Offshore outlet would be unpopular with surfers; Might be unpopular with environmentalists due to its potential impacts on lagoon organisms
OBJECTIVE: REDUCE DRY SEASON ALGAE GROWTH IN THE LAGOON						
25. Apply algicides to lagoon waters	Copper sulfate, Terbutryn; Apply at the earliest indication of a bloom, Apply on a regular basis throughout the bloom season (Atkins et al. 1993)	Uncertain due to regulatory constraints	Inexpensive	Would temporarily reduce algae populations in the lagoon; Would require repeated applications	Significant; Would negatively impact lagoon organisms and water quality	High; Would be unpopular with environmentalists and surfers due to its impacts on lagoon organisms and water quality
26. Biomanipulation to reduce algae populations in the lagoon	Addition of algae grazers or phytophagous fish/insects	Uncertain	Uncertain	Uncertain; May not be very effective in highly-dynamic lagoon environment	Uncertain; Might negatively impact lagoon organisms	High; Would be unpopular with environmentalists due to its potential impacts on lagoon organisms
27. Physically remove algae from lagoon waters	Install floating harvesting devices, Periodically remove algae mechanically (Atkins et al. 1993; McComb 1995)	Feasible	Inexpensive; $12.50/cubic meter (Atkins et al. 1993)	Would reduce algae populations and nutrient concentrations in the lagoon during the dry season; Would require repeated application	Significant; Might negatively impact lagoon organisms	Medium; Would be unpopular with environmentalists due to its potential impacts on lagoon organisms
OBJECTIVE: ENHANCE DRY SEASON [illegible]						
28. Install aerators in the lagoon during the dry season		Feasible	Expensive; $300,000 for installation (R. Morgan, pers. comm.)	Uncertain; Would enhance circulation in the lagoon; Might reduce dry season nutrient concentrations in the lagoon; Might reduce dry season pathogen concentrations in the lagoon	Minor; Physical disturbance of the lagoon bottom might negatively impact benthic organisms	Medium
29. Redirect creek flows to areas with poor circulation		Feasible	Expensive to very expensive	Would enhance circulation in the lagoon	Significant; Lowering lagoon salinity would negatively impact halophilic organisms	Medium

Table 8-6 (cont.). Assessment of water resource management alternatives for Lower Malibu Creek and Lagoon.

Management Alternative	Design Options	Feasibility	Cost	Effectiveness	Environmental Impacts	Potential Controversy
[illegible]						
30. Divert excess creek flows offshore	Outlet immediately offshore or beyond surf zone, System to treat runoff before discharge	Feasible	Very expensive; Would require construction of a conveyance system	Would reduce dry season freshwater, nutrient, and pathogen inputs to the lagoon; Would enhance shorebird habitat in the lagoon	Insignificant	Medium; Offshore outlet would be unpopular with surfers
31. Divert excess creek flows to the City of Malibu for use as a non-potable water supply		Uncertain; Depends on the City of Malibu's plans to construct wastewater reclamation facility	Very expensive; Would require construction of a conveyance system and storage facilities; System to treat creek flows may be required to meet water quality standards	Would reduce dry season freshwater, nutrient, and pathogen inputs to the lagoon; Would enhance shorebird habitat in the lagoon	Insignificant	Uncertain; Might not be acceptable to the City of Malibu
32. Eliminate Tapia's discharge during dry months	Divert discharges offshore, to the Los Angeles River watershed, or elsewhere	Feasible	Expensive	Would reduce dry season freshwater and nutrient inputs to the lagoon	Minor; Might negatively impact steelhead trout populations by reducing freshwater flows down Malibu Creek	Medium; Might be unpopular with state and federal resource agencies due to its potential impacts on steelhead trout populations
33. Reduce water use in the lower watershed	Install high-efficiency faucets, shower heads, toilets, and washing machines; Institute rationing during the dry season	Feasible	Inexpensive	Uncertain; Depends on people's willingness to adopt the measures; Would greatly reduce dry season freshwater flows and slightly reduce dry season nutrient and pathogen inputs if successful	Insignificant	Uncertain; Might be unpopular with local residents and merchants
[illegible]						
34. Install a temporary spillway to allow lagoon waters to drain to the ocean when water levels exceed 3-5 ft.		Feasible	Inexpensive; Would require constant monitoring and maintenance	Would prevent lagoon water levels from becoming problematic during the dry season; Would improve lagoon water quality by decreasing water residence times in the lagoon; Would enhance shorebird habitat in the lagoon	Minor; Would negatively impact beach access	Uncertain; Might be unpopular with surfers due to its potential impact on water quality in the surf zone

Table 8-6. (cont.). Assessment of water resource management alternatives for Lower Malibu Creek and Lagoon.

Management Alternative	Design Options	Feasibility	Cost	Effectiveness	Environmental Impacts	Potential Controversy
OBJECTIVE: PREVENT DRY SEASON LAGOON WATER LEVELS FROM BECOMING PROBLEMATIC						
35. Construct a permanent artificial opening at the lagoon mouth	Breakwater to prevent the intrusion of marine sands, Channel with automated or manual tide gates, Fluidizer system to prevent sand accumulation in the opening, jettied outlet	Feasible; Would have to be designed to withstand flood events and tidal surges	Very expensive; Would require periodic dredging and sand bypassing to avoid sand accumulation	Would prevent lagoon water levels from becoming problematic, increase tidal flushing, and improve lagoon water quality; Would increase overall species diversity in the lagoon	Major; Might negatively impact tidewater goby populations; Would negatively impact beach access; Would cause downdrift erosion, updrift accumulation, and many other problems	High; Breakwater would probably be unpopular with surfers; Permanent opening might be unpopular with state and federal resource agencies due to potential impacts on tidewater goby populations
36. Construct a permanent water exchange system	Pipeline beneath or over barrier beach; Outlet immediately offshore; Outlet beyond surf zone	Feasible; Would have to be designed to withstand flood events and tidal surges	Very expensive; Would require periodic maintenance to avoid sand accumulation and biofouling	Would prevent lagoon water levels from becoming problematic, increase tidal flushing, and improve lagoon water quality during the dry season; Would enhance benthic invertebrate populations in the lagoon	Minor	Medium; Offshore outlet would probably be unpopular with surfers
38. Implement a modified mechanical breaching regime	Breach at the onset of a rising high tide or install a control structure to prevent the lagoon from draining too rapidly; Breach regularly before water levels become problematic (Capelli 1997)	Uncertain due to regulatory constraints	Inexpensive	Would prevent lagoon water levels from becoming problematic, increase tidal flushing, and improve lagoon water quality during the dry season; Would enhance shorebird habitat and benthic invertebrate populations in the lagoon	Uncertain; Might negatively impact tidewater goby populations	Medium; Might be unpopular with state and federal resource agencies due to its potential impact on tidewater goby populations
37. Resume previous mechanical breaching regime		Probably not feasible due to regulatory constraints	Inexpensive	Would not prevent lagoon water levels from becoming problematic and prevent water quality degradation during the dry season	Significant; Would negatively impact tidewater goby populations	High; Unpopular with state and federal resource agencies due to its impact on tidewater goby populations

Table 8-7. Assessment of water resource management alternatives.

Uncertain	Not viable	Low Priority	Medium Priority	High Priority
• Install biological treatment devices (#23) • Install aerators (#28)	• Apply multivalent cation salt (#19) • Biomanipulation to reduce nutrients (#20) • Cover lagoon sediments (#21) • Nitrate injection (#22) • Apply algicide (#25) • Biomanipulation to reduce algae (#26) • Divert creek flows to City of Malibu (#31) • Construct a permanent opening at the lagoon mouth (#35)	• Construct a groundwater cutoff wall (#9) • Divert urban runoff offshore (#12) • Physical algae removal (#27) • Redirect creek (#29) • Install a temporary spillway (#34) • Construct a permanent water exchange system (#36) • Resume past mechanical breaching (#37)	• Eliminate Colony and Civic Center septics (#13) • Retrofit septic systems (#17) • Construct water level management/ disinfection facility (#24)	• Treat creek flows (#10) • Treat urban runoff (#11) • Eliminate illicit discharges and connections (#14) • Implement BMPs (#15) • Retrofit storm drain system (#16) • Reduce nutrients in Tapia's discharge (#18) • Divert excess creek flows (#30) • Eliminate Tapia's discharge during dry months (#32) • Reduce water use (#33) • Modified mechanical breaching (#38)

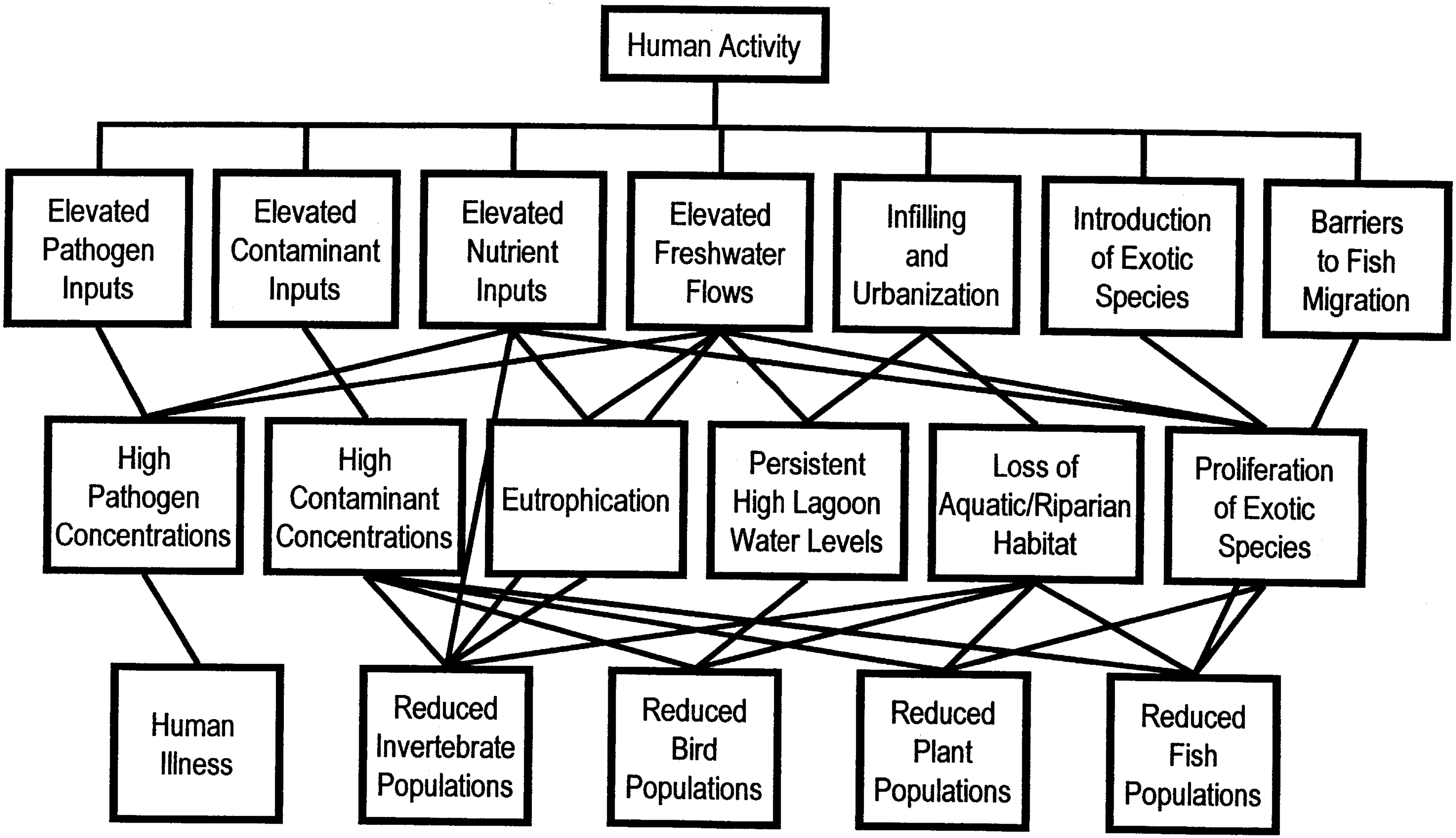

Figure 8-1. Environmental Problem-Cause Diagram for Lower Malibu Creek and Malibu Lagoon.

Chapter 9: Wetland Restoration

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Jonathan Lilien
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9.1. Introduction

Over the past several decades, as scientists and society have recognized the functions and values of wetlands, there has been increasing attention paid to the possibility of restoring lost or degraded wetlands (National Research Council 1992). Historically, the lower Malibu Creek watershed contained extensive wetlands (see Section 1.4), including a much larger lagoon and associated salt marshes, brackish marshes, and freshwater wetlands; and a rich riparian zone associated with the Creek. Since the turn of the century, infilling, road construction, and other activities associated with human population growth have reduced or eliminated wetland habitat. The existing wetlands have been degraded; although they still serve as habitat for fish and wildlife and perform limited hydrologic and water quality functions, inappropriate hydrology and poor water quality impair these habitats. As a consequence, wetlands in the lagoon area are less extensive, comprise a less diverse array of wetland types, and perform decreased biological and physical functions.

In this chapter, we assess the opportunities for wetland restoration in the lower Malibu Creek and Malibu Lagoon areas. Our assessment is based on specific goals for the restoration (see Section 9.3.3.1.1). Basically, these goals are to re-establish natural ecosystem functions and processes and to re-establish a diversity of wetland habitats similar in distribution and relative abundance to the pristine ecosystem. The restoration goals can be accomplished by increasing the size of functioning wetlands and diversity of wetland types in the area. Ideally (from the standpoint of the restoration goals), the Malibu Lagoon ecosystem would be restored to its previous extent; the more wetland habitat restored, the closer we will be to achieving this ideal. However, it is clear that there are substantial obstacles to restoring the entire Lagoon ecosystem to its previous extent. Many of the potential sites are privately owned. There are now significant commercial and transportation structures in the historic wetland, as well as residential and commercial structures in the flood plain. Removing these structures would be complex and costly. For the purposes of this project's analyses, we assumed that wetland creation or restoration would only occur in areas not currently occupied by buildings, roads, or other "hard" structures, with one exception. The exception is an alternative that provides a greater restoration of natural physical and biological processes than would be possible without disturbing current hard structures.

Our exclusion of existing buildings is a matter of practicality, not ecology. The current legal and political environment ensures that the removal of existing commercially viable buildings would be complex and, most likely, extremely expensive. But it is not impossible. In recent years, there has been more and more discussion about removing engineered structures in order to restore natural processes. Proposals to remove the dams in the Pacific Northwest in order to restore salmon populations have received a great deal of publicity lately, but there are other examples (e.g., the Kissimmee River in Florida [Dahm et al. 1995]). In addition, in the wake of widespread flood damages in recent years, there has been a re-evaluation of the wisdom of building in natural flood plains. Changes in policies concerning flood insurance and flood disaster relief could affect the economic viability of commercial activities in flood plains. Finally, public and private funds are increasingly being used to acquire land for restoration. For example, in March 2000, California voters approved billions of dollars in bonds for parkland acquisition. Thus, it is not impossible that extensive wetland restoration could occur in the Malibu area following the removal of shopping centers or other structures.

The remainder of this chapter is divided into two sections, one covering Lower Malibu Creek and one covering Malibu Lagoon. The Lower Malibu Creek section describes the general physical context of lower Malibu Creek, focusing on its suitability for wetland restoration, and identifies alternative restoration opportunities in the Lower Creek. The Malibu Lagoon section describes the physical setting of the Malibu Lagoon area, potential wetland restoration sites, their characteristics, and opportunities and constraints associated with undertaking restoration projects at each of the sites. By providing information on the relative strengths and weaknesses of different sites, this portion of the report may also serve as a guide for future land acquisition efforts. The Malibu Lagoon section concludes with a discussion of conceptual restoration designs, both restoration/enhancement and water treatment alternatives.

9.2. Lower Malibu Creek

9.2.1. Physical Setting

Based on hydrogeomorphic characteristics and vegetation patterns, lower Malibu Creek can be divided into the following six reaches (Figure 9-1):

1. from the Salvation Army Camp Bridge to the entrance of Malibu Canyon,
2. from the entrance of Malibu Canyon to one quarter of a mile or so above Rindge Dam,
3. immediately above Rindge Dam,
4. immediately below Rindge Dam,
5. from below Rindge Dam to the base of Malibu Canyon,
6. from the base of Malibu Canyon to Malibu Lagoon.

9.2.1.1.Reaches 1 and 6

Reaches 1 and 6 have intermediate hydraulic gradients. Compared to other stretches of the creek, floodplains within these reaches are relatively wide, allowing the creek to meander slightly. Despite this geometry, both reaches experience powerful flows during flood events. Accordingly, vegetation is dominated by riparian species adapted to frequent hydrologic disturbance. Wetland plants, which prefer low flow regimes and depositional environments, are generally absent from these reaches of the creek.

The Las Virgenes Municipal Water District (LVMWD) maintains a series of percolation ponds on an terrace below the Tapia Water Reclamation Facility (reach 1). Because they contain wetland plants (e.g., *Typha* sp.) and are periodically inundated, the percolation ponds can be viewed as a constructed wetland. Similar wetlands could be created on terraces elsewhere in reaches 1 and 6. Since the terraces do not have suitable wetland hydrology currently, a supplementary water source is needed. Consequently, constructed wetlands would be expensive to construct and maintain.

Although situated away from the main channel of the creek, wetlands established on terraces would be susceptible to washout during very large flood events. A portion of the terrace containing LVMWD's percolation ponds failed during a powerful winter storm in 1995. For this reason, it is not clear how long constructed wetlands would last in reaches 1 and 6 and how often they would have to be replaced.

9.2.1.2.Reaches 2 and 5

Surrounded on both sides by steep canyon walls, reaches 2 and 5 occupy narrow floodplains and have steep hydraulic gradients. Because of their geometry, both reaches are subject powerful flows during flood events. Accordingly, vegetation is dominated by riparian species adapted to frequent hydrologic perturbations; wetland vegetation is generally absent from these stretches of the creek.

Unlike 1 and 6, reaches 2 and 5 do not contain elevated terraces within their floodplains; vegetation within the entire floodplains is subject to washout during high flow events. Consequently, wetlands established in these sections of the creek probably would be washed out in flood events of modest return interval (2-3 year storms). For this reason, reaches 2 and 5 are not considered suitable for wetland restoration.

9.2.1.3.Reaches 3 and 4

Reaches 3 and 4, the portions of the creek immediately above and below Rindge Dam, are similar to reaches 2 and 5 in being surrounded by steep canyon walls and occupying relatively narrow floodplains. Because of their geometry, the hydraulic gradient of these reaches was steep prior to the construction of Rindge Dam.

The presence of the dam has modified this structure considerably. Following the dam's completion in the mid-1920s, sediments immediately began to accumulate in the reservoir behind the barrier. By the 1950s, the reservoir was completely filled with sediments. This accumulation of sediments has had a marked effect on reach 3, elevating its bed, lowering its hydraulic gradient, and widening its floodplain. These modifications, in turn, have allowed for the development of a rich riparian zone.

Rindge Dam has had entirely different impacts on reach 4. The construction of the barrier and the subsequent accumulation of sediments behind the dam has deprived reach 4 of sediments it had been receiving. Powerful flows over the dam spillway subsequently have scoured existing sediments and carved a pond in the bedrock. The same flows shape vegetation patterns at the site, preventing the establishment of most plants. Consequently, reach 4 is almost entirely devoid of vegetation and is not considered suitable for wetlands.

With a lower hydraulic gradient, nutrient-rich sediments, and diverse riparian vegetation, reach 3 might be suitable for wetland restoration. Given uncertainty regarding the future of Rindge Dam, however, initiating a wetland project in the area is not recommended at this time.

9.2.2. Restoration Opportunities in Lower Malibu Creek

In general, lower Malibu Creek is a high gradient, high discharge stream that experiences powerful flows during flood events. Vegetation in the floodplain is prone to disturbance during flood events of modest return interval. Consequently, plant assemblages are dominated by riparian species adapted to frequent hydrologic disturbance. Most importantly, from the restoration perspective, is the fact that the basic hydrologic processes and land use in the lower Malibu creek have mostly remained unchanged, notable exceptions being Rindge Dam and the elevated creek flows in summer. Thus, there is little need (or opportunity) to undertake typical restoration efforts. Since few wetland species persist in this dynamic environment, wetland restoration is not considered practical.

There are, however, a number of alternative restoration opportunities in lower Malibu Creek. The Resource Conservation District of the Santa Monica Mountains constructed a streambank restoration project in the upper watershed. The project, which involved stabilizing an eroded streambank with a geotextile fabric and revegetating with native plants, is intended to prevent bank erosion and the subsequent release of fine sediments into the watershed. Similar streambank restoration projects might be undertaken in the lower watershed, reducing sediment loads, attenuating non-point source pollutants, and enhancing instream habitat.

Another option would be to restore riparian vegetation. The ecological importance of such vegetation is well documented in the scientific literature (Smith 1992; Osborne and Kovacic 1993). Riparian vegetation provides a number of valuable ecosystem functions including decreasing sediment and nutrient loading, preventing erosion, and enhancing instream habitat. Based on these functions, scientists and environmental practitioners have advocated riparian restoration as a means of reviving degraded watersheds (Ferguson 1991; Howell et al. 1994).

The Malibu Creek watershed, with persistent poor water quality from non-point source pollution, is a strong candidate for riparian restoration. As described earlier, the lower creek and lagoon suffer from eutrophication and high pathogen levels. Nutrients and pathogens, the pollutants of most concern, can primarily be traced to non-point sources, including horse corrals, septic systems, and urban runoff. Surface and ground water from these sources usually passes through riparian vegetation before reaching the creek. Through a variety of physical, chemical, and biological processes, riparian vegetation and soil microbes may remove pollutants in these flows before they reach Malibu Creek, lowering overall pollutant loading.

Destruction and degradation of riparian corridor probably has impaired this function. Although largely intact, some sections of the riparian corridor have been denuded or damaged by road building and channelization. Others parts of the riparian zone have been washed out by powerful creek flows associated with elevated freshwater inputs, urbanization, and channelization upstream. Riparian vegetation could be restored in some of these areas.

One specific area that might support a riparian restoration project is the area above Rindge Dam. As noted above, the dam and subsequent accumulation of sediment have drastically altered the hydraulic gradient in this region. If the dam is not removed, the area above the dam might be restored to enhance riparian functions. This potential restoration site only exists because of the accumulation of sediment above the dam, so obviously if the dam is removed, there will be no restoration opportunity at this site.

In other areas, riparian vegetation could be enhanced to improve its functional capacity. Perhaps the most effective restoration activity would be to control non-native plants along the creek. For example, colonies of the non-native giant reed (*Arundo donax*) could be removed and replaced them with native riparian species. These measures would improve the water purification capacity of the riparian zone, reduce pollutant loading to the lower creek and lagoon, and enhance riparian habitat.

9.3. Malibu Lagoon

9.3.1. Physical Setting

Malibu Lagoon forms at the terminus of Malibu Creek. Although the lower creek and lagoon are not separated by a clear physical boundary, it has been suggested that a point a hundred meters or so north of the Pacific Coast Highway (PCH) bridge be used to demarcate the two systems (A. Orme, personal communication). Malibu Lagoon, a transitional environment influenced by both fluvial and marine forces, occurs below this point; Lower Malibu Creek, a freshwater environment dominated by fluvial forces, lies above. From the standpoint of identifying potential wetland restoration sites, however, it is sensible to consider the lagoon area as it extends farther upstream. The bottom-most segment of Lower Malibu Creek has a low hydraulic gradient, broad flood plain, and might be capable of supporting wetlands; it is sufficiently similar to the lagoon to be considered part of the same system. In this chapter, the lagoon area is therefore seen as extending to a point one kilometer or so north of PCH.

Like the Lower Creek, the lagoon area can be divided into distinct landscape units (referred to as zones in this chapter) based on its hydrogeomorphic characteristics. Zone A, the lagoon-estuary, occupies the area south of PCH (Figure 9-2). Immediately adjacent to the mouth of Malibu Creek, this is a transitional environment between Malibu Creek and Santa Monica Bay, an interface between freshwater and marine systems. In general, this area is low and flat. Depending on the condition of the barrier, the region experiences tidal flushing. Although it has experienced considerable habitat loss, Zone A contains the most extensive coverage of wetlands in the lagoon area.

Zone B, the riparian corridor, extends one kilometer north from the PCH bridge (Figure 9-2). Like the lagoon-estuary, zone B occupies a transitional environment, but in this case between lower Malibu Creek and the lagoon. Under the right conditions (i.e. open barrier, low creek flows, high tidal range), the area immediately north of PCH receives tidal flushing. The rest of zone B is a freshwater environment. The corridor comprises a series of longitudinal bar formations and is dominated by riparian vegetation.

Zone C, the Civic Center area, is the most extensively modified portion of the lagoon area (Figure 9-2). As noted in Chapter 1, the historic lagoon occurred between the barrier beach and the Pacific Coast Highway, but spilled across coarse fluvial sands towards the Civic Center during higher water stages. In the late prehistoric period, there was a deeper, more extensive estuarine-lagoon. Sediments in this region consist of lagoonal muds and fluvial sands beneath artificial fill (Figure 1-8). With a few exceptions, the area no longer contains riparian and wetland vegetation. Huffman and Associates (1999) have evaluated this zone for wetlands or other types of waters that might be subject to regulatory oversight.

9.3.2. Potential Wetland Restoration Sites in the Malibu Lagoon Area

Potential wetland restoration[1] sites may include: (1) areas where wetlands occurred once, but no longer exist, (2) areas with existing wetlands whose function could be enhanced, and (3) areas with the potential to support wetlands.

Many sites in the lagoon area meet the first criterion (i.e., once contained wetlands), but have since been occupied by buildings, roads, and other infrastructure. Acquiring these properties and removing structures would be extremely expensive. Moreover, it appears that the owners of some of these sites are not currently "willing sellers," so that acquisition is problematic. For these reasons, the bulk of this chapter does not consider sites with significant existing buildings or other major infrastructure. The omission of these locations does not imply that such sites would not be extremely valuable for restoring the wetland functions and values in the Lagoon area. In fact,

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[1] For simplicity, the term "restoration" is used broadly here. Different terms related to restoration are defined in Section 9.3.3.

Section 9.3.3.2.1 presents an overall ecosystem restoration alternative that is not constrained by current land use.

On the other hand, there are also a number of areas that were once wetlands and do not yet contain significant infrastructure. The wetlands were destroyed by natural processes and human-induced changes (including filling). These areas include the golf course and vacant lot west of the Lagoon (sites A2 and A3), the western bank of Malibu Creek immediately north of the PCH bridge (site B1), and the "chili cook-off" area (site C2) (Figure 9-2). Note that these areas are privately owned and, although they may once have supported wetlands, they may not currently exhibit wetland characteristics that would subject them to federal or state wetland regulations.

Another series of sites satisfy the second criterion (i.e. contain wetlands whose function could be enhanced). These include the restored salt marsh and eastern bank of Malibu Lagoon (sites A1 and A4) and existing wetland near intersection of Civic Center Way and Webb Way (site C1). An additional pair of sites meet the criterion of having the potential to support wetlands. These include the eastern bank and western banks of Malibu Creek (sites B2 and B3).

A number of field site assessments were conducted to characterize the physical and biological attributes of the different sites (i.e. adjacent conditions, topography, hydrology, soils, vegetation, and wildlife use). Archival data were collected to supplement information obtained in the field; aerial photographs from UCLA's Spence and Fairchild Collections were reviewed to provide information on site history, particularly past functioning as wetland, and property ownership data were acquired from the City of Malibu. The following sections summarize the information obtained during this exercise.

9.3.2.1.Zone A

9.3.2.1.1. Site A1

Site A1, the restored salt marsh, occupies 6.5 ha (16.1 acres) on the western flank of Malibu Lagoon (Figure 9-3). It is bordered by Malibu Colony, the barrier beach, an access road, and the Malibu Lagoon State Beach parking lot. The site is owned by the State of California and managed by the California Department of Parks and Recreation (DPR).

Aerial photographs show the site contained wetlands in the 1920s and 30s. Some of this habitat was filled to accommodate the construction of roads and houses in Malibu Colony. The construction of a levee to prevent flooding in Malibu probably caused further degradation by depriving wetlands of a consistent water source. In the 1950s and 60s, the California Department of Transportation (Caltrans) used the site as a depository for fill material. By the 1970s, the site had been completely filled and occupied by a baseball field.

In 1983, DPR initiated a salt marsh restoration project at the site. Three 1-2 meter deep channels were excavated to reintroduce tidal flow to the area, and the entire site was seeded with salt marsh plants. A walkway was constructed between the parking lot and the barrier beach. The same basic configuration exists at the site today.

The topography of site A1 is unlike most natural southern California salt marshes. Instead of being low and flat, the relief of the restored salt marsh is characterized by elevated islands and peninsulas. The tidal creeks likewise differ from those in natural salt marshes, with broad, relatively straight channels in an "H" configuration rather than meandering channels with a series of branches. This unusual configuration may contribute to problems with water circulation, with stagnant water occurring at the ends of some channels.

The site receives surface water runoff from Malibu Colony and the adjacent shopping center. When Malibu Lagoon is open to the ocean, the site receives tidal flushing; water levels in the restored salt marsh are generally low under these conditions. When the barrier beach closes, the restored salt marsh does not experience tidal flushing and serves as a reservoir for creek flows and urban runoff from the City of Malibu. The site is subject to persistent high water levels under these conditions.

Soils are hydric and mostly consist of fine sediment (i.e. silt and clay). In certain locations, the site contains historic fill material deposited at the site by Caltrans.

Similar to its topography, vegetation in site A1 is unlike most natural southern California salt marshes. Instead of being dominated by halophytes, the restored salt marsh contains an eclectic mixture of salt and brackish marsh species. Pickleweed (*Salicornia virginica*), typically abundant in southern California salt marshes, is relatively rare in the restored salt marsh. Other typically common salt marsh plants such as cordgrass (*Spartina foliosa*) are absent from the restored salt marsh, although this is not unusual in salt marshes that experience limited tidal flushing (Zedler 1982). At the same time, site A1 contains a number of haelophytes such as California bulrush (*Scirpus californicus*). Fleshy jaumea (*Jaumea carnosa*) is the most abundant salt marsh species, occurring commonly along the tidal creeks. Jaumea is relatively freshwater tolerant, and its predominance in the restored salt marsh may reflect the high input of freshwater into Malibu Lagoon. The restoration site lacks the typical plant zonation pattern observed in many southern California salt marshes (Manion and Dillingham 1989). Currently, the vegetation on the areas between the tidal creeks consists largely of salt marsh vegetation that is more characteristic of high marsh zones (Ambrose, personal observation, February 2000). The unusual composition of salt marsh plants may be a result of the compressed area of salt marsh between the tidal creeks and the relatively steep elevational gradient.

Despite its small size, irregular topography, and unusual vegetation patterns, the restored salt marsh is used extensively by wildlife, particularly fish and birds. Ambrose and Meffert (1999) found that the fish using the created tidal creeks were similar to fish in natural salt marshes. Domestic animals and rabbits are also known to use the site.

9.3.2.1.2. Site A2

Site A2, the golf course, occupies 3.5 ha (8.7 acres) immediately west of the restored salt marsh (Figure 9-4). It is bordered by PCH, Malibu Colony Drive, and Malibu Colony. The site is owned by Jerrold Perenchio and has an assessed value of $2.6 million[2].

According to an 1870s topographical map, site A2 once contained an arm of Malibu Lagoon. Although this feature was no longer present by the early 1900s, aerial photographs show wetlands at the site in the 1920s and 30s. These wetlands probably were eliminated by infilling and hydrodynamic alterations in the lagoon area. A golf course was constructed in the 1970s and occupies the site today.

Although it has experienced infilling and is slightly higher than the adjacent salt marsh, site A2 occupies a relatively low position on the landscape. It is generally flat with some modest rises and depressions. Unlike site A1, site A2 has no distinctive wetland characteristics; it is not subject to inundation, does not contain hydric soils, and is not occupied by halophytes. The site receives little surface runoff beyond what is generated on site. Soils primarily consists of fill material. Vegetation is dominated by non-native grasses and trees. Due to the 7-8 foot high walls surrounding the site, the golf course is inaccessible to many animals, although landbirds and domestic animals probably use the site.

9.3.2.1.3. Site A3

Site A3, the vacant lot, occupies 1.1 ha (2.7 acres) west of Malibu Colony Drive (Figure 9-5). It is surrounded by a gas station, post office, parking lot, and Malibu Colony. Like the golf course, the vacant lot is owned by Jerrold Perenchio; it has an assessed value of $2.3 million.

According to an 1870 plat, site A3 once contained an extension of the same arm of Malibu Lagoon as occurred where the golf course is presently located. Aerial photographs show wetlands at the site in the 1920s and 30s. Like site A2, these wetlands probably were eliminated by infilling and changes to the natural hydrologic regime.

Although it has been filled, the vacant lot is flat and occupies a relatively low position on the landscape. Like site A2, it has no distinctive wetland characteristics. The site does not receive appreciable surface runoff and is not subject to inundation. Vegetation is dominated by non-native invasive species such as fennel and ice plant,

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[2] Assessed values were obtained from public records. Throughout this report, they are reported as additional, general information about the sites, but we have made no effort to determine current market values of these properties.

although some mulefat (*Baccharis salicifolia*) is present on the site as well. Soils primarily consist of fill material. Faunal use is limited to domestic animals and landbirds.

9.3.2.1.4. Site A4

Site A4 occupies 0.5 ha (1.2 acres) on the eastern bank of Malibu Lagoon south of PCH (Figure 9-6). It is bordered by a palm grove, the Adamson House, and the beach. Like the existing salt marsh, site A4 is owned by the State of California and managed by DPR. The Adamson House, including the boathouse, is a national historic site.

Historic aerial photographs show a combination of wetland, riparian, and sandy beach habitat at the site in the past. For the most part, the same mixture of habitat is present today. The site has been modified slightly by the construction of the boathouse and the periodic excavation of a channel linking the boathouse to the lagoon.

Site A4 occupies a low position on the landscape. With a few exceptions, its hydrologic regime is similar to site A1. The site receives creek flow surface runoff from adjacent uplands. When the barrier beach at the mouth of the lagoon is open, the site experiences tidal flushing. Because the eastern bank of the lagoon is lower than the restored salt marsh and is not separated from the lagoon mouth by elevated islands and peninsulas, the site experiences more tidal flushing than site A1. Like site A1, the eastern bank is subject to high water levels when the barrier is closed and lower water levels when the barrier is open.

The eastern bank of the lagoon occupies a dynamic area. During flood events, the site is subject to sand and gravel deposition; between flood events, fine sediment (i.e. silt and clay) is deposited at the site. Soils on the eastern bank reflect these deposition patterns.

Like the restored salt marsh, the eastern bank of Malibu Lagoon contains a mixture of vegetation types; salt marsh species such as saltgrass (*Distichlis spicata*) and fleshy jaumea (*Jaumea carnosa*), brackish marsh species such as California bulrush, and upland species are all present. Shorebirds and waterfowl use the site extensively. When the channel between the boathouse and the lagoon is deep and well-defined, it has been known to support fish populations (S. Manion, personal communication).

9.3.2.1.5. Zone A Opportunities and Constraints

Table 9-1 identifies opportunities and constraints associated with wetland restoration at sites A1-A4. Two sets of criteria are considered, ecology and feasibility. Ecological criteria include intrinsic site characteristics such as landscape position, hydrology, and existing habitat value. Feasibility criteria comprise extrinsic site characteristics such as land ownership, acquisition costs, and administrative issues.

All Zone A sites have the advantage of being close to the creek, lagoon, and ocean and occupying relatively low positions on the landscape. Sites A1 and A4 possess the additional advantages of having appropriate wetland hydrology and already containing wetlands. Both sites are publicly owned and thus would not have to be purchased, lowering total project costs considerably. Any modifications to the sites would have to be approved by DPR. Since site A1 already contains functional habitat and site A4 is part of a national historic site, DPR probably would not support the modifications unless the proponent could demonstrate a clear benefit to the environment as a whole.

In addition to the need for administrative approval, there are a number of constraints associated with wetland restoration at sites A1 and A4. Both sites suffer poor water quality, especially during the dry season. While it does not preclude wetland development altogether, poor water quality is problematic in that it inhibits the presence of a diverse wetland flora and fauna. In order to prevent this from occurring, responsible parties should adopt preferred water quality management measures outlined in Chapter 8.

Sites A1 and A4 also are constrained by prolonged inundation. Such a condition is problematic in that it can lead to plant mortality as evidenced by the ring of dead vegetation present in the lower portions of the site A1 channel banks earlier this year. In addition to drowning plants, prolonged inundation can have detrimental impacts on plant recruitment. Prolonged inundation also reduces shorebird habitat and allows Intertidal flats to be colonized by opportunistic plants such as *Typha* and *Scirpus* (Zedler 1982).

Attenuated tidal flushing also constrains wetland restoration at sites A1 and A4. When the barrier beach at the mouth of Malibu Creek is closed, the lagoon area experiences limited tidal flushing. Although it does not preclude wetland development altogether, attenuated tidal flushing is problematic from the standpoint of salt marsh if that is the desired goal (at least where freshwater inputs are high enough to reduce salinity when tidal flushing is interrupted). The development of a diverse salt marsh flora and fauna depends on a healthy tidal flushing regime, high salinity levels, and an abundance of propagules. In the absence of such conditions, salt marsh organisms are often outcompeted by their freshwater counterparts. This process is evident in one of the restored salt marsh channels where *Scirpus* has replaced salt marsh plants. If enhancing or increasing salt marsh habitat is a goal of the restoration plan, it may be desirable to actively manage the barrier to encourage tidal flushing.

Like sites A1 and A4, sites A2 and A3 have a number of constraints associated with their restoration. Both sites are privately owned and would have to be purchased. Acquisition of the sites probably would be very expensive given their proximity to Malibu Colony. Estimating real estate market values is beyond the scope of this report. However, property in Malibu Colony generally sells for $1 million per half-acre (R. Morgan, personal communication); based on this value, sites A2 and A3 would command prices of $20 million and $7 million, respectively, although their assessed values are lower. In addition to large dollar amounts, acquisition depends on having a willing seller. It is unclear whether Mr. Perenchio would be willing to sell his properties at this time.

Wetland restoration at sites A2 and A3 also is constrained by attenuated tidal flushing. Actively managing the barrier beach to promote tidal flushing may represent one way of providing adequate tidal flow to the sites. A second alternative would be to construct a pump and pipeline to bring ocean water directly to the sites, circumventing the lagoon mouth. These alternatives will be discussed further in Section 9.3.3.2.2.

Potentially poor water quality represents another constraint associated with wetland restoration at sites A2 and A3. Like the rest of Malibu Lagoon, the golf course and vacant lot are likely to experience poor water quality, particularly during the dry season. Due to their proximity to roads and developed areas, sites A2 and A3 might also be subject to edge effects.

In spite of these constraints, sites A2 and A3 represent the best opportunity for expanding tidal wetland habitat in the Lagoon area.

9.3.2.2.Zone B

9.3.2.2.1. Site B1

Site B1 occupies 0.6 ha (1.4 acres) on the western bank of Malibu Creek immediately north of PCH (Figure 9-7). It is surrounded by the shopping center and the riparian corridor. The site is owned by Mariposa Land Corporation. The entire Mariposa parcel covers an area of 1.0 ha (2.4 acres) and has an assessed value of $175,000.

Historical aerial photographs show the site contained a mixture of wetlands and riparian vegetation. Most of this habitat was destroyed to accommodate the construction of the shopping center and adjacent parking lot. In order to prevent undercutting and protect the shopping center and parking lot from flooding, the bank has been anchored with fill material and rip-rap.

Most of site B1 occupies a flat terrace 1-2 meters above the creek depending on creek water levels. Soils primarily consist of hydric coarse fill material with a thin surface layer of fine sand and silt. The eastern portion of the site (i.e. the creek-bank interface) is steep, dominated by boulder-sized rip-rap.

The site receives local surface runoff and overbank flow from the creek. A channel runs through the southern portion of the site conveying urban runoff from a storm drain outfall. When the right conditions exist (i.e. open barrier, low creek flow, high tidal range), the adjacent creek experiences tidal flushing.

Vegetation is dominated by non-native grasses and herbaceous vegetation; some riparian plants (e.g., mulefat) occupy the site as well. Fauna known to use the site include domestic animals and waterfowl. Fish surveys have shown the adjacent channel is used extensively by tidewater goby populations (Manion 1993; Ambrose et al. 1995).

9.3.2.2.2. Site B2

Site B2 occupies 5.2 ha (12.8 acres) on the eastern bank of Malibu Creek, approximately 100 meters north of PCH (Figure 9-8). The site is bordered by Serra Road and the riparian corridor. It is owned by the State of California and managed by DPR.

According to aerial photographs, the site has contained riparian vegetation in the recent past. This coverage is essentially intact today, although the site has experienced some alterations. In the late 1920s, the Roosevelt Highway was constructed, bisecting the site from north to south. A bridge was built across the creek and fill material deposited at the site to buttress the road. The southern portion of the site was used by the Adamson family as a picnic area (S. Goode, personal communication).

Site B2 is low near Malibu Creek and higher toward Serra Road. Since it occurs within the floodplain, the site receives overbank flow and is subject to episodic sand and gravel deposition. Some sections of the bank are experiencing undercutting. Soils consist of fluvial cobbles, sand, and silt. Vegetation includes native plants such as mulefat and non-native invasive species such as *Arundo donax*. A row of sycamores that were planted alongside Roosevelt Highway runs through the center of the site. Coastal sage scrub occurs on the upper reaches of the site near Serra Road. Wildlife present include birds, deer, raccoons, and domestic animals.

9.3.2.2.3. Site B3

Site B3 occupies 4.3 ha (10.6 acres) on the western bank of Malibu Creek, 500 meters or so north of PCH (Figure 9-9). It is bordered by Cross Creek Road and the riparian corridor. The site is owned by the State of California and managed by DPR.

Aerial photographs show riparian vegetation at the site throughout the recent past. Although the site has been subject to minor modifications, this coverage is essentially intact today. The topography of the western bank is generally similar to the opposite bank; the site is low near the creek and relatively high toward Cross Creek Road. Like site B2, site B3 occupies part of the floodplain. Channels have been cut through the site during high flow events, scouring material from some locations and depositing fluvial material in others. As a result of this pattern, the site contains of a series of alternating bars and swales; soils are dominated by fluvial cobbles, sand, and silt.

Vegetation comprises a mixture of native and non-native riparian species. Like the opposite bank, site B3 has been invaded by *Arundo donax*. The lack of late successional vegetation suggests the site is subject to frequent hydrologic disturbance. Wildlife use is similar to the eastern bank of the creek and includes deer, raccoons, landbirds, waterfowl, and domestic animals.

9.3.2.2.4. Zone B Opportunities and Constraints

Table 9-2 identifies opportunities and constraints associated with wetland restoration at sites B1-B3. All of the sites have the advantage of being close to the creek and lagoon. Sites B1 and B3 present additional opportunities in being relatively low; hence, wetland restoration at the sites would not require extensive excavation. Sites B2 and B3 are well-buffered, thereby reducing the likelihood of edge effects. Since they are publicly owned, sites B2 and B3 would not have to be purchased, lowering overall project costs considerably.

All of the sites occur within the floodplain. Site B1 occupies an especially precarious position in that it is adjacent to one of the most powerful portions of creek; as a result, the site experiences intense scouring during high flow events. During the powerful, El Niño-related storms of February 1998, parts of the western bank had to be reinforced with rip-rap.

Given this dynamic geomorphic context, site B1 is not a strong candidate for wetland restoration. Wetlands developed at the site would be subject to washout; lowering the bank to the level of the creek would expose the entire bank to failure and threaten the physical integrity of adjacent structures (e.g. the PCH bridge). The only way to prevent wetlands from being washed out would be to construct a berm or other barrier to deflect creek flows away from the western bank. Such a device would destabilize the creek elsewhere and, hence, is not highly recommended.

Sites B2 and B3, further upstream, do not occupy as dynamic a stretch of the creek, but nonetheless would be subject to washout and high rates of sand and gravel deposition during flood events. Both sites contain functional riparian habitat, some of which would have to be destroyed to accommodate the development of wetlands. The replacement of functional riparian habitat with wetlands would result in little increase in ecological value. A decision to effect such a replacement would require a comparison of ecosystem functions between the two habitat types and/or a value judgment as to which habitat type is more desirable. In any case, creating a wetland in these areas would involve a design that resists natural physical processes, which is generally undesirable. It is unlikely DPR would approve wetland restoration in these sites given the lack of an unequivocal ecological benefit and their philosophy of managing for natural conditions.

9.3.2.3.Zone C

9.3.2.3.1. Site C1

Site C1, an existing wetland, occupies 3.9 ha (9.7 acres) near the intersection of Civic Center Way and Webb Way (Figure 9-10). The site is bordered by PCH, condominiums, and a nursery. The wetland and its surroundings are owned by the Tokiye Yamaguchi Trust (TYT), the Reco Land Corporation (RLC), and Wave Property Inc. (WPI). The TYT property occupies 4.1 ha (10.2 acres) and has an assessed value of

$750,000; the RLC parcel covers 3.0 ha (7.3 acres) and has an assessed value of $700,000; and the WPI property spans 3.0 ha (7.1 acres) and has an assessed value of $3.4 million.

Our analyses (Chapter 1) indicate that the construction of the Pacific Coast Highway ramp in the late 1940s led to the development of the wetland on site C1. In the early 20th century, the inner limits of a salt flat approached this area from the south, but there was no wetland on site. Aerial photographs show the site covered with water in the 1920s and 30s. Just as modern runoff is held back by PCH, the 1938 floods were held back by the old coast highway embankment. By the 1950s, the site was being used for agriculture and a horse corral. In addition, wetland restoration activities undertaken on the Reco Land Corporation portion of site C1 played a major role in establishing the wetlands on this site (L. Konheim and D. Reznick, personal communication).

Site C1 occurs at a low spot on the landscape. The site is generally flat with a slight rise toward the north. It receives surface runoff from surrounding hills and adjacent roadways. During the wet season, the wetland becomes fully inundated. It is not clear whether standing water remains at the site throughout the dry season.

Soils at site C1 are probably hydric. Based on the tendency of water to accumulate at the site, it is reasonable to assume the site is poorly-drained and has a subsurface impermeable layer (e.g. clay lens) that prevent the downward movement of water. Vegetation at the site is mixed; in addition to common wetland species (e.g. *Distichlis*, *Scirpus*, and *Typha*), the site contains riparian plants such as mulefat and non-native invasive species such as castor bean and fennel. When inundated, the wetland attracts waterfowl. The site is one of the best locations in the region for a breeding Pacific tree frog population (S. Manion, personal communication).

9.3.2.3.2. Site C2

Site C2, "chili cook-off" area, occupies 6.4 ha (15.8 acres) in the heart of the Civic Center area (Figure 9-11). A commercial area, PCH, site C1, and Civic Center Way border the site. The Reco Land Corporation owns the site, which has been assessed at $4.8 million. The total acreage of the property is 19.61 acres, which includes the adjacent commercial development (L. Konheim and D. Reznick, personal communication).

Before berms were constructed to prevent flooding over the western bank of Malibu Creek, the "chili cook-off" site received overbank flow and experienced periodic inundation. Aerial photographs taken after flood events in the 1930s show considerable amounts of standing water at the site. The site was used for agriculture throughout the first half of the twentieth century. A baseball field, constructed at the site in the 1950s, was abandoned in the 1970s. The site has been vacant ever since and served as a depository for fill material. Read (1999) summarizes the history and current status of this property as part of a delineation for the Malibu Bay Company.

Site C2 is relatively flat. The southern portion of the site is a meter or so higher than the northern portion due to the presence of fill material. A 1-2 meter deep flood control channel runs through the center of the site, conveying urban runoff from the Civic Center area to Malibu Creek via a pair of 36-inch culverts beneath the shopping center area. Since the hydraulic gradient between the "chili cook-off" area and Malibu Creek is weak, stormwater tends to accumulate in the channel.

Soils at the site primarily consist of coarse fill material. Vegetation is dominated by non-native grasses and herbs such as mustard and castor bean. Ground squirrels use the site extensively; waterfowl may congregate in the flood control channel when it contains standing water.

9.3.2.3.3. Site C3

Site C3 comprises a series of vacant lots (and possibly an area currently used as a nursery) near the Civic Center (Figure 9-12). The site occupies an area of 3.2 ha (7.9 acres) is bordered by foothills, Cross Creek Road, and Civic Center Way. It is owned by Joan Knapp and Malibu Residential Housing (MRH). The Knapp property covers an area of 7.6 ha (18.8 acres) and has an assessed value of $690,000; the MRH property spans 3.4 ha (8.5 acres) and has an assessed value of $2.3 million.

Prior to the 1970s, the site was primarily used for agriculture. The western portion of the site has since served as a depository for fill material. As evidenced by the presence of decomposing organic matter, a local nursery apparently uses the center portion of the site for composting.

Site C3 occupies the base of an alluvial fan. The central portion of the site is flat with a gradual rise to the north. The western portion of the site, which contains large quantities of fill material, is 1-2 meters higher than the remainder of the site. The eastern portion of the site is low and flat.

Like many of the other sites, site C3 has no distinctive wetland characteristics. It receives surface runoff from adjacent hills, but is not subject to inundation. A drainage channel conveying urban runoff runs along the southern and eastern flanks of the site (i.e. the perimeter of the Civic Center).

There are no hydric soils present on the site. Soils in the western portion of the site consist of coarse fill material; finer-textured, alluvial soils occur in the central and eastern portion of the site. The City of Malibu (1997) has identified the site as a potential irrigation/infiltration area for treated wastewater effluent. Based on this finding, it is reasonable to assume soils are highly permeable and have good drainage characteristics.

Vegetation is dense in the central and western portions of the site; common plants include mulefat and non-native invasive species such as castor bean and fennel. Wildlife known to use the site include birds, deer, ground squirrels, raccoons, and domestic animals.

9.3.2.3.4. Zone C Opportunities and Constraints

Table 9-3 identifies opportunities and constraints associated with wetland restoration at sites C1-C3. Site C1 presents a number of opportunities; it occupies a low position on landscape and already contains wetlands. Furthermore, the probable presence of jurisdictional wetlands might constrain development opportunities at the site. Property owners might be willing to sell the land given administrative constraints associated with developing the site or accept mitigation credits in exchange for relinquishing rights to part of their property.

All of the sites are isolated from the creek, lagoon, and ocean and are likely to experience edge effects given their proximity to roads and other developed areas. Sites C1, C2, and C3 are privately owned and would have to be purchased. Acquisition costs probably would be high given the commercial value of property in the Civic Center area, especially the "chili cook-off" area. In addition to the potential high cost of property, acquisition of the sites depends on the willingness of property owners to sell their properties.

Wetland restoration at sites C1 and C2 could be constrained by poor drainage. Our observations at site C1 suggest that is serves as a sink for locally generated surface runoff. It appears water that accumulates at the site is only removed from the system via evaporation and infiltration. However, the Malibu Bay Company states that "[b]ased on testing conducted on the property, the site does drain quickly after storm events, and ponding is apparent only in a few discrete, depressions on the property caused by uneven leveling when fill was placed on the site a number of years ago" (letter to C. Kroll from L. Konheim and D. Reznick, 5-12-99).

Site C2 is connected to Malibu Lagoon through a series of culverts beneath the shopping center area. The culverts have a weak hydraulic gradient and make a pair of ninety-degree turns before discharging into Malibu Creek. Consequently, the site is not well drained and experiences ponding after storm events.

Sites C2 and C3 have additional constraints in containing large quantities of fill material. This material would have to be removed before wetlands could be established at the site, requiring large capital investments. Since neither of the sites have appropriate hydrology, wetland restoration would require the provision of supplementary water sources. The construction of conveyance systems and ongoing costs associated with providing water to the sites would further increase restoration costs.

9.3.3. Restoration Alternatives

Although they are often used interchangeably, the terms wetland restoration, enhancement, and creation can each be defined simply and unambiguously. Wetland enhancement is the physical modification of existing wetlands to improve one or more of their structural or functional attributes. Wetland restoration is the re-establishment of wetlands at sites where wetlands once existed, but no longer occur. Wetland creation is the establishment of wetlands in upland areas that have never contained wetlands, but have the potential to support wetlands (Lewis 1990; National Research Council 1992).

This section identifies and evaluates wetland restoration, enhancement, and creation alternatives in the Malibu Lagoon area. A distinction is made between attempting to enhance or restore wetlands to perform multiple functions (wetland restoration and enhancement alternatives) versus those aimed at creating wetlands to improve water quality (treatment wetland alternatives). Accordingly, this section has two major parts, following a brief discussion of objectives (Section 9.3.3.1). Section 9.3.3.2 evaluates potential wetland restoration and enhancement alternatives that could be undertaken in the lagoon area. Section 9.3.3.3 follows with an assessment of treatment wetland alternatives for the lower Malibu Creek watershed. Discussion of each alternative includes description of the project and its goals; the design; advantages and disadvantages of the project, and a priority ranking.

The priority rankings were based largely on technical feasibility and an assessment of the likely ecosystem benefits, including the benefit-cost ratio (i.e., the magnitude of ecosystem benefits derived per unit cost of restoration). We do not include societal or political considerations in the rankings because our focus has been on technical factors. In fact, the multitude of interest groups in Malibu makes it infeasible for us to include social considerations – some groups would like to remove all commercial and residential buildings in the lagoon area in order to recreate the original lagoon/floodplain system, while others favor new commercial or residential development on sites we have identified as potential for restoration, and we have no way to determine the proper weighting to give to each perspective. Social considerations need to be evaluated by the community, decision-makers, and others who wish to implement wetland restoration in the region. In general, we also do not base the priority rankings on property ownership. Clearly, sites that are privately owned must be restored with the owner's permission or acquired before restoration can take place. However, many factors can influence these conditions, and these factors will vary over time. We have made no attempt to assess these factors in this report.

It is important to note that all of the alternatives discussed in this section are discussed on a conceptual level. No new studies were undertaken to assess various aspects of the designs, since that was beyond the scope of this project. In all cases, more detailed analysis will be required before deciding to pursue a particular design. Where specific studies are clearly needed, we have identified these. In some cases, additional information may change the priority rankings we assigned to an alternative. The alternatives are presented to provide an overview of what could sensibly be achieved in the Malibu Lagoon area, given the availability of undeveloped areas and the likely constraints for each area.

9.3.3.1.Objectives

Efforts to restore, enhance, or create wetlands should start by clearly defining objectives. Such objectives are vital in selecting suitable sites, guiding the design process, and measuring success. A number of factors should be considered in formulating these objectives, including regional and local habitat loss and specific problems in the watershed that can be corrected by wetland restoration, enhancement and creation. Responsibility for developing wetland restoration, enhancement, and creation objectives ultimately falls in the hands of resource agencies such as the California Department of Parks and Recreation and stakeholder groups like the Malibu Lagoon Task Force. However, to aid in the prioritization of alternatives for the lower Malibu Creek watershed, we have formulated objectives for both (1) restoration and enhancement of wetlands and (2) creation initiatives for stormwater/wastewater treatment wetlands.

9.3.3.1.1. Wetland Restoration and Enhancement Objectives

The first objective for restoration and enhancement of wetlands in the lower Malibu Creek Watershed is to re-establish more natural ecosystem functions and processes. Important functions of the watershed, which we aim to restore or improve, include support of native biodiversity, resilience from natural disturbance, and overall sustainability. By restoring wetlands in the lower watershed, we also wish to return more natural biogeochemical processes to the lagoon area. Restored marshes will help to cycle nutrients in the water; produce organic matter as food for lagoon biota and structure for development of soils; and improve water quality.

Support of endangered species is frequently an important goal of wetland restoration projects. One endangered species, the tidewater goby, is a resident of Malibu Lagoon, and a number of other species (e.g., southern steelhead, least tern, brown pelican) pass through or use the Lagoon. There are also endangered species that might be able to occur in Malibu Lagoon even though they do not presently occur there (see Chapter 3). Although support of endangered species is one important ecosystem service provided by wetlands, we feel that the overriding objective should be the re-establishment of natural ecosystem functions and processes. The needs of endangered species should be considered in the context of restoration projects and incorporated into restoration plans when appropriate, but at Malibu they should not drive the restoration planning and design.

Another major goal of the restoration/enhancement effort is to increase the amount of high quality wetland habitat in the lower watershed, thereby re-establishing a diversity of wetland habitats similar in distribution and relative abundance to what occurred in the pristine ecosystem. The wetland habitats we wish to establish should be self-sustaining with a minimal requirement for ongoing maintenance efforts and costs. Finally, we believe it is important to establish habitats with natural appearances.

9.3.3.1.2. Treatment Wetland Objectives

The possibility of improving lagoon water quality through wetland restoration, enhancement, and creation is particularly promising. Wetlands remove waterborne pollutants through a variety of mechanisms, including sedimentation, filtration, plant assimilation, adsorption, and microbial transformations (Corbitt and Bowen 1994). Over the past thirty years or so, environmental professionals have begun to take advantage of these processes by incorporating wetlands into conventional wastewater treatment systems. In their application, treatment wetlands have proven effective in removing a variety of constituents, including heavy metals, nutrients, pathogens, and suspended solids (Hammer 1989, Moshiri 1993).

Nutrients and pathogens, constituents that pose the biggest threats to human health and ecological integrity in Malibu, are the logical target pollutants of treatment wetlands in the lower watershed. Urban runoff from the City of Malibu and flows from Malibu Creek could potentially be treated. If a wastewater treatment facility is constructed, treatment wetlands could also be used polish secondary or tertiary wastewater effluent. Given high flow volumes during the wet season, treating wet season flows probably is not feasible. Consequently, this report focuses on the potential for constructed wetlands to treat dry season urban runoff and creek flows.

The two primary objectives for creation of treatment wetlands are to improve water quality and create freshwater wetland habitat. More specific goals for water quality improvement depend on the location of the wetland in the lower watershed and the size of the property available. Water quality in the Creek and Lagoon can be improved by treatment of non-point source pollution from stormwater runoff and dry season urban runoff in created wetlands. Also, created wetlands may be used to polish secondary and tertiary wastewater effluent from treatment plants before discharging them back into the Creek/Lagoon. These goals will be expressed as alternatives in the following section on Treatment Wetlands Alternatives (Section 9.3.3.3).

The second objective of treatment wetlands is simply to create more freshwater wetland habitat in the lower Malibu Creek Watershed to replace historic wetlands that have been lost. For this objective, the various ecological objectives identified for wetland restoration and enhancement hold, although it is recognized that in practice they may need to be compromised to achieve the water quality objectives.

9.3.3.2.Wetland Restoration and Enhancement Alternatives

The following sections discuss each of the restoration and enhancement alternatives in detail. We begin the discussion of wetland restoration and enhancement alternatives by considering an alternative that restores to the maximum extent possible the ecosystem processes originally present in the Lagoon area. This alternative, the "Malibu Lagoon Ecosystem Restoration Alternative," is not constrained by current land uses in the area, including the presence of existing structures. The remaining alternatives focus on the areas that do not currently support significant infrastructure. The alternatives identified include lagoon and salt marsh restoration, salt marsh enhancement, east lagoon salt marsh restoration, freshwater wetland preservation, and freshwater wetland enhancement. Table 9-4 identifies opportunities and constraints associated with these wetland restoration and enhancement alternatives for the Malibu Lagoon area.

9.3.3.2.1. Malibu Lagoon Ecosystem Restoration Alternative

Site description and project goals. The proposed Malibu Lagoon Ecosystem Restoration Alternative would encompass much of the area around the current estuary, including commercial buildings and portions of the Malibu Colony as well as areas A1-3 and B1-3 (Figure 9-13). The goal of this alternative is to restore to the extent possible the original physical and ecosystem processes of the creek-estuary system. In particular, this alternative removes some of the physical hydrological constraints, thereby allowing the system to recover some of its innate dynamics. The artificial constraint on the western bank of the Lagoon, currently enforced by rip-rap, would be removed, allowing the creek to move to the west, as it once did. The opening to the ocean would not be constrained to its current location, but could also move westward where there houses currently prevent its movement. Moreover, the removal of houses would restore the barrier-beach dynamics, including allowing wash-over from the ocean.

Description of design. This design would entail removal of buildings, parking lots and other permanent structures within the restoration footprint, and fill and rip-rap. Removal of commercial buildings north of PCH would allow the re-establishment of natural fluvial processes. Removal of houses from the eastern end of Malibu Colony would allow the re-establishment of beach and near-shore processes.

Most of the existing roads in the restoration area would be removed. Pacific Coast Highway would need to be re-constructed in a way to minimize its influence on the creek and lagoon dynamics. Most likely, this would involve elevating the road on pilings from the eastern edge to the western edge of the restoration area. The road might also be moved somewhat to the north to provide a larger area for the reconstructed lagoon.

This alternative would provide enough area for construction of a lagoon with similar configuration to the lagoon depicted in the earliest maps of Malibu Lagoon. Although the total area available for the lagoon and surrounding habitats would be smaller than the lagoon of 200 years ago, the basic configuration and mix of habitat types could be reconstructed. Excavation would be necessary to construct a deeper lagoon. In addition, the area bordering the lagoon would be graded to provide the appropriate elevations.

Full success of this alternative is contingent on proper water level management. The larger area would provide a somewhat larger capacity for absorbing freshwater flowing down the Creek before the Lagoon would reach excessively high levels. Nonetheless, continued freshwater influx through the dry season would compromise the ecological integrity of this alternative.

Advantages. This alternative provides the greatest restoration of original ecosystem structure and process of all the alternatives considered here. This alternative does not restore all of the original features of the lagoon area; for example, the areal extent of the wetland system would smaller than in the pristine ecosystem and the diversity of habitat types would be lower than occurred previously in the entire region. Nonetheless, it restores critical physical processes to the central core of the lagoon ecosystem. By minimizing constraints on physical processes in the most dynamic area, problems with flooding and erosion would be resolved. This alternative would be successful in achieving the aforementioned objective of restoring a diversity of wetland habitats similar in distribution and abundance to what occurred in the natural ecosystem. The larger wetland area would support larger populations of native animals and plants, and most likely more species than currently occur in the area. A subtidal basin similar to (albeit smaller than) the historic Lagoon area would provide high quality habitat for fishes and invertebrates and help ameliorate water quantity problems during the summer months. Expanded mudflats would support increased benthic invertebrate and shorebird populations and increased subtidal area would provide more habitat for native fish. Enhancing and increasing salt marsh habitat would improve wetland plant species abundance and diversity, which would help to assimilate nutrients and pollutants in the water.

Disadvantages. There are no long-term ecological disadvantages to this alternative. In the short term, there would be disruption of existing habitats as the larger restoration site was constructed. Care would need to be taken to minimize impacts to birds and fish, especially. For example, construction activities would need to be designed to ensure that the tidewater goby population was not adversely affected.

The greatest disadvantage of this alternative are the substantial legal, economic and political implications of such an extensive restoration. At present, there do not appear to be willing sellers for most, if not all, of the properties that would be affected, making acquisition of the properties problematic. Acquisition costs are likely to be extremely high, at any rate. This is the only alternative that would demolish existing commercial and residential structures, further increasing the costs of property acquisition compared to other alternatives. Property acquisition is an issue for other restoration alternatives, but the magnitude of the issue is much greater for this alternative.

Although we do not wish to minimize the cost and difficulty that would be associated with this alternative, it is worth noting that even larger-scale restoration projects are being planned and implemented nationally. The Kissimmee River and related Everglades Ecosystem Restoration projects in Florida are much more extensive and will be much more expensive, costing billions of dollars. They include removal of established infrastructure such as river channels. There is also increasing attention being paid to the possible removal of dams (including Rindge Dam) as a means of restoring river dynamics and native fish populations. Dam removal is seen by some as a viable means of restoring declining salmon populations in the Pacific Northwest. Large scale (and expensive) restoration projects are becoming increasingly common in the United States as the environmental and societal costs of human impacts on natural habitats are becoming better understood.

Priority: From an ecological perspective, this is by far the most preferred restoration alternative. This is also the alternative that is most disruptive to the current human activities in the Lagoon area. The legal, financial and social considerations for this alternative far surpass the other alternatives. Therefore, this alternative is not prioritized with the other alternatives; it is truly in a class of its own.

9.3.3.2.2. Lagoon and Salt Marsh Restoration Alternatives

9.3.3.2.2.1.Lagoon and Salt Marsh Restoration Alternative I

Site description and project goals. The proposed Lagoon and Salt Marsh Restoration Alternative I encompasses three sites, site A1, A2 and A3 (Figures 9-2, 9-3, 9-4 and 9-5). These sites lie directly west of Malibu Lagoon where an arm of the Lagoon was once located (see Chapter 1). The goals of this alternative are to increase subtidal, intertidal mudflat, and salt marsh habitats, thereby restoring a diversity of high quality historic habitats in the lower watershed. Also, more natural ecosystem functions and processes should be established by connecting three previously separated properties into one larger functioning unit.

Description of design. This alternative entails re-connection of hydrology in sites A1, A2 and A3 and subsequent restoration of salt marsh habitat in those sites (Figure 9-14). In addition, subtidal and intertidal mudflat habitats would be restored in site A1. The total area of this proposed restoration is 11.1 ha (27.5 acres).

General restoration design plans include hydrologic connection of the three sites, excavation of soil for habitat creation, grading of the sites, and planting of native salt marsh vegetation. The State Park emergency access road would be removed in order to connect sites A1 and A2 hydrologically. Hydrologic connection of sites A2 and A3 could be designed two ways, either by removal of Malibu Colony Drive within the project or installation of a large box culvert underneath the road. The later of the two designs would probably be more cost effective. Although box culverts impose hydrologic constraints on restored wetlands, the amount of wetland proposed for Site A3 is small enough that this constraint would be acceptable. Site A3 may become a salt, brackish or freshwater marsh, depending on the design of the hydrologic connection between sites A2 and A3 and the hydrologic response to the design used.

Soil would be excavated from sites A2 and A3 to create a salt marsh community with a sinuous tidal channel system. Excess soil would be disposed of off-site. All three sites would be graded to specific elevations for creation of specific habitat types. Native salt marsh plants could be planted to accelerate re-vegetation of salt marsh habitats.

Success of this restoration design is contingent upon water management in the present Lagoon area and elevations created in sites A2 and A3. If water level in the lagoon is not managed at an appropriate level (either by breaching the barrier or other action), then persistent high water levels will preclude the establishment or survival of salt marsh plants. During persistent high-water conditions, water quality will likely decrease toward the back of the restored Lagoon arm (site A3) as it becomes stagnant. Low salinity, caused by excess freshwater entering the lagoon, would also inhibit the establishment of a salt marsh community; in particular, the benthic invertebrates that would serve as food for birds using the mudflat habitat would depend on appropriate salinity. Creating appropriate elevations in this restoration is critical to the establishment of the various habitats. If A3 is only flooded a few times a year and/or elevations in sites A2 and A3 are too high, salt marsh communities may not be able to persist. Rates of sedimentation in the Lagoon and sea level rise should be accounted for when elevations are determined.

Advantages. This alternative has a number of distinct advantages. It would greatly increase salt marsh habitat in the lagoon area, expand lagoon water holding capacity, enlarge the subtidal basin for fish and other aquatic organisms, and lessen the water quantity problem in the Lagoon that is exacerbated during the dry season. The resulting configuration of the lagoon and adjacent salt marsh habitats would be similar to (albeit smaller than) the historic Lagoon conditions present prior to modern human occupation. Consequently, this alternative would be successful in achieving the aforementioned objective of restoring a diversity of wetland habitats similar in distribution and abundance to what occurred in the natural ecosystem. In turn, this diversity of habitats created would support a variety of aquatic and wetland biota not present on much of the sites now. Specifically, expanded mudflats would support increased benthic invertebrate and shorebird populations and increased subtidal area would provide more habitat for native fish. Enhancing and increasing salt marsh habitat would improve wetland plant species abundance and diversity, which help to assimilate nutrients and pollutants in the surface water.

Disadvantages. The greatest constraint associated with this alternative is hydrology in winter. Since Malibu Creek has been channelized and levied, the water in the main channel flows extremely fast during the rainy season and empties directly into the ocean. Freshwater from the stream may then completely bypass this extended arm of the Lagoon, thus depriving it of some of the characteristics that would historically have occurred in this habitat type. On the other hand, given the force of the high creek flows, this bypass would help ensure the integrity of the restoration site. Other important drawbacks of the alternative include potentially poor water quality due to urban runoff and effluent from nearby septic systems and short-term disturbance to existing habitat.

Priority: Lagoon/Salt Marsh Restoration I would recreate a large wetland area with a variety of habitat types similar to what occurred in the pristine ecosystem. Implementation of this alternative is considered high priority. The most serious issue regarding this alternative is the availability of the property needed for the restoration project. In general, we have not considered availability in assessing the restoration alternatives, but if the property is not available, then clearly this restoration project cannot be completed. Given the expense associated with acquiring these properties at full market value and questions about the willingness of the current owner to sell his property, the likelihood of implementing this alternative is unclear.

9.3.3.2.2.2.Lagoon and Salt Marsh Restoration Alternative II

Site description and project goals. Lagoon/Salt Marsh Restoration Alternative II is a variation of the alternative described above and encompasses sites A1-3 (Figure 9-14). This design would be treated as a contingency plan for the first alternative in the event that not enough salt water reaches the back of the restoration area (site A3) through normal tidal action.

Description of design. In this design, salt marsh habitat would be restored in sites A2 and A3, connected to the existing salt marsh in site A1, and supplemented with a ocean water via a pump and pipeline beneath Malibu Colony. The purpose of this pumping is to provide fresh seawater and enhance tidal flushing throughout the Lagoon.

Advantages. By providing seawater directly rather than relying on flushing via the main lagoon, this alternative avoids the potential water quality problems associated with Lagoon/Salt Marsh Restoration Alternative I. In addition, salt marsh, intertidal mudflats and subtidal habitats would be increased. These expanded and improved aquatic habitats would potentially support a diversity of fish, invertebrates and birds.

Disadvantages. This Lagoon/Salt Marsh Restoration Alternative has many of the same drawbacks as the first alternative. It would require the re-routing of Malibu Colony Drive or construction of a box culvert under Malibu Colony Drive and would temporarily disturb existing habitat/biota in site A1. More importantly, this alternative has additional drawbacks in that it would be expensive (capital and maintenance costs), require frequent maintenance, and is not a self-sustaining system. The goal of creating a tidal salt marsh community would be difficult to achieve with simply a unidirectional tidal flow from pumped seawater; a fairly sophisticated system of automatic tide gates might be required to ensure a "tidal" fluctuation in water level on the site. Moreover, the impacts of pumping seawater beneath the Malibu Colony barrier on the barrier structure would need to be evaluated more closely.

Priority: The disadvantages of this alternative are substantial, especially the much greater cost and complexity of Lagoon/Salt Marsh Restoration I, and so this alternative is assigned a low priority. As stated at the outset, this alternative is really a contingency, in case the Lagoon/Salt Marsh Restoration I project does not work as designed. Additional analyses should be conducted to determine whether and under what conditions the expanded salt marsh at sites A1-A3 would receive adequate tidal flushing. Careful management of the barrier beach may eliminate the need for an open water delivery system. Implementing a modified mechanical breaching regime in which the barrier is opened on a regular basis may provide sufficient tidal flushing to allow for salt marsh development in the restoration site without the construction of a pumping system.

9.3.3.2.3. Salt Marsh Enhancement/Restoration Alternatives

Salt Marsh Enhancement/Restoration Alternatives I, II, and III are potential enhancement and restoration measures that could be implemented within site A1 (Figures 9-2, 9-15, 9-16, and 9-17). The goal of these alternatives is to improve conditions at the salt marsh (especially topography and hydrology), thereby creating habitats that more closely resemble and function like natural southern California salt marshes.

9.3.3.2.3.1.Salt Marsh Enhancement/Restoration Alternative I

Site description and project goals. Salt Marsh Enhancement/Restoration I would entail the minimal effort and thus impact biota the least. The objective of this alternative is to enhance salt marsh habitat and create more mudflat habitat within the restored salt marsh site (site A1) (Figures 9-2 and 9-3).

Description of design. Enhancement design would consist of eliminating the unnatural, elevated islands and peninsulas throughout the site (Figures 9-3 and 9-14). The pedestrian walkway would be removed from the middle of the site and either re-routed around the west side of the marsh or elevated on stilts to decrease disturbance of marsh biota and increase tidal circulation. Back channels could be connected to improve water circulation within the site (Figure 9-15). This enhancement may be constructed in sections by restricting flow to portions of the site at different times.

Advantages. Only the major problems in this site would be solved by this alternative. Salt marsh habitat would be enlarged and its functions improved. Also, circulation in this site would be somewhat improved by connecting the island in the southwestern corner of the marsh with the island to the east of it. In addition, existing biota would be impacted the least of the three related enhancement/restoration alternatives. A major advantage of this project is that it is the least expensive of the three salt marsh enhancement/restoration alternatives. If the golf course and vacant lot to the west (sites A2 and A3) become available for purchase in the future, only minimal effort would have been expended on site A1, leaving the opportunity for implementation of the Lagoon/Salt Marsh Restoration Alternatives I or II.

Disadvantages. One disadvantage of this alternative is that it does not include sites A2 and A3 to the west, and therefore, true restoration to a similar historic state cannot be accomplished. Compared to the other Salt Marsh Enhancement/Restoration Alternatives, this alternative retains the unnatural tidal creek configuration of the current restored area. Consequently, biotic and hydrologic processes and functions would not be restored as fully as in the other alternatives.

Priority: Salt Marsh Enhancement I involves minor physical modifications of the existing salt marsh to increase wetland acreage, expand intertidal habitat, improve tidal flushing, and enhance water circulation. This alternative represents a good fallback position if acquisition of sites A2 and A3 proves impossible. Consequently, Salt Marsh Enhancement I is assigned high priority status.

9.3.3.2.3.2.Salt Marsh Enhancement/Restoration Alternative II

Site Description and Project Goals. The Salt Marsh Enhancement/Restoration Alternative II is located in A1 (Figure 9-2 and 9-3). The objective of this alternative is to enhance salt marsh and intertidal habitats in order to restore more natural processes and functions.

Description of Design. Salt Marsh Enhancement/Restoration Alternative II would involve re-grading site A1 and creating a new, more naturally-shaped, meandering tidal channel network (Figure 9-16). The pedestrian walkway would be removed from the middle of the site and either re-routed around the west side of the marsh or elevated on stilts to decrease disturbance to marsh biota and increase tidal circulation. The site will be graded from highest in the back or west to lowest near the Lagoon. One main tidal channel will be excavated and connected to a series of smaller sinuous tidal channels. These channels would be designed to mimic the tidal creek networks of natural salt marshes in the region. Salt marsh plants would be planted to expedite the establishment of a salt marsh community.

Advantage. This alternative would allow for the creation of a more natural salt marsh and tidal channel system on a short time scale. Natural marsh processes and functions would be reestablished more quickly, and the restored marsh would function more like a natural marsh. Water quality problems in the restored site, such as areas of stagnant water and brackish water conditions, would be resolved.

Disadvantage. This alternative would be more expensive than Alternative I. If the properties to the west become available for purchase, the restoration would have to be modified again to include those properties.

Priority: Salt Marsh Enhancement II would involve significant alterations to existing habitat and have a higher cost than Salt Marsh Enhancement I. However, the ecosystem benefits would be substantially greater than Salt Marsh Enhancement I. For this reason, this alternative is assigned a high priority. (Whether this alternative is preferred over Salt Marsh Enhancement I depends on a variety of factors, including the likelihood of implementing Lagoon/Salt Marsh Restoration I. The Lagoon/Salt Marsh Restoration I project has by far the greatest ecosystem benefits of all of the salt marsh alternatives, since the restoration alternative would expand the wetland area while the enhancement alternative would only enhance the functioning of the existing wetland area. If the Lagoon/Salt Marsh Restoration I could be implemented fairly soon, it would not make sense to undertake Salt Marsh Enhancement II.)

9.3.3.2.3.3.Salt Marsh Enhancement/Restoration Alternative III

Project Description and Project Goals. Salt Marsh Enhancement/Restoration Alternative III would involve re-grading the existing salt marsh and intertidal habitat to lower the elevation of the entire site and allowing natural processes to shape salt marsh topography following Mitsch and Wilson's (1996) self-design paradigm. Success of this restoration alternative depends primarily on sedimentation/erosion rates. Salt marsh restoration by self-design has been employed in the San Francisco Bay recently, where former salt marshes have subsided due to diking and sedimentation rates are relatively high (e.g., Sonoma Baylands, U.S. Army Corps of Engineers 1997). This type of restoration assumes that sediment will accrete over time to raise marsh elevations and form natural tidal channels much the way new marshes are formed historically. Depending on desired elevations in the Malibu Lagoon, sedimentation rates may be important in the self-design restoration process. However, the only data we have on sedimentation rates for the Malibu watershed are from post-fire conditions in which the rate is unnaturally high (Ambrose et al. 1995).

Description of Design. The entire site A1 would be graded to a level that would allow for the self-creation of salt marsh and intertidal habitats (Figure 9-17). As in Alternative II, the site would be graded to a relative level that is higher in the back (west) and lower at the opening (east) of the site with the Lagoon. Excess excavated material could be used for beach replenishment if it has appropriate characteristics. Wetland plants and benthic invertebrates would be allowed to recolonize the site naturally. This alternative would require replacing the existing walkway between the Malibu Lagoon State Park parking lot and the beach with an elevated walkway or new walkway around the perimeter of the marsh. A new walkway around the perimeter of the marsh would have a greater impact on public access than the elevated walkway.

Advantages. The philosophy behind this type of self-design restoration stems from the fact that the most natural and highest functioning association of habitats develops with minimal engineering. Since all mechanisms behind salt marsh formation are not yet well known, this alternative would allow the driving hydrologic forces to establish the marsh (Simenstad and Thom 1996, Haltiner et al. 1997). We do know, however, that increased water delivery to the site and improved water circulation within the site itself would enhance existing salt marsh habitat over the long-term. In addition, this design would partially alleviate water quantity problems in the Lagoon by increasing lagoon water holding capacity, and provide increased protection for resident bird populations by reducing domestic animal encroachment. Until the marsh had accreted enough to be emergent, the area would appear and function as a subtidal basin or lagoon.

Disadvantages. This alternative would disturb existing habitat and reduce habitat function in the short-term. We are unsure how long it would take to create a high functioning salt marsh ecosystem, since this method of restoration has not yet been tested in southern California. Under Alternative II, the salt marsh would probably regain its functional capacity within a few years. However, the salt marsh restoration process in Alternative III might take ten years or more. If self-design does not work immediately, the site could exist as a subtidal lake or mudflat for many years. Furthermore, this design may not work due to constraints, such as decreased tidal flushing.

Priority: Like Salt Marsh Enhancement II, this alternative would significantly alter existing habitat at site A1 and involves a great deal of uncertainty. The natural processes that are thought to control the self-design process, hydrodynamics and sedimentation, have been greatly altered in Malibu Lagoon. Self-design is probably not appropriate under these conditions. Salt marsh enhancement may take many years to develop or may never develop at all. Given existing functions and values of site A1, this alternative is not warranted and, consequently, is assigned low priority status.

9.3.3.2.4. East Lagoon Salt Marsh Restoration Alternative

Site description and project goals. The East Lagoon Salt Marsh Restoration Alternative involves site A4 on the eastern bank of Malibu Lagoon (Figures 9-2 and 9-6). Presently, this site consists of a small peninsula extending southeast to northwest and a small depression to the north and east (Figure 9-6). The peninsula supports mostly weedy, non-native species and a few wetland plants; the depression is relatively barren. Sediment within the depressional area consists of coarse sand deposits. The depression is periodically inundated or saturated by stormwater runoff and creek flows and therefore exhibits low salinity levels. The objective of this alternative is to restore salt marsh habitat to the site and create nesting habitat for sensitive and endangered bird species.

Description of design. This alternative would increase salt marsh habitat in Malibu Lagoon, thereby providing additional acreage of a habitat type that was once found in greater abundance (Figure 9-18). The edges of the peninsula and southern/southwestern bank of the depression would be graded to encourage establishment of appropriate salt marsh hydrology. Salt marsh plants could be planted to facilitate colonization by native salt marsh plant species. A nesting island would be created from the peninsula to encourage nesting by California Least Tern (*Sterna antillarum*) and other terns and Snowy Plovers (*Charadrius alexandrinus*). Design of the nesting habitat would entail modification of an existing, island-like topographic feature on the eastern bank of the lagoon (similar to the design used in the recent Batiquitos Lagoon restoration in San Diego County). It would comprise three steps: deepening of the depression to form a channel between the Adamson boathouse and the island to prevent predator encroachment from adjacent uplands, connection of the southeastern end of the depression with the lagoon to improve circulation, and vegetation removal to provide an open sandy substrate suitable for nesting. It also may be necessary to regrade the island to provide improved nesting habitat.

Advantages. Due to its proximity to the mouth of Malibu Creek and its relatively low elevation, site A4 may receive more tidal flushing than the opposite side of the lagoon (site A1) which, theoretically, would allow for improved salt marsh development. However, salt marsh development may be inhibited because site A4 receives elevated freshwater flows and high rates of sand and gravel deposition. This alternative would increase shorebird habitat, improve salt marsh plant diversity, and provide nesting habitat for endangered birds. Major modifications to the site would not be required; consequently, this alternative would be relatively inexpensive. Since the property is owned by DPR, there is no issue with land acquisition, and there is no apparent land-use conflict associated with this alternative.

Disadvantages. Periodic maintenance might be required to prevent weedy vegetation from reoccupying the nesting island and the sediment from accreting in the channel. Water quality would depend on the conditions in the lagoon. If high water levels or low salinity conditions persist in the lagoon, then the quality of the restored habitat would suffer as with other restoration alternatives. The present elevation at the depression/lagoon interface is such that intertidal flats are exposed frequently. Thus, the channel would not keep predators off of the nesting island if it is not deep and wide enough.

Priority: Other than small size, this alternative has no major drawbacks. Since it would reestablish a function that was present in the past (nesting habitat for endangered birds) and would increase overall habitat value and diversity, this alternative is considered high priority.

9.3.3.2.5. Freshwater Wetland Alternatives

9.3.3.2.5.1.Freshwater Wetland Preservation Alternative

Site description and project goals. The Freshwater Wetland Preservation Alternative targets site C1, the existing freshwater wetland (approximately 1.6 ha) near the intersection of Civic Center Way and Stewart Ranch Road (Figures 9-2 and 9-10). The primary objective of this alternative is to protect the wetland and associated uplands from future development.

Description of design. This alternative would involve protecting the freshwater wetland (site C1) and surrounding area by 1) purchasing privately-held parcels, 2) procuring development rights, or 3) establishing a conservation easement to maintain the site in perpetuity. In any case, the wetland should be protected by a buffer zone around the site and an arrangement for maintaining/managing the wetland in its current state.

Some maintenance of the wetland might be required, but it would be minimal, except perhaps for control of non-native species (such as castor bean and pampas grass).

Advantages. By protecting the site from development and establishing a buffer zone, this alternative would prevent further wetland loss and enhance existing wetland functions at the site. Aside from the costs of purchasing the parcels, this alternative would be relatively inexpensive.

Disadvantages. The major drawback of this alternative is that it would not increase overall wetland acreage. Furthermore, since the current wetland was initially artificially created without planning, one could question the wisdom of preserving it. (However, the Reco Land Corporation later enhanced the wetland.)

Priority: Freshwater wetland protection would not involve major engineering. Although it would not create additional wetland habitat, this alternative would protect existing wetland from degradation. This alternative is considered high priority since it has no major drawbacks.

9.3.3.2.5.2.Freshwater Wetland Enhancement/Restoration Alternative

Site description and project objectives. The Freshwater Wetland Enhancement/ Restoration Alternative would involve many of the same steps as the Freshwater Wetland Preservation Alternative on site C1, but would enlarge the existing wetland as well (Figures 9-2 and 9-10). The goals of this alternative are to protect and expand the existing freshwater wetland area.

Description of design. Specifically, this design would increase the freshwater wetland size (by approximately 0.8 ha) by deepening the existing wetland basin and enlarging it laterally to the north (Figure 9-19). A liner may need to be installed to retain water for slow percolation, depending on current soil conditions. Supplementary water might need to be added to the site to support the larger wetland size, or prolong the period of time standing water is present in the wetland. In the latter case, supplementary water would alter the character and function of the site. The current drainage system may need to upgraded to account for the potential increase in water due to increased basin size and/or water additions.

Advantages. In addition to protecting and increasing freshwater wetland habitat, this alternative would enhance habitat conditions for local Pacific tree frog (*Hyla regilla*) populations, increase bird habitat, and provide water quality improvement. This alternative would also maintain this property in a relatively natural state.

Disadvantages. There are several disadvantages of implementing this alternative, including the creation of a potential flood hazard. Also, this wetland is isolated from the creek, lagoon and other wetland habitats, thus reducing some of its wetland functions.

The project would be expensive due to the need for land acquisition and improvements to the existing drainage system. In addition, this alternative may require the construction of a conveyance/irrigation system depending its the hydrology. We have not investigated the potential water sources; addition of water could involve high construction and operation costs, or they might involve minimal expense, depending on the availability of appropriate water nearby.

Additional studies needed. A detailed soil survey should be conducted in and around the existing and proposed freshwater wetland to determine if soil amendments or liners are necessary to sustain adequate wetland hydrology. A hydrological study is needed to better understand the current and proposed hydrology and associated drainage system. If an additional water source is required, a detailed cost analysis should be conducted to determine the feasibility of incorporating an irrigation/conveyance system into this alternative.

Priority: The Freshwater Wetland Enhancement would be more complex than the Preservation Alternative, involving artificial irrigation and improvements to local drainage. Although it would increase wetland habitat, this alternative would be more expensive than simple protection. It would expand the area of freshwater wetland habitat in the region, but would not add to diversity of habitat or functions. Consequently, this alternative is assigned medium priority status.

9.3.3.2.6. West Malibu Creek Bank Stabilization Alternative

Site description and project goals. The Malibu Creek Bank Stabilization/Restoration Alternative would be conducted at site B1, located along the western bank of Malibu Creek just north of Pacific Coast Highway (Figures 9-2 and 9-7). Presently, the site consists of a rock rip-rap lined bank with very low plant or wildlife habitat value. The objectives of this alternative are to improve riparian and subtidal habitat along this reach.

Description of design. This design would remove rip-rap and other existing stabilization materials where they are not essential to protect against erosion, particularly in the southern portion of the site. In this area, the bank would be re-stabilized with a combination of bioengineering techniques, such as armor-flex or willow plantings (Figure 9-20). Various riparian trees and shrubs would be planted above the toe of the stabilized bank. Rock, concrete and other hard materials could be removed from the subtidal habitat adjacent to the bank to increase fish habitat.

Advantages. This alternative would enhance resource values by restoring fish and other aquatic invertebrate habitat and enhancing the riparian zone. Site aesthetics would improve considerably after clean-up and restoration, which is particularly important for this site since it is visible from Pacific Coast Highway.

Disadvantages. Bank stabilization design and implementation may be expensive. There would probably be maintenance costs associated with this design (e.g., repair of structure after a major storm event). However, since there are maintenance costs associated with the current stabilization approach, this alternative may not involve a net increase in costs. The major disadvantage is the consequences of failure. The west bank receives the brunt of Malibu Creek's erosive force as the creek enters the lagoon. There is a major commercial development behind the west bank. Failure of the bank could have catastrophic consequences for commercial properties. Thus, property owners and regulatory agencies may be reluctant to try this unconventional protection technique. Therefore, modification of current stabilization techniques should only be undertaken after studies have demonstrated that there would be no loss of protection by using bioengineering techniques.

Priority: There are positive and negative aspects to the bank stabilization alternative. Since the site currently has virtually no habitat value, modifications would result in a significant increase in resource values. On the other hand, although the bioengineering bank stabilization techniques exist, there would be a risk to implementing them at this site given the erosive force on the bank and the potential for property to be damaged if the bank failed. Balancing these positive and negative aspects, this alternative is assigned a medium priority.

9.3.3.3. Treatment Wetland Alternatives

Table 9-5 identifies opportunities and constraints associated with the creation of treatment wetland alternatives for the Malibu Lagoon area. With a few exceptions, opportunities associated with the different alternatives are identical (i.e., water quality improvement, freshwater wetland creation). For this reason, the alternatives are best differentiated based on constraints associated with sites for which they are proposed, the flows they would treat, and their anticipated effectiveness in reducing pollutant inputs to the lower creek and lagoon. The latter, in turn, depends on the relative contribution of different flows to overall pollutant loading.

9.3.3.3.1. Alternative 1: Stormwater/Dry Season Runoff Treatment Wetland (Site A3)

Site description and project goals. This treatment wetland alternative would occupy site A3 (approximately 1.1 ha [2.7 acres]) (Figures 9-2 and 9-5). The objective of this alternative would be to treat dry season urban runoff and/or polish secondary/tertiary wastewater from the City of Malibu in created wetlands prior to discharge offshore or in the lagoon.

Description of design. Based on the wastewater treatment facility's 250,000 gallon per day projected capacity (City of Malibu 1997) and the 10-12 day retention times required for nutrient and pathogen removal (Gearheart and Waller 1989; Gersberg et al. 1989), site A3 is not big enough to serve as wastewater polishing wetland. An urban and stormwater runoff treatment wetland would be a more appropriate design for the site.

This alternative would consist of grading the site and constructing a treatment wetland covering most of the site (Figure 9-21). Storm drains would have to be re-routed from the city of Malibu to the northwest corner of the site. There are two main design options for the drainage outfall. The outfall could be directed straight into the ocean through a pipe under the Malibu Colony. If site A2 is purchased and restored as salt marsh, the treatment wetland could drain to site A2 through a culvert beneath Malibu Colony Drive. Freshwater wetland vegetation may need to be planted to facilitate wetland plant establishment.

Advantages. This site is located at an elevation, which would enable urban runoff to flow into the proposed treatment wetland by gravity. If the City of Malibu decides to retrofit the local stormwater drain network, this project would be easier to implement.

Disadvantages. Site A3 is only large enough to treat urban dry season and stormwater runoff. This alternative would be expensive to construct and would require frequent maintenance. Because its primary water source would be urban runoff, the wetland might experience poor sediment and water quality, which, in turn, could negatively impact aquatic/wetland organisms (Helfield and Diamond 1997). If water from the treatment wetland flows into the restored salt marsh in A2, it may create water quality problems in the restored salt marsh system.

Priority: As described earlier, treatment wetland alternatives are best differentiated based on the sites where they would be implemented. Treatment Wetland Alternative 1 would occur on site A3, the vacant lot across from the golf course. Salt marsh restoration would be a more appropriate use of this site. Developing the site as a treatment wetland should only be considered if acquisition of site A2 proves impossible, thus precluding the implementation of Salt Marsh Restoration I. For this reason, Treatment Wetland Alternative 1 is assigned medium priority status.

9.3.3.3.2. Alternative 2: Stormwater/Dry Season Runoff Treatment Wetland (Site B1)

Site description and project objectives. Alternative 2 would be located in the southernmost corner of site B1 (Figures 9-2 and 9-7). The objective of this alternative would be to treat urban runoff in created wetlands and re-stabilize a section of bank along the western side of Malibu Creek.

Description of design. A 0.5 acre wetland would be created in the southern corner of site B1 (Figure 9-22). The existing Cross Creek Plaza storm drain would be re-directed to flow into this wetland. The discharge from this wetland would be directed through an outfall pipe just above the northwestern edge of the PCH bridge. In addition to construction of a treatment wetland, the remainder of site B1 would be restored using bioengineered bank stabilization techniques.

Advantages. Two objectives would be met on a single site; wetland habitat would be created to treat urban runoff and the bank would be stabilized by bioengineering techniques.

Disadvantages. As described in Chapter 8, site B1 is adjacent to the deepest and most powerful section of the lower creek. Consequently, a treatment wetland constructed at the site would be subject to washout during high flow events, which, in turn, might threaten the structural integrity of the PCH Bridge. However, by stabilizing the bank above the treatment wetland with bioengineering methods, this treatment wetland would be better protected. The treatment wetland proposed is very small and would provide minimal water quality benefits.

Priority: This alternative would be constructed on site B1, the western bank of Lower Malibu Creek immediately north of the PCH bridge. This site receives runoff from the City of Malibu through a pair of 36-inch diameter culverts and is thus well situated to treat urban runoff before it reaches the lagoon. Due to its small size and washout potential, however, Treatment Alternative 2 is considered low priority.

9.3.3.3.3. Alternative 3: East Bank Creek Treatment Wetland (Site B2)

Site description and project objectives. The East Bank Creek Treatment Wetland Alternative would occupy site B2, the eastern bank of lower Malibu Creek (Figures 9-2 and 9-8). The main objective of this alternative is to treat dry season creek flows in created wetlands.

Description of design. The treatment wetland would consist of several large, hydrologically connected wetlands; a levee upstream of the first wetland to protect the system; an intake from flood flow and pump system along the levee to direct stream flows into the wetlands; and an outfall structure in the southwest corner of the site to dispose treated water back into the creek (Figure 9-23).

Advantages. Creek flows high in nutrients or other pollutants could be filtered and treated.

Disadvantages. This system would be subject to washout during high flow events. It would also result in a loss of well-functioning riparian habitat. In addition, this alternative would be expensive to construct and maintain due to the high degree of engineering involved.

Further study. A detailed assessment of the relative functions and values of a constructed treatment wetland and natural riparian habitat should be conducted to determine whether this alternative is warranted.

Priority: Because site B2 already contains functional riparian habitat, occurs within the floodplain, and would be subject to washout during high flow events, this alternative has been assigned low priority.

9.3.3.3.4. Alternative 4: West Bank Creek Treatment Wetland (Site B3)

Site description and project objectives. This Creek Treatment Wetland Alternative would occupy site B3 on the western bank of lower Malibu Creek (Figure 9-2 and 9-9). The objective of this alternative is identical to the east bank alternative, to treat dry season creek flows in created wetlands.

Description of design. A series of constructed wetlands could be designed at this site to treat dry season creek flows (Figure 9-24). An intake structure attached to a pumping system would be installed above at the upstream end of site B3 to direct creek flows into the treatment wetland system. Also, an outfall structure would be designed at the downstream end of the site to return treated waters to the creek. In order to protect the system from damage due to large flows, a levee would be created at the upstream end of the site.

Advantages. Creek flows high in nutrients and other pollutants could be filtered and treated.

Disadvantages. This system would be subject to washout during floods and would result in a loss of functional riparian habitat. This alternative would also be expensive to construct and maintain.

Further study. An assessment of functions and values related to this alternative should be conducted, since wetland habitat areas would not necessarily be increased; healthy riparian habitat would be replaced with a series of constructed freshwater treatment marshes.

Priority: Because site B3 already contains functional riparian habitat, occurs within the floodplain, and would be subject to washout during high flow events, this alternative has been assigned low priority.

9.3.3.3.5. Alternative 5: Stormwater/Wastewater Treatment Wetland (Site C2)

Site description and project objectives. This Stormwater/Wastewater Treatment Wetland Alternative would occupy site C2, the "chili cook-off" area, which is currently a level, grassy area (Figures 9-2 and 9-11). Currently, an open, grassy flood control channel runs west to east through the site. Because developed areas surround the site, a restored wetland at site C2 would be subject to edge effects. For this reason, the site may not be well suited to serve as wetland habitat for fauna that are sensitive to human disturbance, but could function effectively as a treatment wetland.

There are multiple objectives associated with this alternative. The primary objective is to treat urban runoff from the City of Malibu and secondary/tertiary effluent from a local wastewater treatment facility using constructed wetlands. In addition, this alternative is designed for recreational use (e.g. running, walking and picnicking).

Description of design. Two elongate freshwater wetlands would be constructed within site C2 (Figure 9-25). These wetlands would be connected roughly in the center of the site with the flow directed from the northern to the southern wetland. In this design, water from the local storm drain system and/or wastewater treatment plant would enter into the northern wetland from the west, flow into the slightly lower southern wetland, and exit the system through an outflow pipe at the eastern side of the site. It may be possible to re-route the storm drain from the freshwater wetland at site C1 into the western side of the northern wetland. Under high flow events, water may exit directly at the eastern end of the northern wetland.

The design of these wetlands will facilitate colonization of native biota. For example, islands could be built in the center of the constructed wetlands for bird habitat. Also, native freshwater wetland vegetation may be planted to expedite establishment.

This design attempts to incorporate several recreational facets for use by the Malibu community. An unconsolidated trail would be constructed around and between the islands for walking and running. A bridge would be built over the connecting stream between the northern and southern wetlands. Picnic shelters and grills could be sited in several locations around the lakes. An educational boardwalk could be built over one of the wetlands.

Advantages. Unlike sites B1, B2, and B3, this site is not located within the Malibu Creek floodplain and, consequently, would not be subject to washout during high flow events. Site C2 is centrally located within the City of Malibu, which would facilitate water delivery to the proposed treatment wetland system. The current state of the site exhibits low habitat function and value. Furthermore, the large size of this site enables a multi-objective conceptual design.

Disadvantages. Acquisition costs, improvements to drainage, and construction and maintenance of this wetland treatment system would all be expensive.

Risks. There may be a slight health risk associated with permitting/promoting public access around a treatment wetland. Proper fencing and signs may be necessary to keep children and animals out of the wetland. The wetland constructed for the sewage treatment plant in Richardson Bay, Mill Valley, CA represents a good example of how these combined uses can be accommodated.

Priority: This alternative would be constructed at site C2 in the Civic Center area. This site is ideal for a treatment wetland because it is surrounded by developed areas, has low habitat value, and is well situated to treat urban runoff or polish secondary/tertiary effluent from a wastewater treatment facility. Accordingly, this alternative is assigned high priority status.

9.3.3.3.6. Alternative 6: Stormwater/Wastewater Treatment Wetland (Site C3)

Site description and project objectives. This Stormwater/Wastewater Treatment Wetland Alternative would be located at site C3 northeast of the Civic Center (Figure 9-2 and 9-12). Similarly to site C2, this site is not well suited for habitat creation because it is isolated from the lower creek and lagoon. However, a combination stormwater and wastewater treatment wetland may be constructed for the City of Malibu within this site. The objectives of this alternative are several; they may include, but are not limited to, stormwater/dry season runoff treatment using a created wetland, wastewater treatment using a created wetland, traditional wastewater treatment and/or public access/recreation.

Description and design. The design of this alternative would be slightly different depending on the objective(s) chosen. Exact siting of the treatment wetlands/ponds and treatment facility would depend on results of additional studies. A conceptual design entails construction of a series of treatment wetlands or ponds situated in a relatively flat portion of the site C3 footprint (Figure 9-26). Unconsolidated trails for walking and running could be designed around the wetlands.

Advantages. The biggest advantage of this alternative is that site C3 is large, which would allow flexibility in siting. Like site C2, site C3 is near the center of Malibu, but is not directly visible from Civic Center Way or other public thoroughfares. In addition, many objectives could be met with this alternative.

Disadvantages. There are no obvious disadvantages to using this site for a wastewater treatment wetland. The site is not ideal for extensive stormwater treatment because of its distance from the creek.

Further studies. Additional analyses should be conducted to determine the feasibility of this alternative; these studies should evaluate nearby storm drain systems, hydrology, and site geology in order to situate the proposed entities properly within the site.

Priority: This alternative would be constructed at site C2 in the Civic Center area. This site is ideal for a treatment wetland because it is surrounded by developed areas, has low habitat value, and is well situated to treat urban runoff or polish secondary/tertiary effluent from a wastewater treatment facility. Accordingly, this alternative is assigned high priority status.

9.3.3.4.Comparison of Wetland Restoration Alternatives

Table 9-6 summarizes the priorities assigned to the different restoration alternatives discussed in the previous sections. The prioritization of the wetland restoration and enhancement alternatives is discussed in Section 9.3.3.4.1, and the prioritization of the treatment wetland alternatives is discussed in Section 9.3.3.4.2.

As with the management alternatives discussed in Chapter 8, it is not possible to implement all high-priority alternatives. For example, Salt Marsh Restoration I and II and Salt Marsh Enhancement I all involve site A1, so not all of these alternatives could be implemented.

9.3.3.4.1. Wetland Restoration and Enhancement Alternatives

Seven different wetland restoration and enhancement alternatives have been evaluated for the Malibu Lagoon area.

Malibu Lagoon Ecosystem Restoration Alternative would provide the greatest ecological benefits, and because it would provide the greatest restoration of natural physical processes, it would also be the most self-sustaining of the restoration alternatives. However, the political, economic and social issues associated with this restoration are so much greater than the other alternatives that it has not be prioritized with the other alternatives.

The assessments of the remaining alternatives are summarized in Table 9-6. Two alternatives were assigned a low priority, and two alternatives were assigned a medium priority. Finally, these four alternatives were given a high priority:

- Lagoon/Salt Marsh Restoration I
- Salt Marsh Enhancement I
- Salt Marsh Enhancement II
- Freshwater Wetland Protection

Three of these four alternatives involve site A1, so they all cannot be implemented. The choice of which to implement depends on the availability of sites A2 and A3. Lagoon/Salt Marsh Restoration I is, by far, the superior alternative of those prioritized, since it provides the most restored wetland habitat and best achieves the restoration goals.

If sites A2 and A3 cannot be acquired in the near future, one of the salt marsh enhancement alternatives should be implemented. The choice between these alternatives depends on funds available for restoration and the likelihood that sites A2 and A3 may become available in the foreseeable future. If funds are limited and the possibility of implementing Salt Marsh Restoration I seems feasible, a moderate improvement in the existing salt marsh restoration area could be achieved with Enhancement Alternative I as an interim measure. On the other hand, if there appears to be little chance of implementing Salt Marsh Restoration I in the foreseeable future, great resource values could be achieved by implementing Enhancement Alternative II.

Although not included as a restoration alternative, **land acquisition** is perhaps the most important activity that could be undertaken to provide maximal long-term restoration opportunities. Although not impossible, restoration of property that requires the removal of existing structures rarely occurs. The Malibu Lagoon area still has a number of undeveloped properties. Acquiring some of these properties would ensure their availability for restoration in the future, and may be more important than undertaking any individual restoration project in the short term.

9.3.3.4.2. Treatment Wetland Alternatives

Six different treatment wetland alternatives have been evaluated for the Malibu Lagoon area. The assessments of these alternatives are summarized in Table 9-6. Three alternatives were assigned low priority and one was assigned a medium priority. Finally, these two alternatives were given a high priority:

- Alternative 5 (Site C2)
- Alternative 6 (Site C3)

Both of these alternatives are designed to treat wastewater. In all likelihood, only one site will be needed for this purpose. The choice between the alternatives depends mainly on the cost of acquiring the sites and whether the community prefers a central park-like treatment wetland (site C2) or a treatment wetland away from the general public (site C3) (not to mention the willingness of the property owners).

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Table 9-1. Opportunities and constraints associated with sites A1-A4.

	ECOLOGICAL CRITERIA		**FEASIBILITY CRITERIA**	
SITE	**OPPORTUNITIES**	**CONSTRAINTS**	**OPPORTUNITIES**	**CONSTRAINTS**
A1	• Already contains wetlands • High wildlife use • Low elevation • Proximity to creek, lagoon, and ocean • Suitable wetland hydrology	• Attenuated tidal flushing • High rates of fine sediment deposition • Persistent high water levels • Poor water quality	• Public ownership • No acquisition costs	• State Dept. of Parks and Recreation might object to modifying site since it already has relatively high resource value
A2	• Low elevation • Proximity to creek, lagoon, and ocean	• Attenuated tidal flushing • Potential edge effects • Potentially poor water quality		• Private ownership • High acquisition costs
A3	• Low elevation • Proximity to creek, lagoon, and ocean	• Attenuated tidal flushing • Potential edge effects • Potentially poor water quality		• Private ownership • High acquisition costs
A4	• Already contains wetlands • Low elevation • Proximity to creek, lagoon, and ocean • Suitable wetland hydrology	• Attenuated tidal flushing • High rates of sand and gravel deposition • Persistent high water levels • Poor water quality	• Public ownership • No acquisition costs	• Modifications would have to be approved by State Dept. of Parks and Recreation and other responsible agencies

Table 9-2. Opportunities and constraints associated with sites B1-B3.

	ECOLOGICAL CRITERIA		**FEASIBILITY CRITERIA**	
SITE	**OPPORTUNITIES**	**CONSTRAINTS**	**OPPORTUNITIES**	**CONSTRAINTS**
B1	• Low elevation • Proximity to creek and lagoon	• Developing wetland at site might promote flooding and erosion problems • Potential edge effects • Subject to washout	• Lower acquisition costs than other privately-owned parcels	• Private ownership
B2	• Proximity to creek and lagoon • Well-buffered	• Already contains functional riparian habitat • Deep layer of fluvial material • High rates of sediment deposition • Subject to washout	• Public ownership • No acquisition costs	• Dept. of Parks and Recreation might object to the creation of wetlands in area containing functional riparian habitat
B3	• Low elevation • Proximity to creek and lagoon • Well-buffered	• Already contains functional riparian habitat • High rates of sediment deposition • Subject to washout	• Public ownership • No acquisition costs	• Dept. of Parks and Recreation might object to the creation of wetlands in area containing functional riparian habitat

Table 9-3. Opportunities and constraints associated with sites C1-C3.

	ECOLOGICAL CRITERIA		**FEASIBILITY CRITERIA**	
SITE	**OPPORTUNITIES**	**CONSTRAINTS**	**OPPORTUNITIES**	**CONSTRAINTS**
C1	• Already contains wetlands • Low elevation	• Isolated from creek, lagoon, and ocean • Might dry up during the summer months • Poor drainage • Potential edge effects • Potentially poor water quality	• Presence of jurisdictional wetlands	• Private ownership • High acquisition costs
C2	• Proximity to existing wetland	• Deep layer of fill material • Isolated from creek, lagoon, and ocean • No natural wetland hydrology • Poor drainage • Potential edge effects		• Private ownership • High acquisition costs • Developing wetland at site might promote flooding problems
C3		• Contains deep layer of fill material • Isolated from creek, lagoon, and ocean • No natural wetland hydrology • Potential for edge effects		• Private ownership • High acquisition costs

Table 9-4. Assessment of wetland restoration and enhancement alternatives.

SITE	DESCRIPTION	OPPORTUNITIES	CONSTRAINTS
A1-3	Lagoon and Salt Marsh Restoration I	• Would increase salt marsh habitat • Would increase lagoon water holding capacity	• Potentially poor salt marsh development • Potentially poor water quality • Would disturb existing habitat • Would require re-routing of Malibu Colony Drive
A1-3	Lagoon and Salt Marsh Restoration II	• Would increase salt marsh habitat • Would increase tidal flushing in the lagoon • Would increase lagoon water holding capacity • Would increase lagoon water quality	• Might exacerbate dry season water quantity problems in the lagoon • Would disturb existing habitat • Would require re-routing of Malibu Colony Drive • Expensive • High maintenance
A1	Salt Marsh Enhancement/ Restoration I	• Would improve water circulation in the restored salt marsh • Would increase intertidal habitat • Would increase tidal flushing in the restored salt marsh • Would increase lagoon water holding capacity • Would reduce predator encroachment in areas heavily frequented by birds	• Would disturb existing habitat • Would not increase total wetland acreage

Table 9-4 (cont.). Assessment of wetland restoration and enhancement alternatives.

SITE	DESCRIPTION	OPPORTUNITIES	CONSTRAINTS
A1	Salt Marsh Enhancement/ Restoration II	• Would improve water circulation in the restored salt marsh • Would increase intertidal habitat • Would increase tidal flushing in the restored salt marsh • Would increase lagoon water holding capacity • Would reduce predator encroachment in areas heavily frequented by birds	• Would disturb existing habitat • Would not increase total wetland acreage
A1	Salt Marsh Enhancement/ Restoration III	• Would improve water circulation in the restored salt marsh • Would increase intertidal habitat • Would increase tidal flushing in the restored salt marsh • Would increase lagoon water holding capacity • Would reduce predator encroachment in areas heavily frequented by birds	• Would disturb existing habitat • Would not increase total wetland acreage • Might take a long time to develop a functioning salt marsh
A4	East Lagoon Salt Marsh Restoration	• Would increase salt marsh habitat • Would increase intertidal habitat • Would increase nesting habitat for endangered birds • Relatively inexpensive	• Potentially poor wetland development • Might require frequent maintenance
C1	Freshwater Wetland Preservation	• Would prevent further wetland loss and degradation • Would enhance existing habitat • Relatively inexpensive Might provide water quality improvement	• Would not increase total wetland acreage

Table 9-4 (cont.). Assessment of wetland restoration and enhancement alternatives.

SITE	DESCRIPTION	OPPORTUNITIES	CONSTRAINTS
C1	Freshwater Wetland Enhancement/ Restoration	• Would increase freshwater wetland habitat • Would enhance Pacific tree frog habitat • Might provide water quality improvement	• Expensive • High maintenance

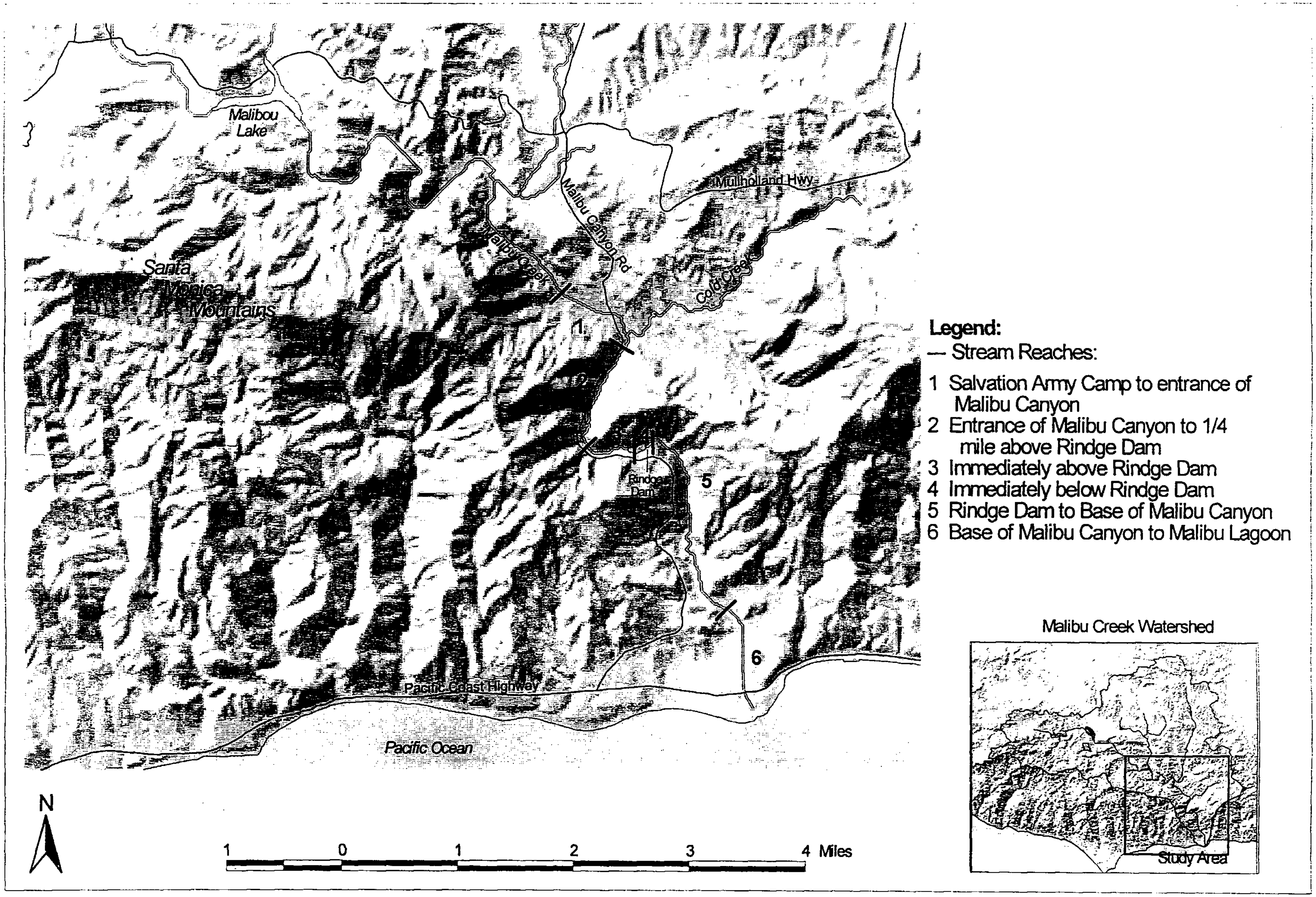
Table 9-5. Assessment of treatment wetland alternatives.

	SITE	OPPORTUNITIES	CONSTRAINTS
1	A3	• Would increase freshwater wetland habitat • Would improve lagoon water quality	• Offshore outlet would be unpopular with surfers • Discharge into lagoon might worsen lagoon water quality • Potentially poor sediment and water quality • Expensive • High maintenance
2	B1	• Would increase freshwater wetland habitat • Would improve lagoon water quality	• Potentially poor sediment and water quality • Might be subject to washout • Developing wetland at site might threaten PCH bridge • Water quality benefit may be minimal
3	B2	• Would increase freshwater wetland habitat • Would improve lagoon water quality	• Might be subject to washout • Would result in loss of functional riparian habitat • Expensive • High maintenance
4	B3	• Would increase freshwater wetland habitat • Would improve lagoon water quality	• Might be subject to washout • Would result in loss of functional riparian habitat • Expensive • High maintenance
5	C2	• Would increase freshwater wetland habitat • Would improve lagoon water quality	• Potentially poor sediment and water quality • Expensive • High maintenance
6	C3	• Would increase freshwater wetland habitat • Would improve lagoon water quality	• Expensive • High maintenance

Table 9-6. Prioritization of wetland restoration alternatives. The Malibu Lagoon Ecosystem Restoration Alternative is in a separate category from the other restoration alternatives, and so is not included in this table.

Low Priority	**Medium Priority**	**High Priority**
Lagoon/Salt Marsh Restoration II	Freshwater Wetland Enhancement	Lagoon/Salt Marsh Restoration I
Salt Marsh Enhancement III	Bank Stabilization	Salt Marsh Enhancement I
		Salt Marsh Enhancement II
		Freshwater Wetland Protection
Alternative 2 (Site B1)	Alternative 1 (Site A3)	Alternative 5 (Site C2)
Alternative 3 (Site B2)		Alternative 6 (Site C3)
Alternative 4 (Site B3)		

Figure 9.1 Lower Malibu Creek Stream Reaches



Map by Suzanne Dallman, UCLA Department of Geography

Figure 9-2. Malibu Lagoon Area Potential Restoration Site Locations

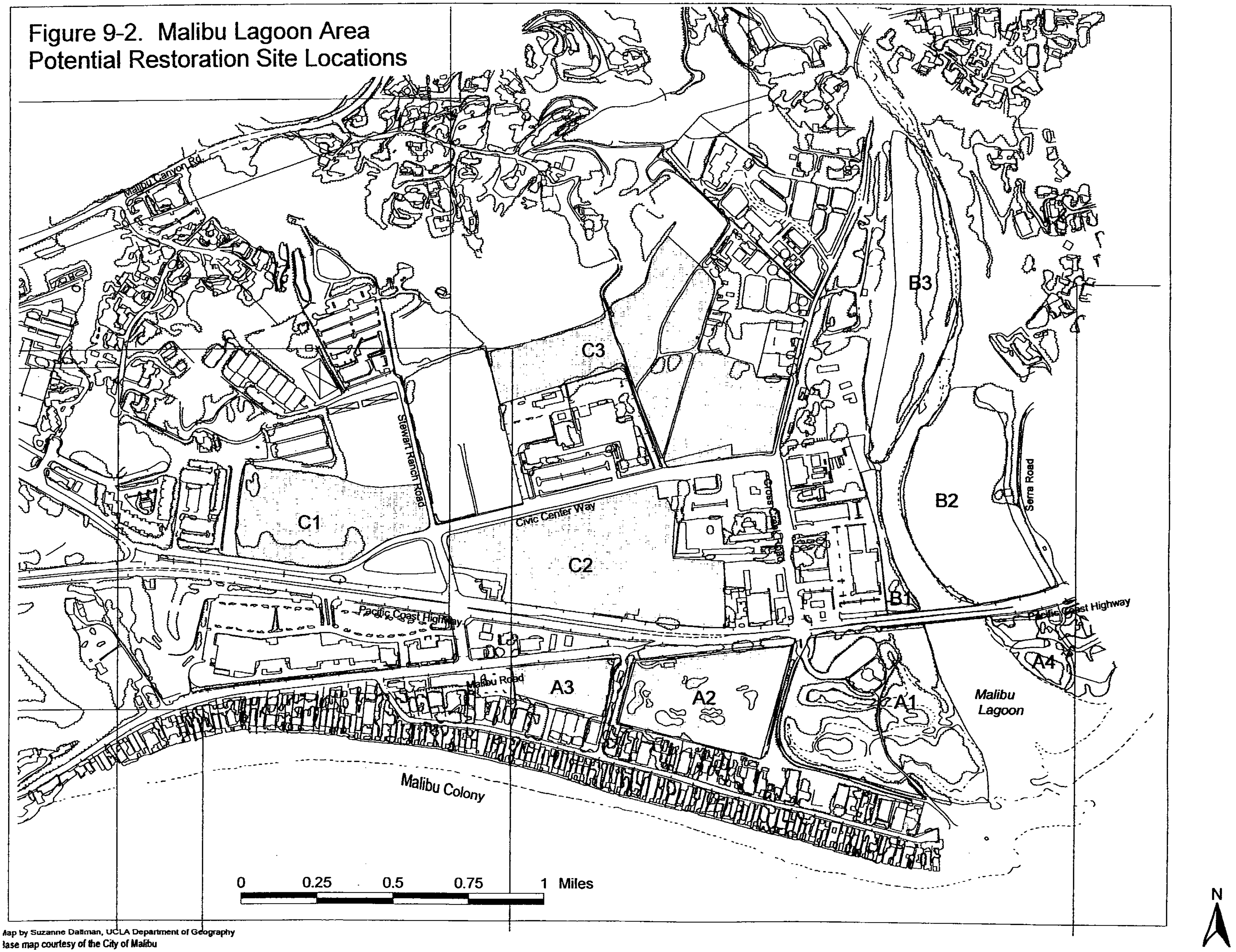


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Figure 9-3. Restoration Site A1

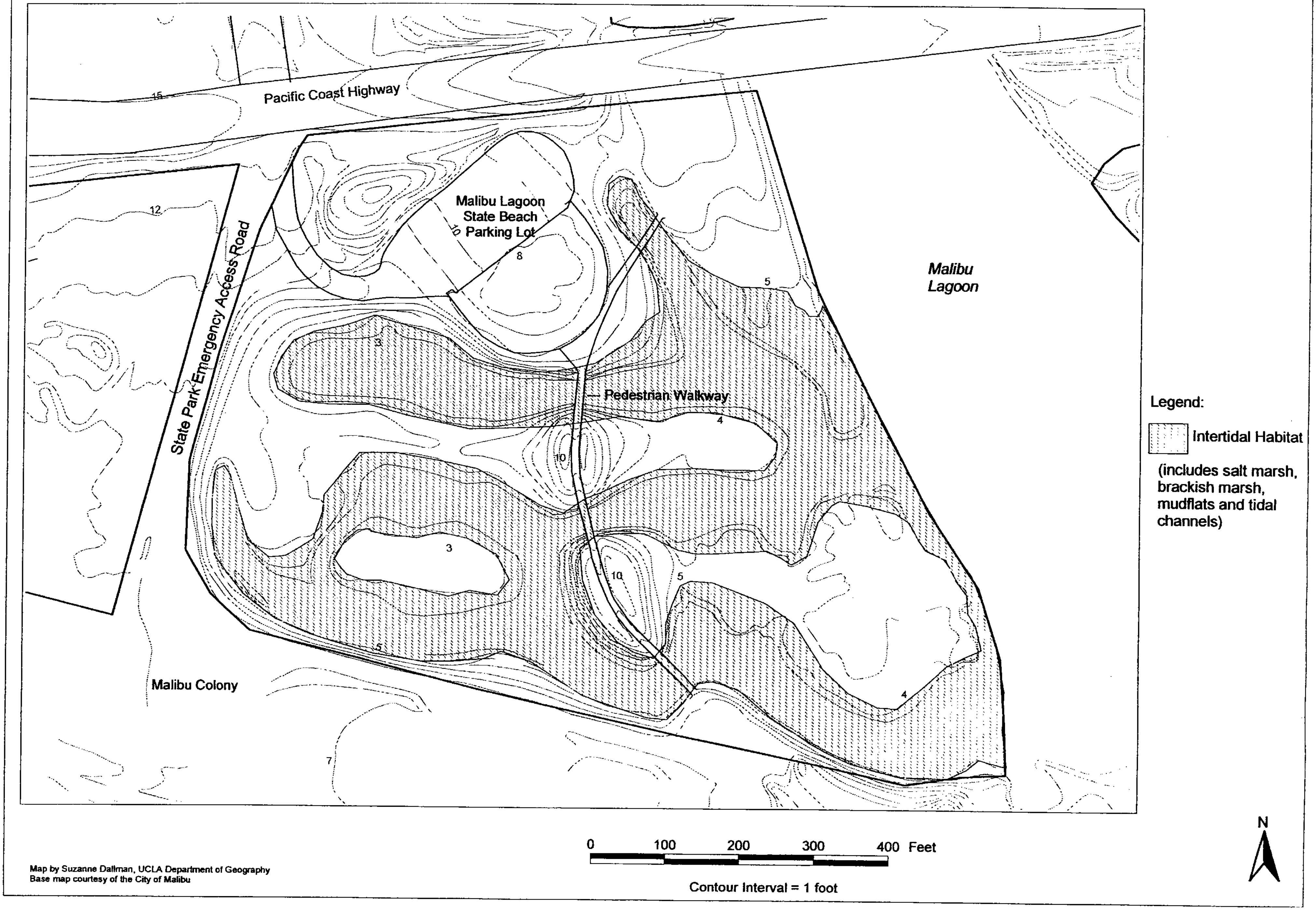

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Figure 9-4. Restoration Site A2

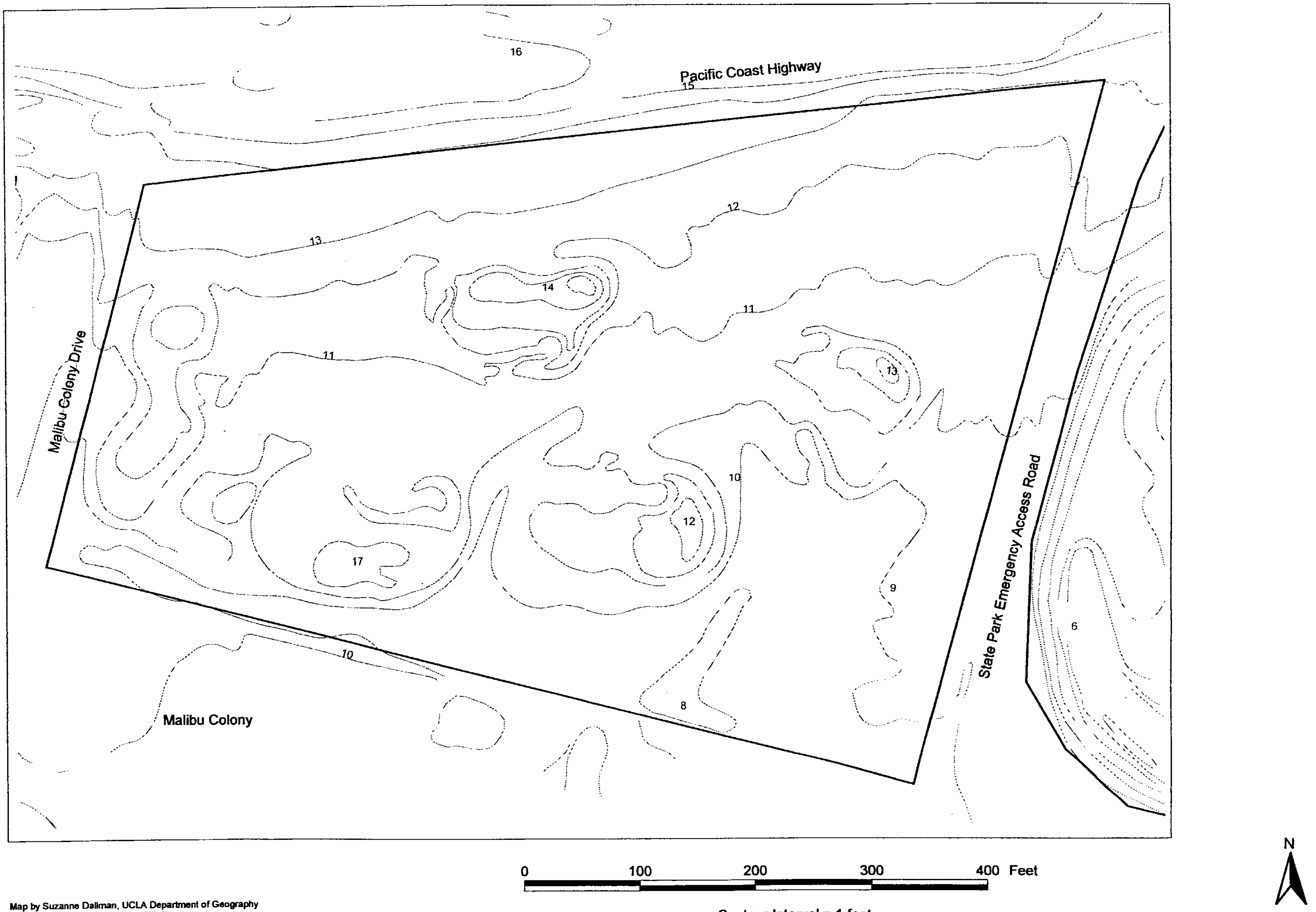

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Figure 9-5. Restoration Site A3

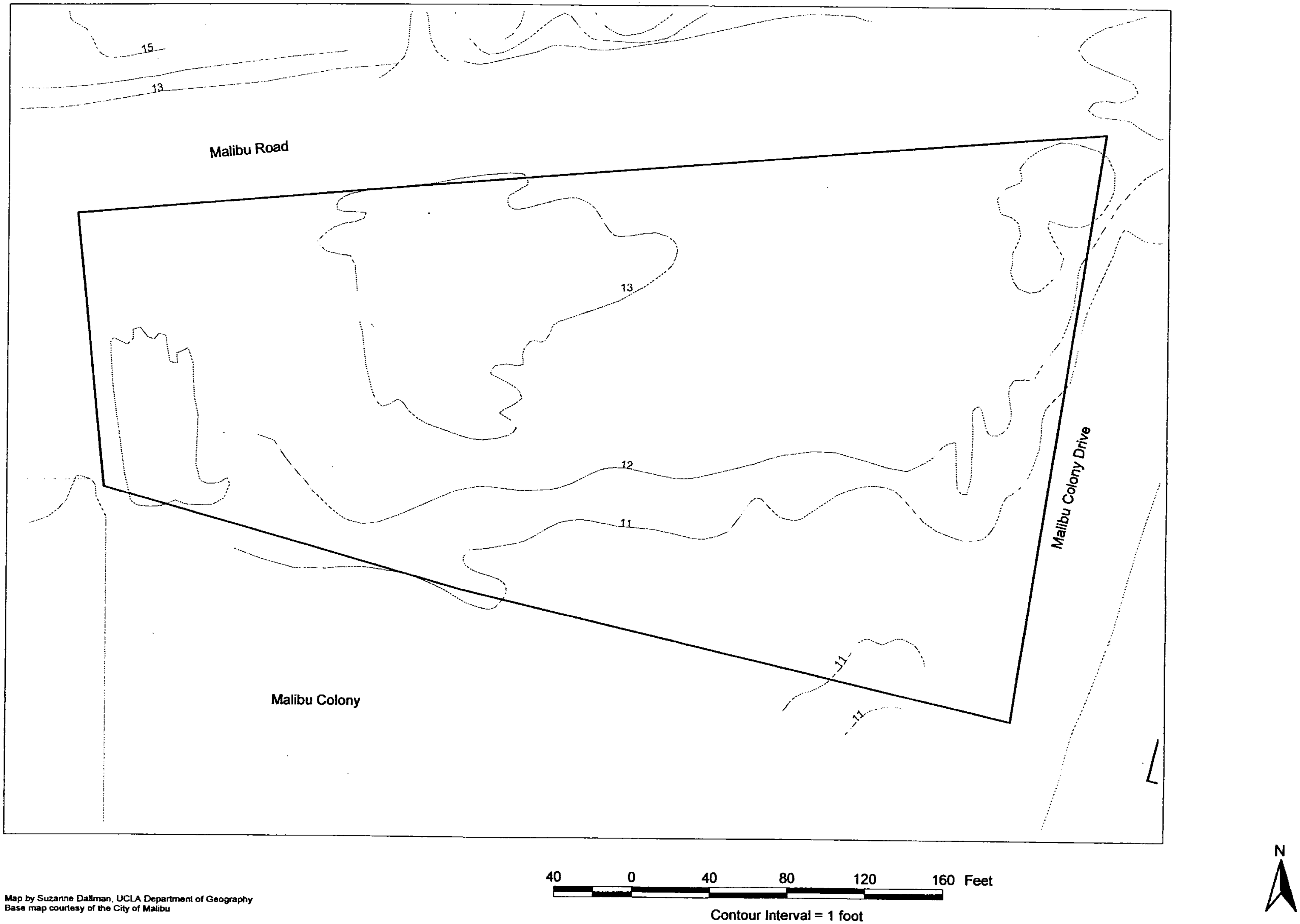

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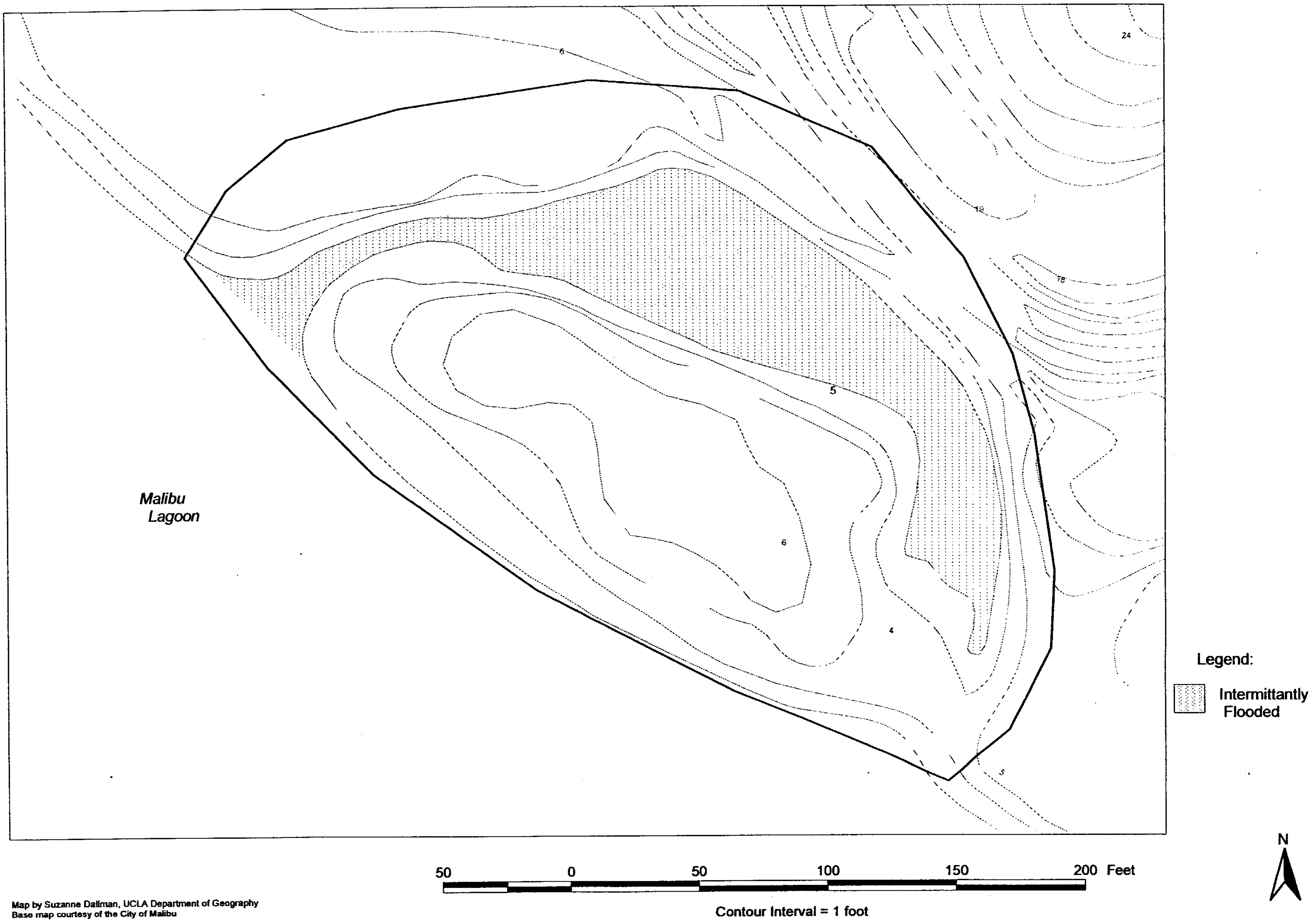
Figure 9-6. Restoration Site A4



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Base map courtesy of the City of Malibu

Figure 9-7. Restoration Site B1

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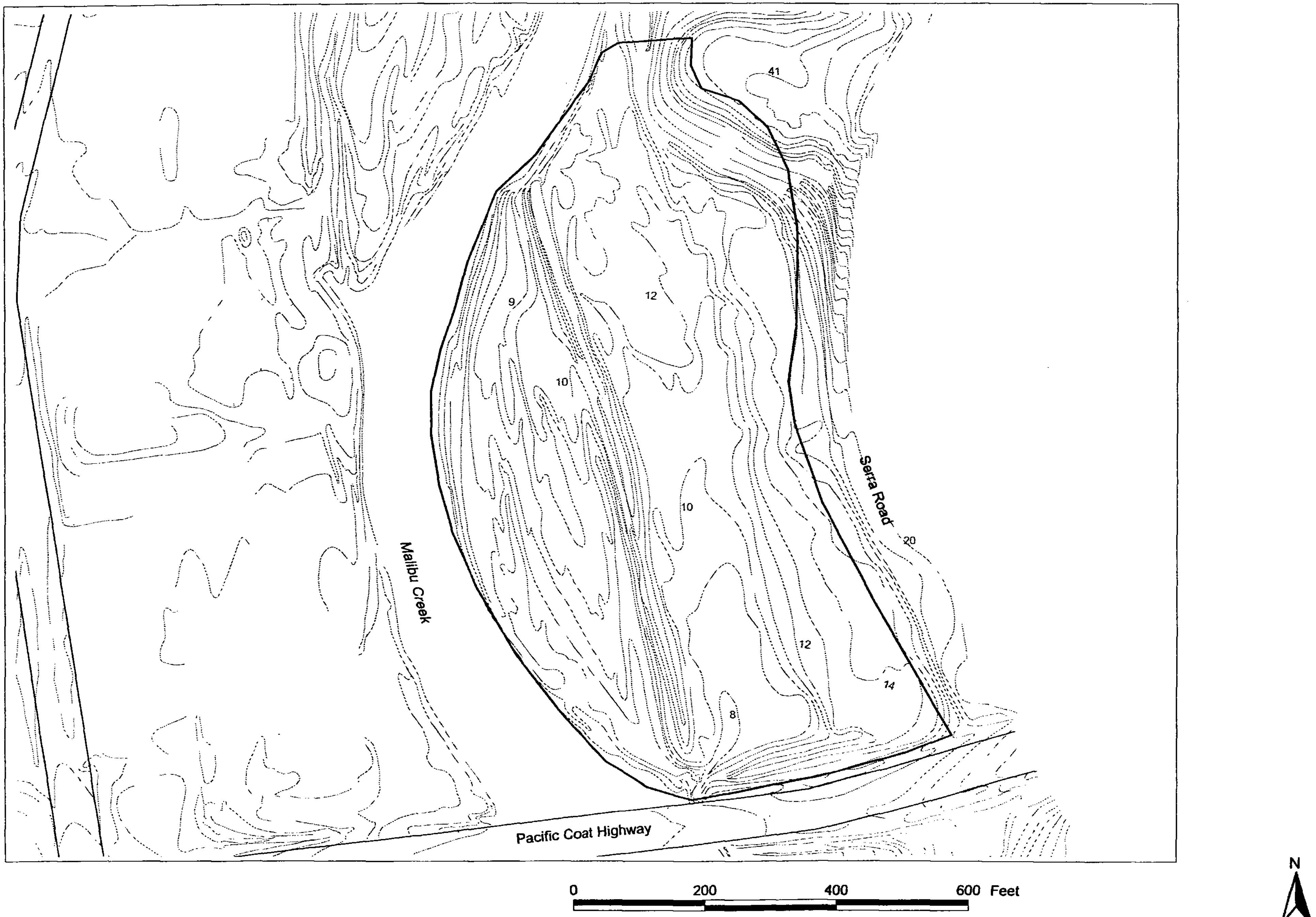
Figure 9-8. Restoration Site B2



Contour Interval = 1 foot

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Base map courtesy of the City of Malibu

Figure 9-9. Restoration Site B3

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Figure 9-10. Restoration Site C1

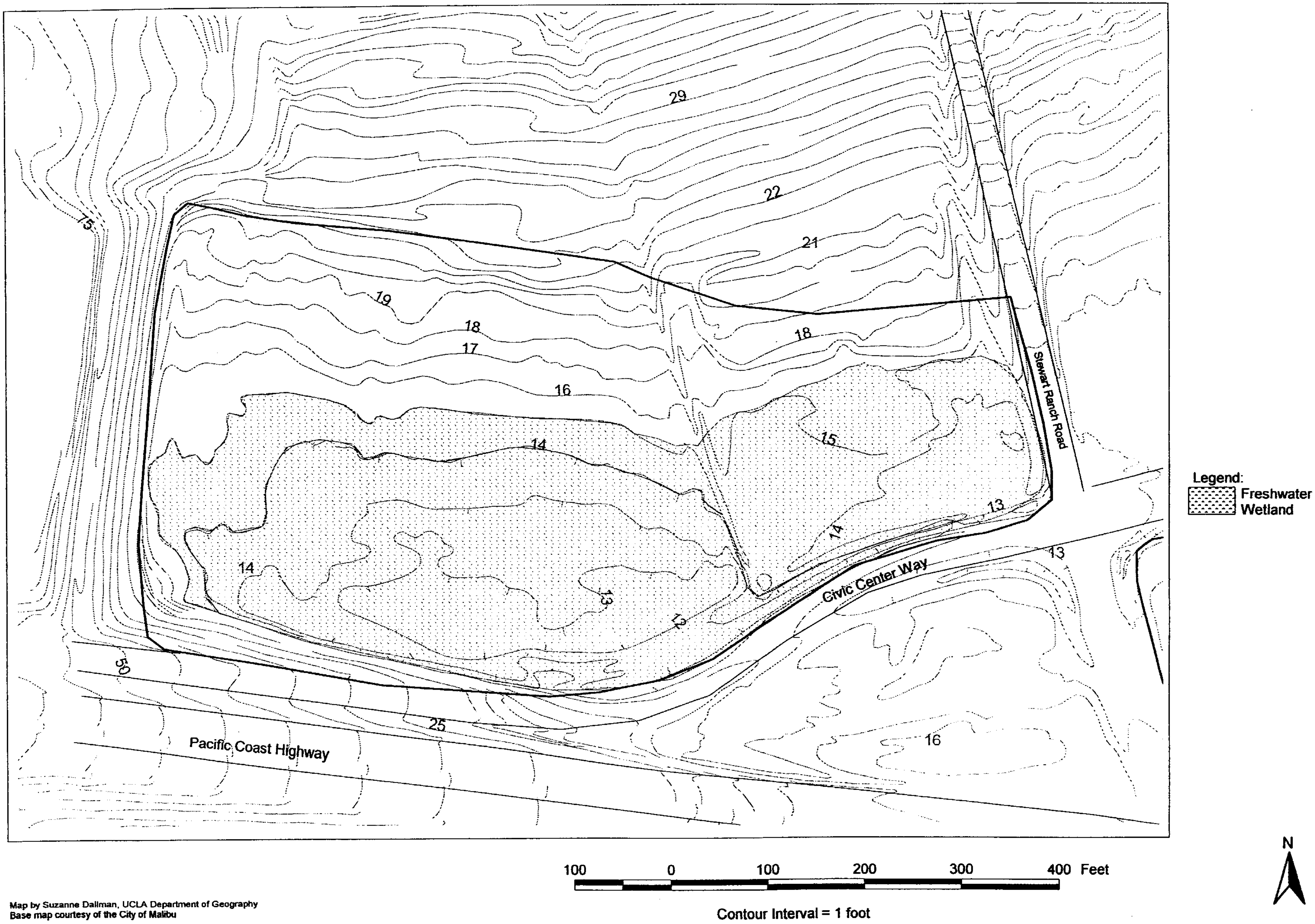

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Figure 9-11. Restoration Site C2

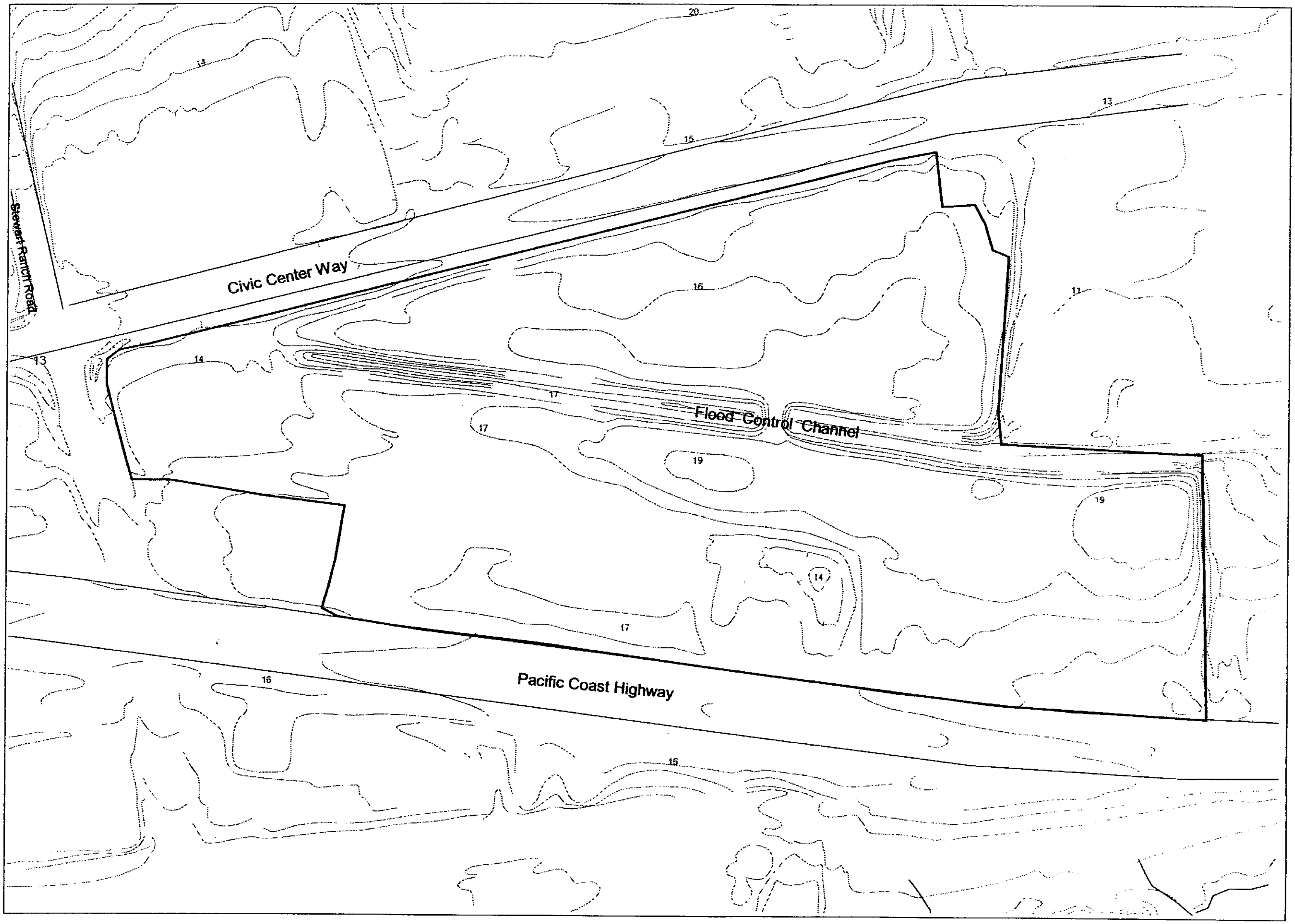

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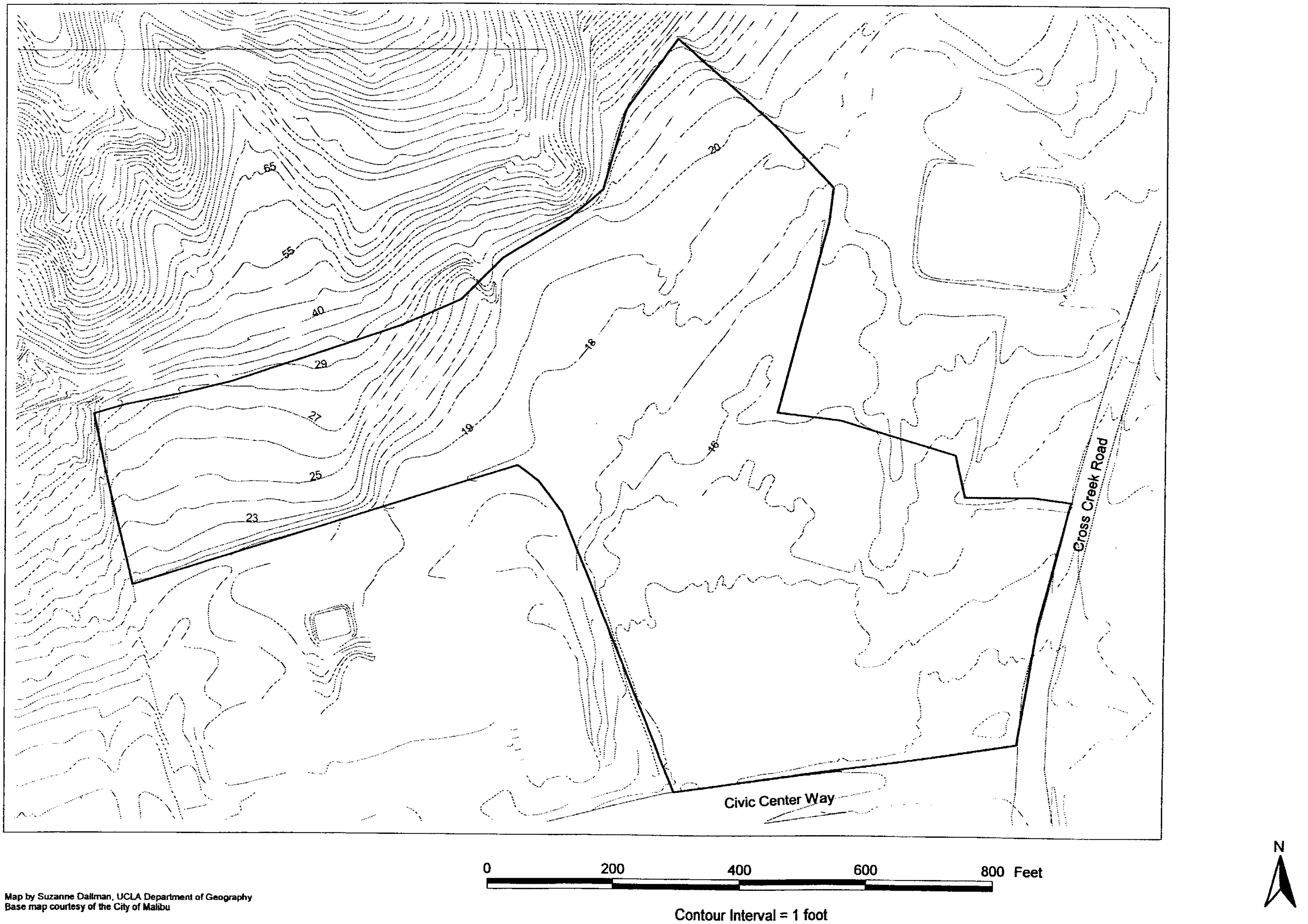
Figure 9-12. Restoration Site C3



Map by Suzanne Dallman, UCLA Department of Geography
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Figure 9-13. Malibu Lagoon Ecosystem Restoration Alternative

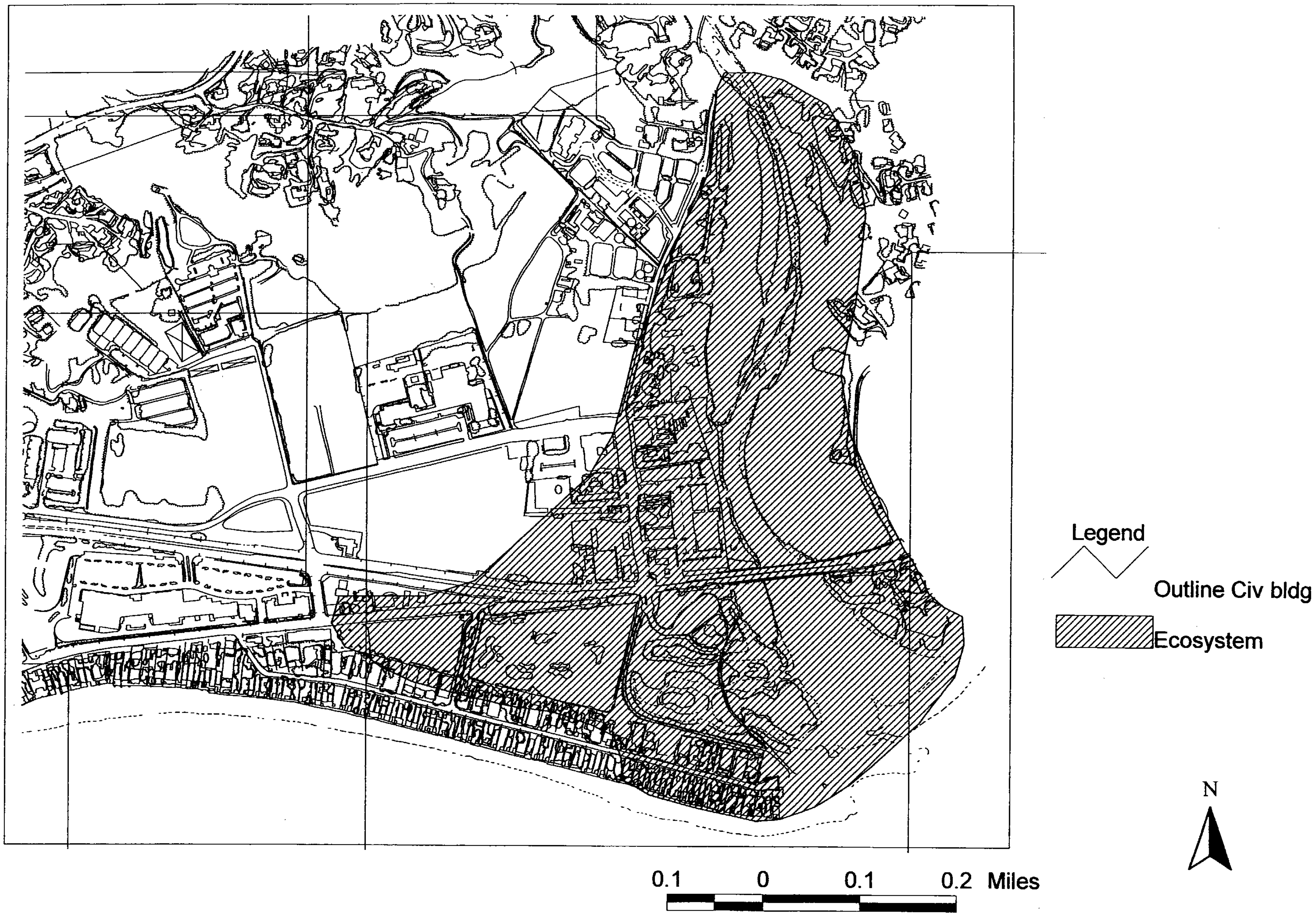

Figure 9-14. Lagoon and Salt Marsh Restoration Alternative (Restoration Sites A1-A3)

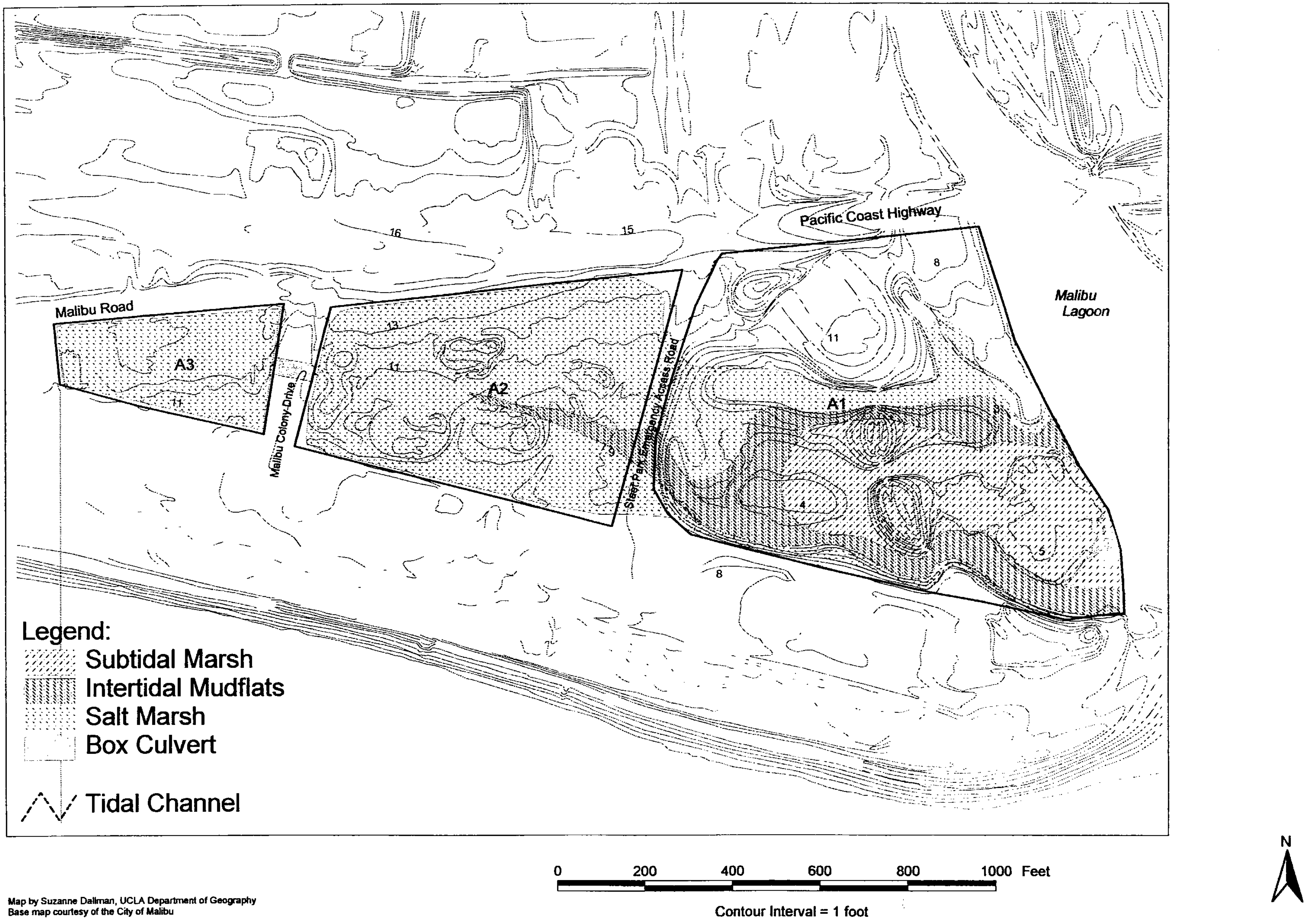

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Figure 9-15. Salt Marsh Enhancement/Restoration -- Alternative I (Restoration Site A1)

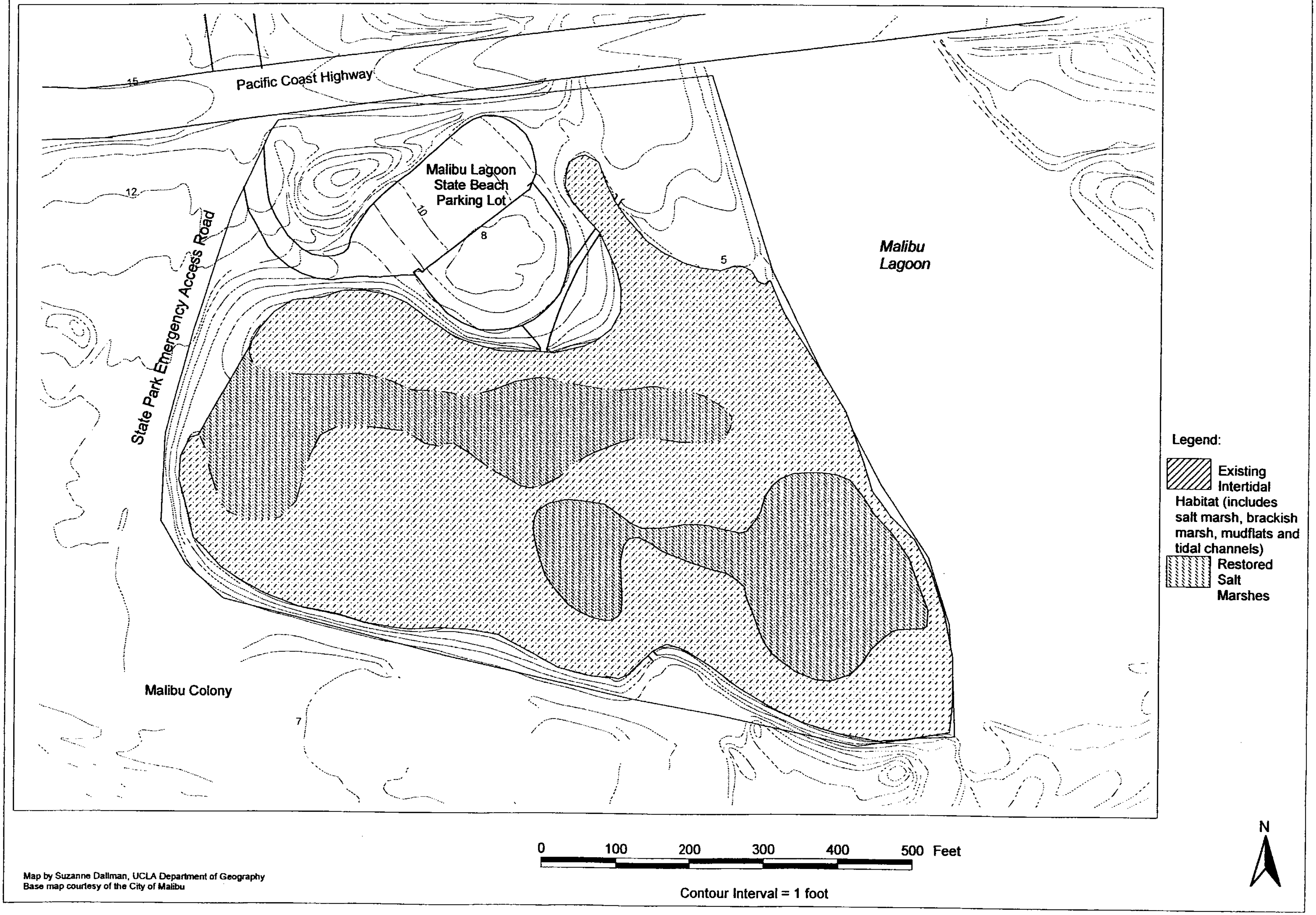

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Figure 9-16. Salt Marsh Enhancement/Restoration -- Alternative II (Restoration Site A1)

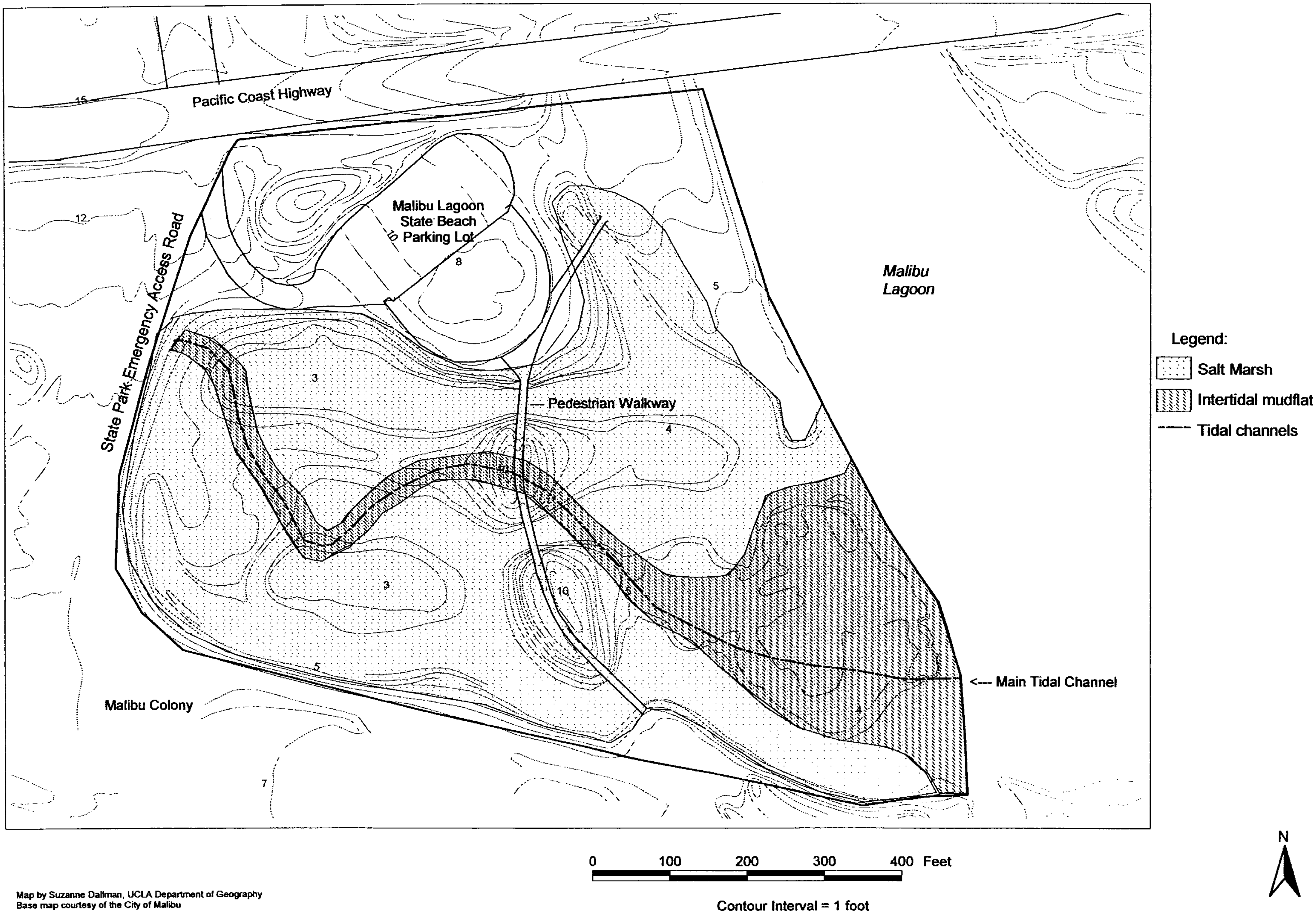

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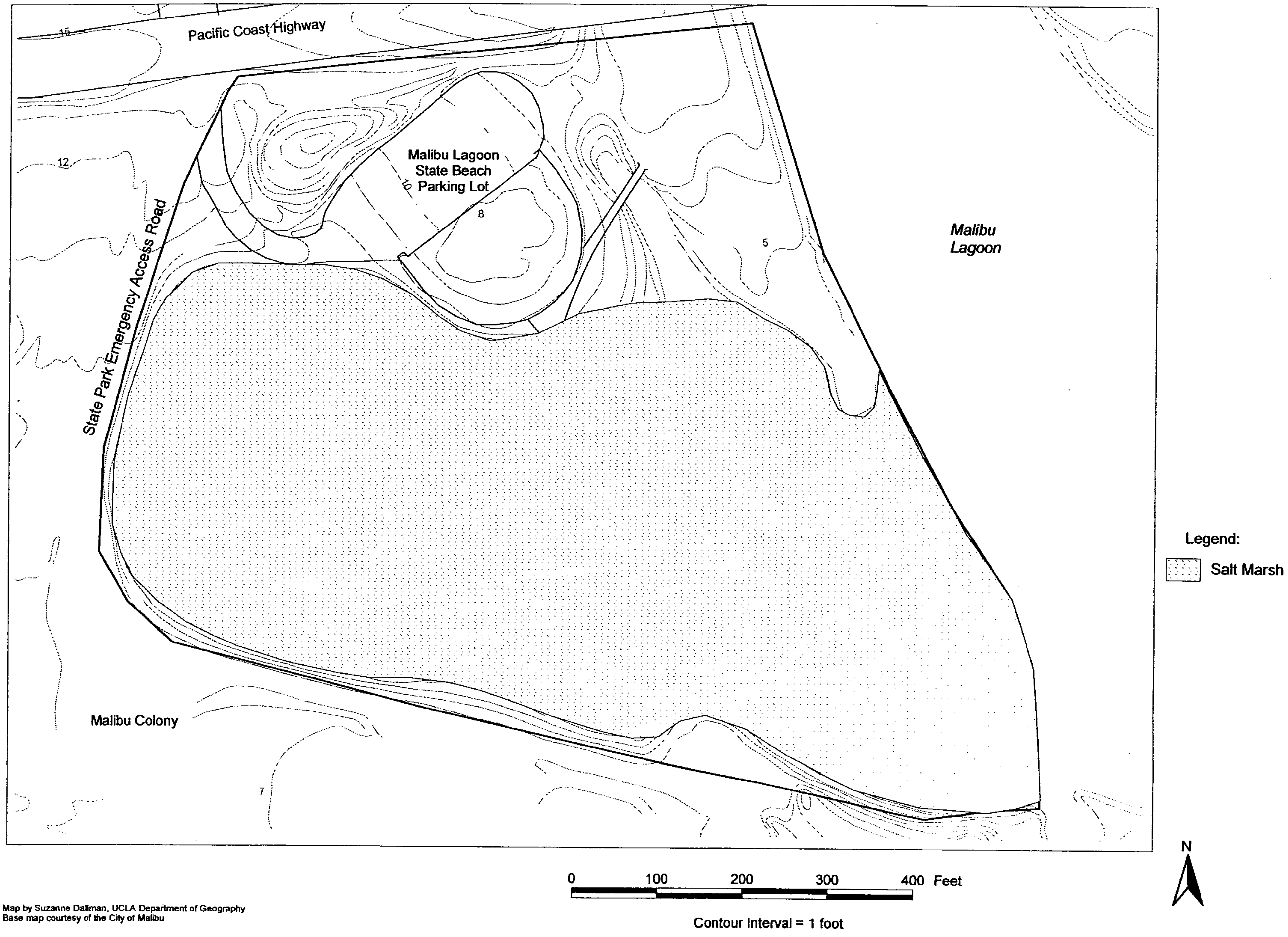
Figure 9-17. Salt Marsh Enhancement/Restoration -- Alternative III (Restoration Site A1)



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Base map courtesy of the City of Malibu

Figure 9-18. East Lagoon Salt Marsh Restoration Alternative (Restoration Site A4)

Map by Suzanne Dallman, UCLA Department of Geography
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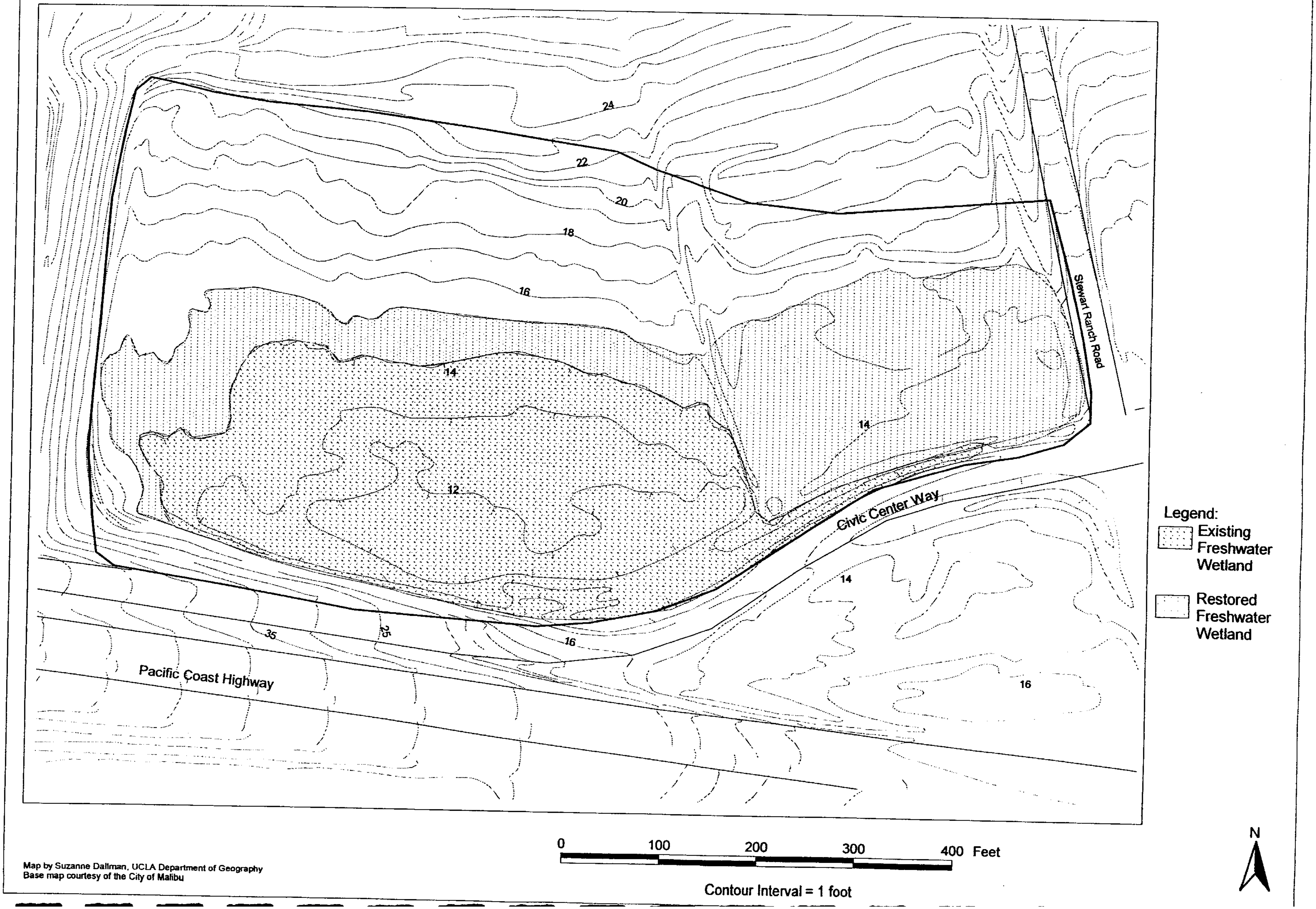
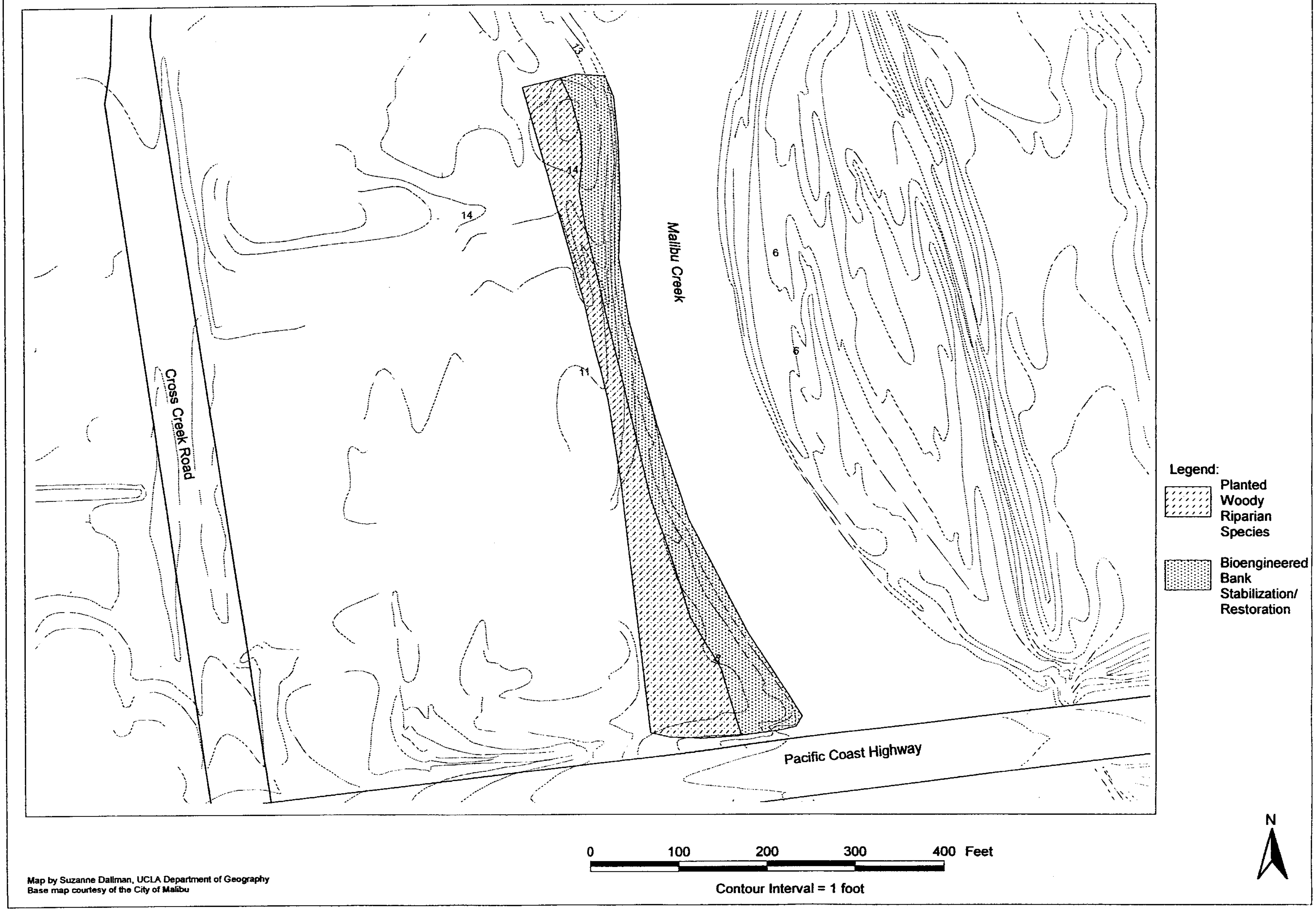
Figure 9-19. Freshwater Enhancement Alternative (Restoration Site C1)



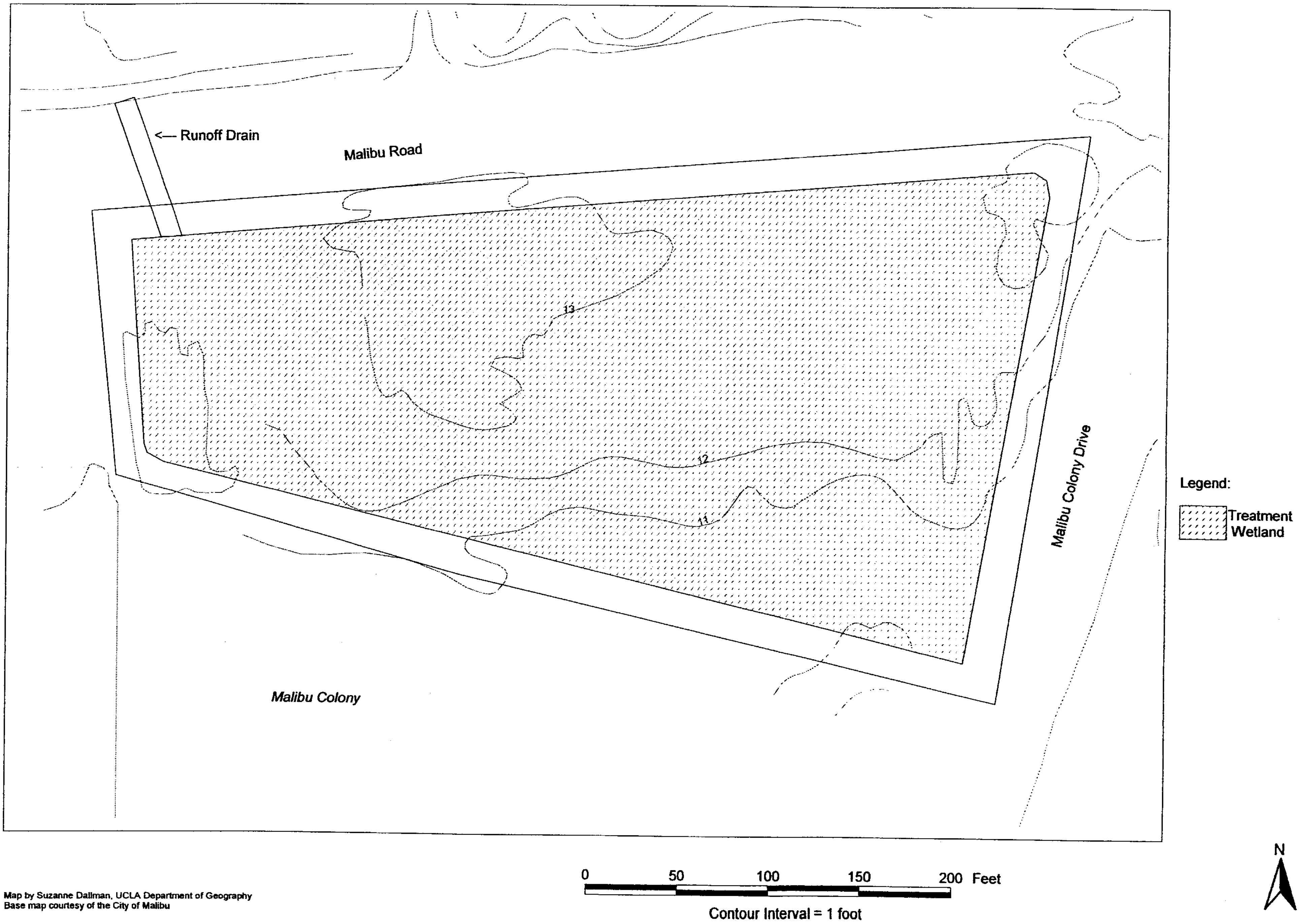
Map by Suzanne Dallman, UCLA Department of Geography
Base map courtesy of the City of Malibu

Figure 9-20. Malibu Creek Bank Stabilization/Restoration Alternative (Restoration Site B1)



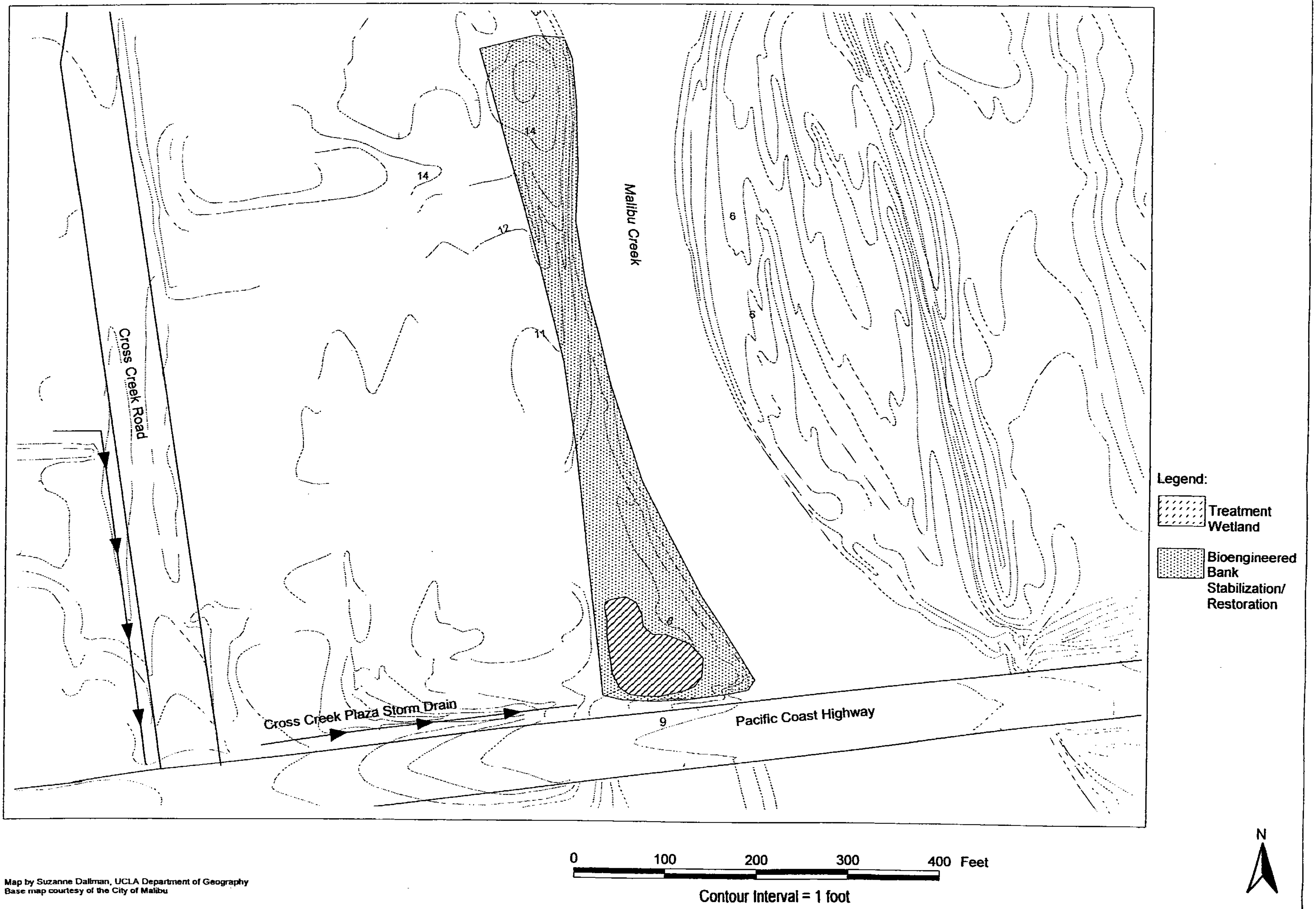
Map by Suzanne Dallman, UCLA Department of Geography
Base map courtesy of the City of Malibu

Figure 9-21. Stormwater/Dry Season Runoff Treatment Wetland - Alternative I (Restoration Site A3)



Map by Suzanne Dallman, UCLA Department of Geography
Base map courtesy of the City of Malibu

Figure 9-22. Stormwater/Dry Season Runoff Treatment Wetland - Alternative II (Restoration Site B1)



Map by Suzanne Dallman, UCLA Department of Geography
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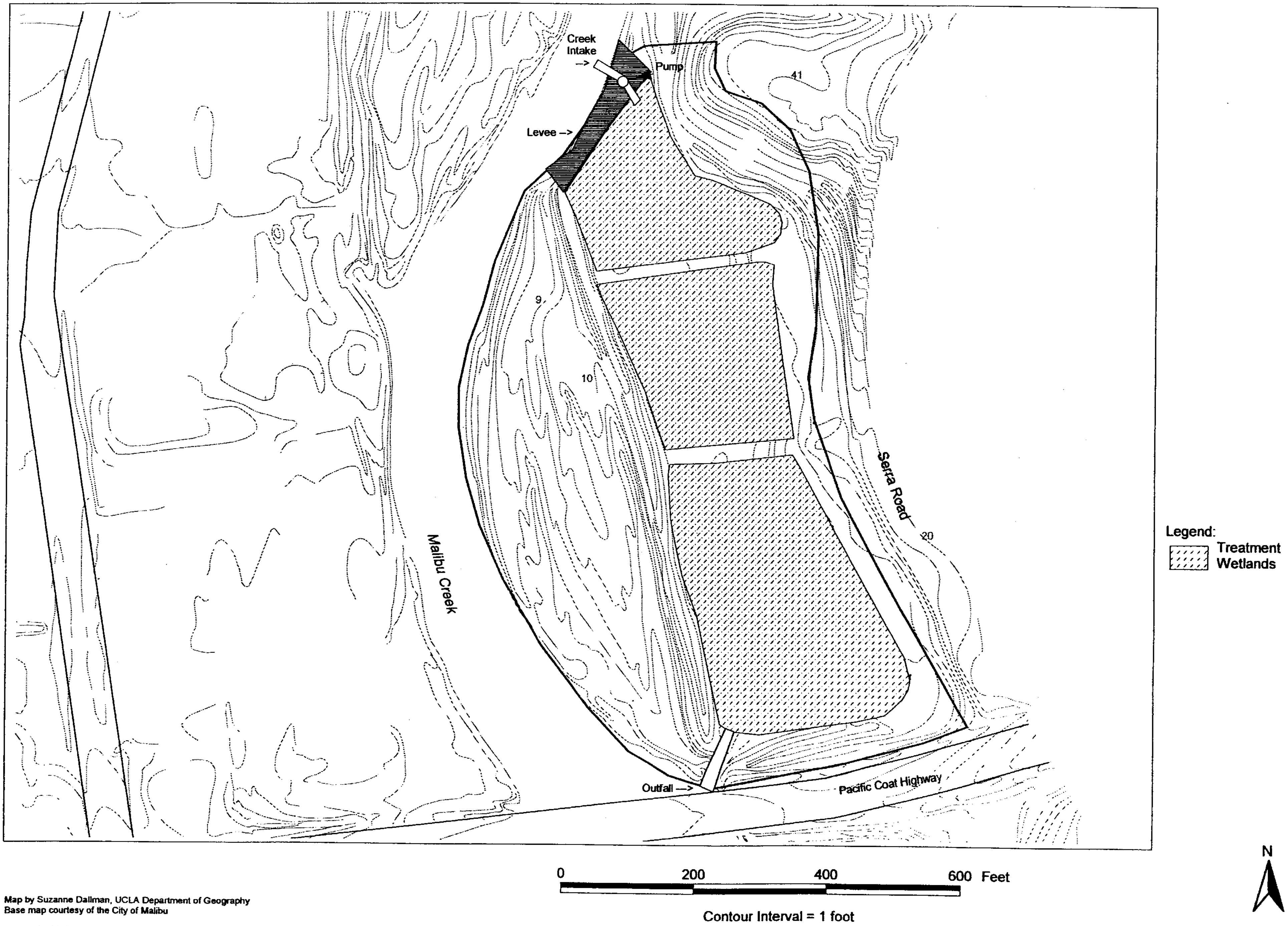
Figure 9-23. East Bank Creek Treatment Wetlands Alternative (Restoration Site B2)



Map by Suzanne Dallman, UCLA Department of Geography
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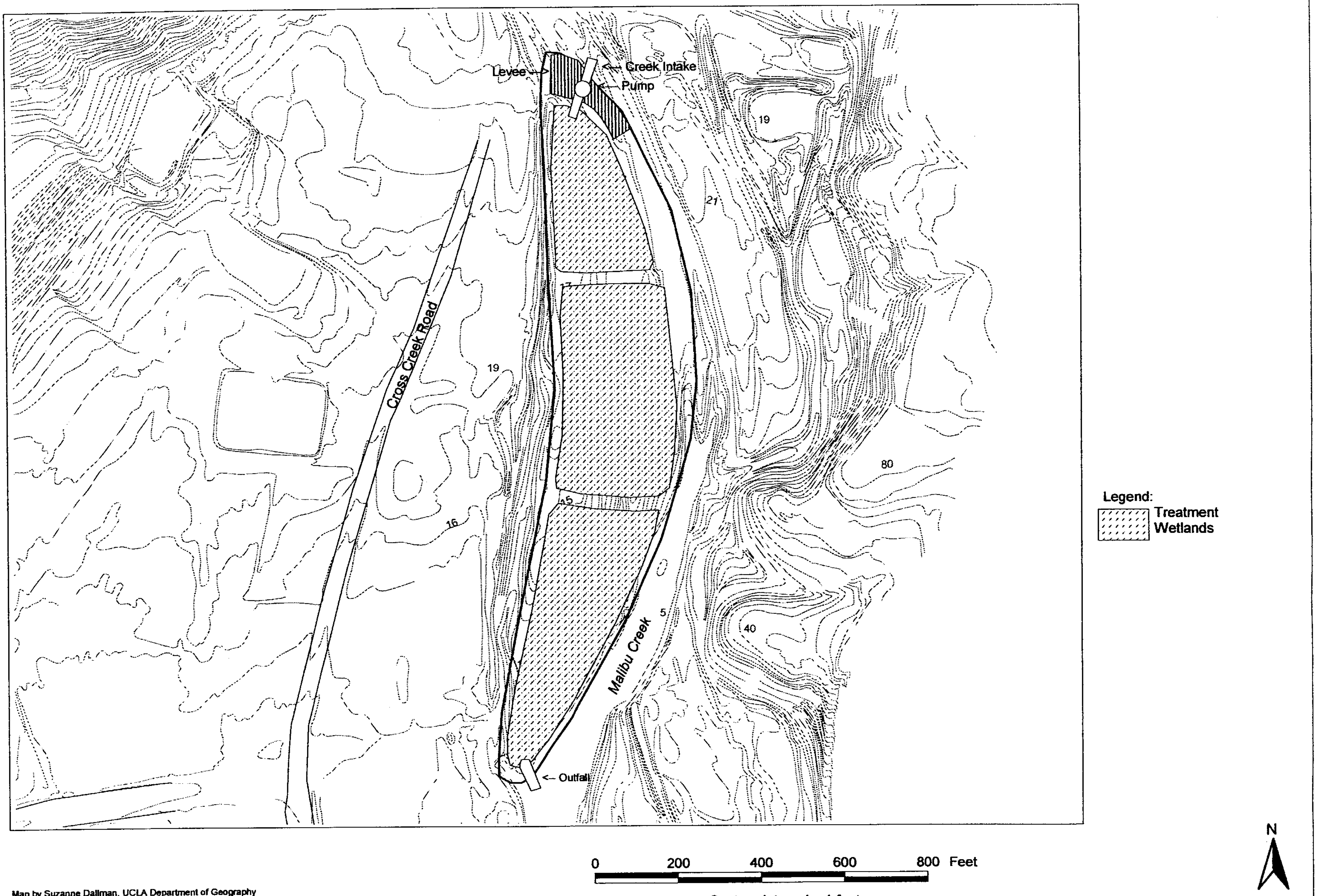
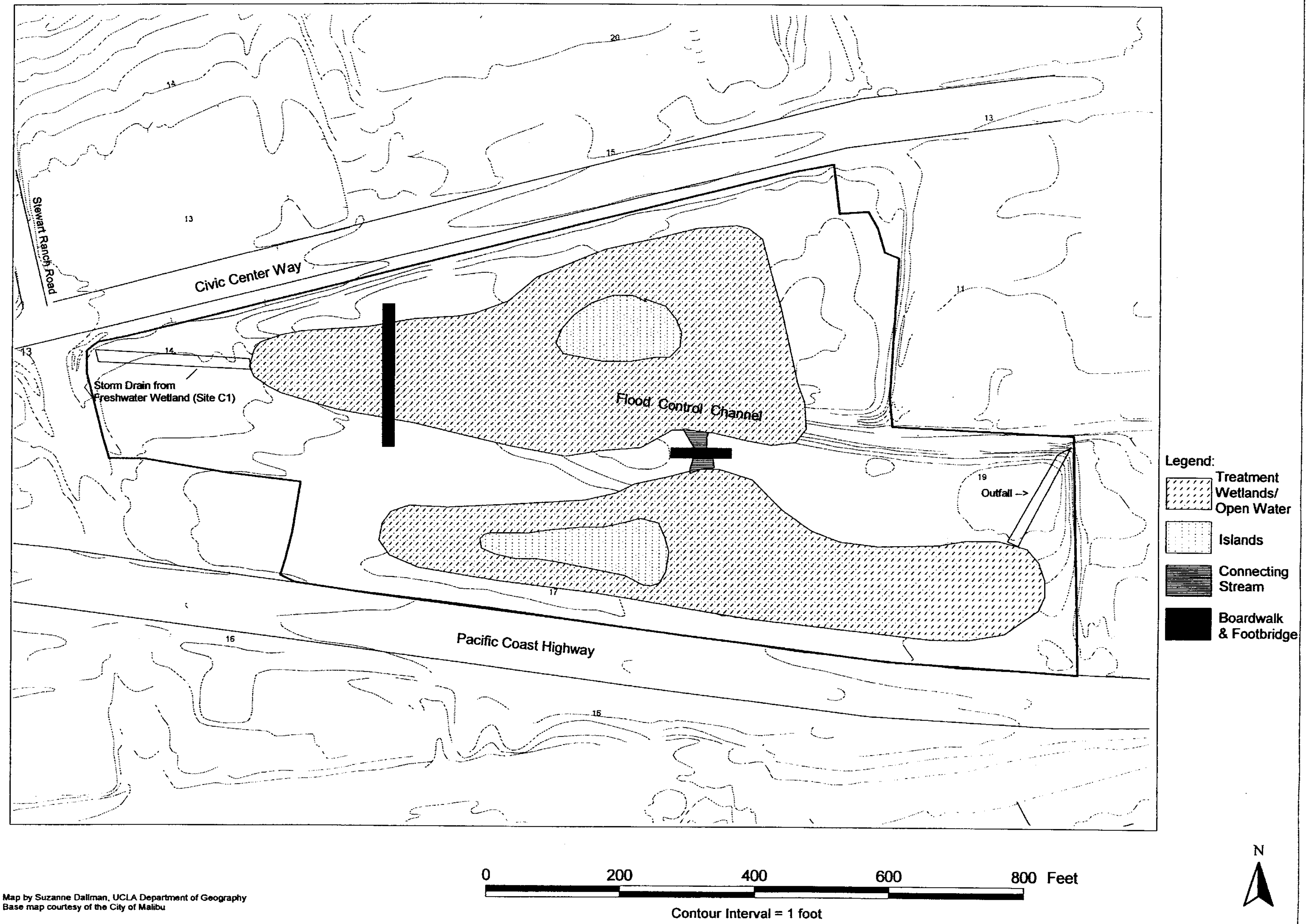
Figure 9-24. West Bank Creek Treatment Wetlands Alternative (Restoration Site B3)



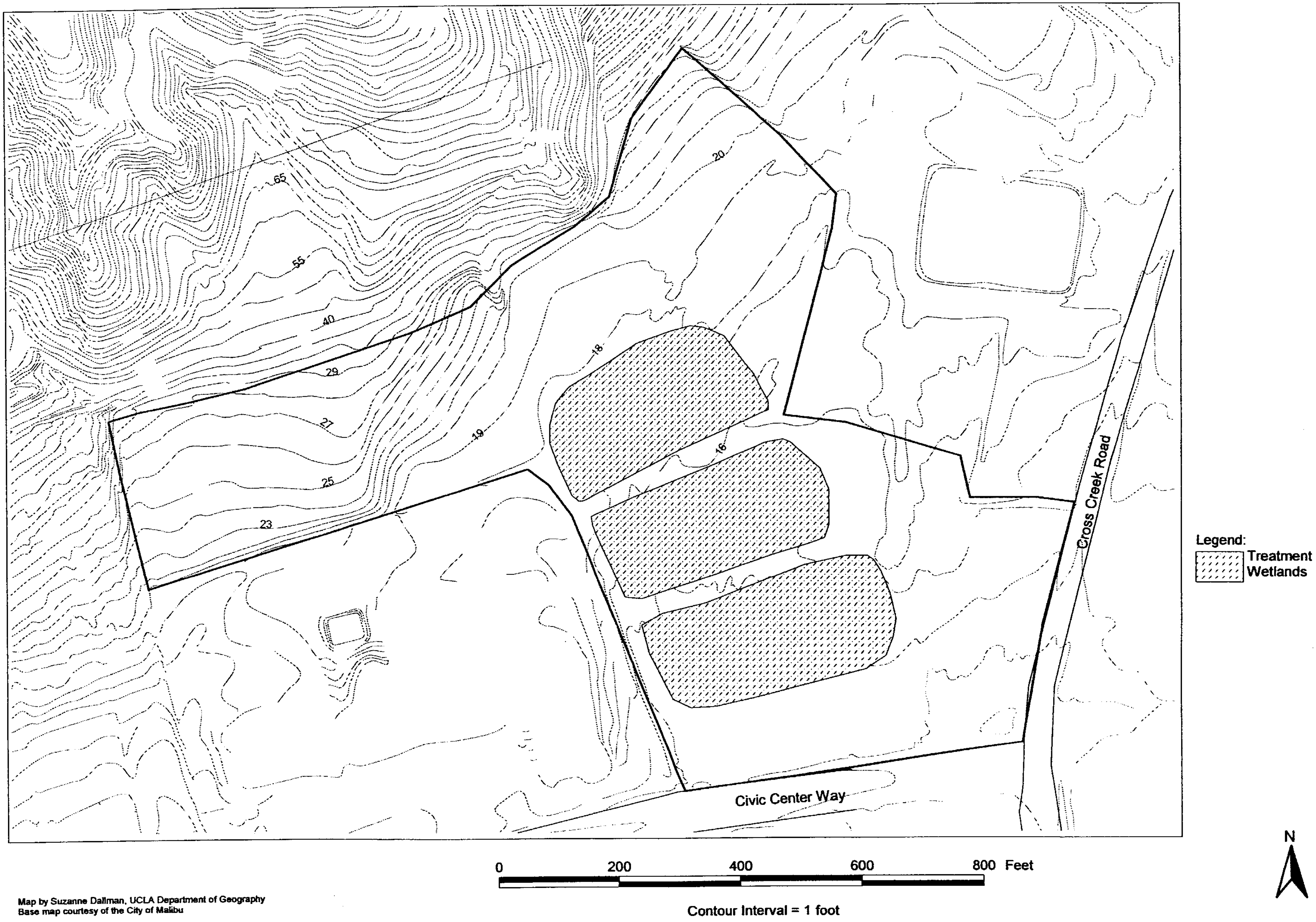
Map by Suzanne Dallman, UCLA Department of Geography
Base map courtesy of the City of Malibu

Figure 9-25. Stormwater/Wastewater Treatment Wetland - Alternative I (Restoration Site C2)



Map by Suzanne Dallman, UCLA Department of Geography
Base map courtesy of the City of Malibu

Figure 9-26. Stormwater/Wastewater Treatment Wetland - Alternative II (Restoration Site C3)



Map by Suzanne Dallman, UCLA Department of Geography
Base map courtesy of the City of Malibu

Chapter 10: Summary of Management and Restoration Alternatives

Richard F. Ambrose
Jonathan Lilien

10.1. Introduction

This chapter reviews the major findings from Chapters 8 and 9 and develops recommendations to guide future management and restoration efforts in the lower Malibu Creek watershed. The goals of the chapter are: (1) to identify critical issues that shape which management and restoration options should be pursued; (2) to resolve inconsistencies between some of the medium- and high- priority management and restoration alternatives; and (3) to develop a set of clear directives for local agencies and stakeholder groups to follow when implementing management and restoration programs in Malibu.

Although our assessment has been comprehensive and follows other studies of the Malibu Creek watershed, there nonetheless remain a number of unresolved issues affecting our conclusions and recommendations. There are four main sources of uncertainty:

1. Uncertainty about nutrients. Although we have provided (Chapter 5) the most comprehensive evaluation of nutrients in lower Malibu Creek and Malibu Lagoon to date, many uncertainties still remain. Many relevant sources simply have not been measured, or have not been sampled intensively enough to provide reliable estimates. Our nutrient budget is based on the best available estimates, sometimes from literature sources, but nonetheless there are substantial uncertainties remaining.

2. Uncertainty about pathogens. The issue of pathogen inputs to Malibu Lagoon and the ocean is perhaps the most controversial and emotional issue associated with the management of the Lagoon, and yet there still have been relatively few studies on

pathogens and their origins and fates in the creek/lagoon/ocean system. Our study (Chapter 6) has provided new information about the types of pathogens in this system and their possible human health risks, but substantial uncertainties remain. We have recommended more frequent and consistent monitoring of pathogens as one way of improving our understanding of human health risks from pathogens in the Creek and Lagoon. One of the most important sources of uncertainty is the contribution of Lagoon-area septic systems to pathogens in the Lagoon. When we started this project, the City of Malibu planned to conduct a study of septic systems around the Lagoon. This study would have provided invaluable information to support specific management actions, but unfortunately it was not completed in time for the information to be included in this project. The absence of this information has had a profound influence on our assessment of several management alternatives. In the absence of the results of this study, we have had to prioritize management actions based mainly on nutrient and water inputs. Our prioritization might have been quite different with information about the septic systems' contributions to pathogens in the Lagoon.

3. Uncertainty about engineering feasibility and costs for some of the construction/ management alternatives. Some of the management alternatives involve significant engineering and construction activities. Engineering analyses are beyond the scope of this project, but could have an important effect on prioritization of management alternatives. Some of the alternatives we have considered may no longer be considered feasible after an engineering analysis. Alternatively (although less likely), some of the alternatives we have considered too expensive or difficult might, in fact, be cheaper or easier than we believe. Engineering analyses will be particularly important for distinguishing between some of the moderate- and high-priority alternatives.

4. Uncertainty about the disposition of Rindge Dam. Although there have been a number of studies and discussions about removing Rindge Dam, nothing has yet been decided. In this report, we have avoided detailed assessments of management alternatives affected by Rindge Dam because of the uncertainty about what will happen to the Dam. Once a decision is made about the disposition of the Dam, more effort could be devoted to evaluating the alternatives associated with the Dam.

These four sources of uncertainty set constraints on our analyses of management alternatives and, especially, our prioritization of these alternatives. These uncertainties should not preclude action to solve some of Malibu's problems. For some alternatives, these uncertainties have little effect on our conclusions. However, further studies to remove these uncertainties might simplify the choice of which alternatives to implement. For example, clear information about the contribution of the Lagoon-area septic systems to pathogens in the Lagoon would certainly affect the prioritization of some management alternatives. In addition, more detailed engineering and feasibility studies must be conducted before any of the construction-intensive alternatives are adopted. Although our prioritization is based on our best judgement about the advantages and disadvantages of these alternatives, we have not attempted the type of detailed studies that would be needed to confirm our assessments. We recommend that a planning/engineering study be conducted to compare the different engineering alternatives.

10.2. Biota and Habitat Management

Eight biota and habitat management alternatives were identified and evaluated in Chapter 8. Of these, six are considered impractical or assigned low priority. This lack of medium- and high- priority management alternatives reflects our belief that most measures focused directly on the biota, such as biomanipulation or fish habitat enhancement structures, are unlikely to be effective in the highly dynamic lower creek and lagoon environment and, in many cases, may prove counterproductive.

In most cases, biota and habitat problems are best addressed by improving the overall condition of the lower creek and lagoon. Reducing pollutant inputs and restoring natural hydrologic processes, thereby eliminating two of the most pervasive stressors in the lower watershed, probably represents the best means of achieving this objective. If successful, these measures would reestablish populations that have been eliminated or reduced in abundance, and allow for the persistence of a more diverse flora and fauna.

One management alternative assigned high priority would use signs to try to protect birds in the Lagoon area. As with some of the other alternatives focused directly on the biota, the effectiveness of this alternative is not certain, but unlike these other alternatives, signs would cost little and have few if any negative consequences.

Removing non-native plants and revegetating with native species is the only other biota and habitat management alternative assigned high priority status. This alternative is considered urgent because of the rapid proliferation of non-native plants in the lower watershed (Manion and Dillingham 1989), and that fact that, unlike many of the biota and management alternatives discussed in Chapter 8, removal and revegetation would have minimal adverse impacts.

Potential target species include pampas grass (*Cortaderia selloana*), castor bean (*Ricinus communis*), and giant reed (*Arundo donax*). As described in Chapter 8, *Arundo donax* is especially problematic because it rapidly displaces native species, forms monotypic stands with little habitat value, and may allow fire to encroach into the riparian zone (Bell 1995).

Although it is simple conceptually, eliminating non-native plants may prove difficult from a logistics standpoint. Many non-native plant species resist treatment and rapidly reestablishing themselves following initial removal efforts. For this reason, non-native plant removal must take place as a concerted, watershed-wide effort, and proceed on an ongoing basis.

State agencies such as the California Department of Parks and Recreation (DPR) and Resource Conservation District of the Santa Monica Mountains (RCD) should spearhead non-native plant eradication efforts in the watershed. Unlike current exotic removal programs, which take place on an ad hoc basis, the program should be maintained continuously by securing funds from internal or external sources. Compensatory mitigation associated with regulatory actions (i.e., California Department of Fish and Game streambed alteration agreements, U.S. Army Corps of Engineers Section 404 permits) represent one potential source of funding. Similar arrangements have been established to fund *Arundo donax* eradication efforts in the Santa Ana River watershed.

In addition to a stable funding source, non-native plant removal efforts must employ a determined and energetic pool of laborers since, to a large part, it may depend on manual removal methods. Toward this end, DPR or RCD should enlist local environmental groups such as the California Native Plants Society and Audubon Society, and mobilize volunteer teams similar to those that participate in Heal-the-Bay's volunteer monitoring program.

10.3. Water Resource Management

Chapter 8 identified and evaluated 30 management alternatives that could be implemented to alleviate water quality and quantity problems in Lower Malibu Creek and Lagoon. As was the case in the biota and habitat category, many alternatives are considered impractical or assigned low priority. Three water resource management alternatives are considered medium priority: eliminating Malibu Colony and Civic Center septic systems, retrofitting septic systems, and constructing a water level management and/or disinfection facility. The ten high priority alternatives are: treating creek flows before they reach the lagoon, eliminating illicit connections and discharges, treating urban runoff before it reaches the lagoon, eliminating illicit discharges and connections, implementing Best Management Practices (BMPs) to reduce non-point source pollution, retrofitting the storm drain system to reduce contaminant inputs to the lagoon, requiring the Tapia Water Reclamation Facility to reduce nutrients from their effluent, diverting excess creek flows offshore, eliminating Tapia's discharge into the creek during the dry season, reducing water use in the lower watershed, and implementing a modified mechanical breaching regime. The rationale behind these rankings is discussed in Chapter 8. Pending the outcome of additional studies, especially of pathogens and engineering costs and feasibility, we think that both medium and high priority alternatives should be considered promising possibilities.

Several alternatives are already mandatory under current regulations. Tapia must reduce nutrients in their effluent prior to discharging to the creek and refrain from discharging into the creek during the dry season in order to comply with its National Pollutant Discharge Elimination System (NPDES) permit. Similarly, the cities of Agoura Hills, Calabasas, and Malibu must eliminate illicit connections and discharges to the storm drain system within their jurisdictions since they are covered under the Los

Angeles County municipal storm water permit. These measures should be implemented (and enforced) immediately. Although these alternatives are already required, we include them as high priority alternatives because they should be implemented whether or not they are required by law and regardless of possible future changes in regulations (such as a change in Tapia's NPDES permit).

Although they will reduce water resource problems in the lower watershed, these measures will not eliminate the problems altogether. Additional management strategies will have to be adopted. It is not practical to adopt <u>all</u> of the medium- and high- priority management alternatives identified above because many of the alternatives are redundant, incompatible, or mutually exclusive. For example, installing a temporary spillway, constructing a water level management and/or disinfection facility, and implementing a modified mechanical breaching regime are redundant because they all address the same problem. None of these measures would be needed if creek flows were diverted because the diversion would eliminate the need to control lagoon water levels at the lagoon. Treating creek flows before they reach the lagoon and diverting excess creek flows offshore are also mutually exclusive; treating creek flows would be unnecessary if a system to divert excess creek flows offshore were constructed.

Because of these and other incompatibilities among medium- and high-priority water resource alternatives, a coherent framework is needed to guide the selection of different combinations of water resource management alternatives in Lower Malibu Creek and Lagoon.

As described in Chapter 8, water resource management measures can be divided into three general categories reflecting different conceptual approaches: (1) source reduction, (2) treatment, and (3) diversion. Source reduction is considered the most desirable of the three approaches because it does not interfere with natural hydrologic processes and addresses the ultimate causes of water resource problems, rather than their symptoms. Treatment measures are not viewed as favorably as source reduction because they deal with material inputs within receiving waters as opposed to at their point of origin. Similarly, diversion strategies are not viewed as favorably as source reduction because they simply divert contaminants from one receiving water to another.

This ranking of approaches suggests that water resource management should be addressed in sequence, with source reduction measures implemented before treatment or diversion measures. The timing between the implementation of the steps within this sequence may depend on how effective the approaches prove to be, how long people are willing to wait to see an improvement in water resource conditions in Malibu, and how much people are willing to spend. It is anticipated that treatment and diversion might provide quicker results than source reduction, but would be significantly more expensive to implement and involve more complex (and perhaps disruptive) engineered structures.

Accordingly, high-priority source reduction measures (i.e., implementing BMPs, reducing water use) should be adopted immediately in the lower Malibu Creek watershed[1]. If these methods prove successful, treatment or diversion measures may not be necessary (Table 10-1). If they are not sufficient to eliminate water resource problems in the lower creek and lagoon or do not provide substantial improvement in the short-term, treatment and diversion measures (i.e., treating creek flows, treating urban runoff, and diverting creek flows offshore) will need to be adopted. In particular, if the source-reduction approaches cannot solve the problem of persistent high lagoon water levels during the dry season (and it seems likely they will not, certainly not in the short term), then some type of active management of lagoon water levels will be necessary. Only one of these alternatives, diverting excess creek flows offshore, would reduce pollutant (including nutrient) inputs to the lagoon as well as reducing freshwater flows and alleviating water quantity problems; for this reason, it is assigned high priority. This alternative is not a source-reduction approach, however, and it does not reduce pollutant inputs into the *ocean* (unless the water is diverted to the upper watershed for reuse). It is considered a high priority because it would work even if other management techniques do not reduce pollutant loads and water volume in the creek, and it does not allow these loads to enter the lagoon. Allowing untreated creek water to enter the ocean is not ideal, even though the ocean has a much greater assimilative capacity and the elevated nutrient levels would cause fewer problems in the ocean. However, it is important to remember that the excess water with its pollutants enters the ocean in any case when the lagoon is breached.

If source reduction strategies are not effective, the alternative to diversion is to manage lagoon water levels after the water has entered the lagoon. Implementing a modified mechanical breaching regime is given a high priority. Other possible approaches include installing a temporary spillway to allow lagoon waters to drain to the ocean or constructing a water level management facility (either with or without a disinfection facility).

Finally, it is important to note that the analyses conducted in this study are general in nature and do not take the place of detailed engineering studies. We recommend that detailed engineering studies be conducted to provide a better evaluation of the engineering feasibilities and costs of different alternatives, especially the alternatives concerning creek flow diversion and lagoon water level management/treatment. Such studies are needed to define the costs and constraints of these alternatives with better precision. Until such studies have been completed, the alternatives that were placed in the medium and high priority classes because of engineering consideration should be considered as having equal priority.

10.4. Wetland Restoration

Habitat loss has played a central role in the decline of native bird, fish, and

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[1] As noted in Chapter 8, source reduction measures or other management actions must also be implemented in the upper watershed, since that is where the majority of human activity takes place.

invertebrate populations in Lower Malibu Creek and Lagoon. Restoring or enhancing wetland habitat represents the best means of combating this problem. Wetland restoration would lead to a more abundant and diverse fauna by increasing overall habitat availability and diversity in the lagoon area. Since wetlands filter waterborne pollutants and attenuate flows, restoration would also address water quality and quantity problems in the lower watershed.

Before considering the prioritization of restoration alternatives, we make two general observations. First, undeveloped land available for restoration is in short supply in the Malibu Lagoon area as well as elsewhere in southern California. Since existing buildings are rarely demolished for habitat restoration, the availability of undeveloped land sets an ever-shrinking constraint on restoration opportunities. Therefore, the acquisition of potentially restorable land should be the highest priority for restoration and the first step in restoring the Malibu Lagoon ecosystem. The actual restoration work can take place later if the land is acquired, but any new construction in the Lagoon area represents a restoration opportunity that is lost. This principle of giving highest priority to the acquisition of land before it is developed has been adopted by the Scientific Advisory Panel for the Southern California Wetlands Recovery Project, a consortium of state and federal agencies concerned with wetland restoration in southern California.

Second, the Malibu Lagoon Ecosystem Restoration alternative clearly provides the greatest ecosystem benefits to the Malibu Lagoon area. This alternative comes closest to achieving the goal of restoring the processes, functions and mix of wetland habitats that originally occurred in the Malibu Lagoon area. The populations of wetland plants, invertebrates, fish and birds would all increase as a result of this restoration. However, this is the only alternative that would require the demolition of existing commercial and residential buildings as well as the removal or re-engineering of roads. Thus, this would be, by far, the most expensive restoration alternative. The ecosystem benefits and social costs of this alternative are both so significant that we have not prioritized it.

Ten potential wetland restoration sites lacking existing buildings were evaluated in Chapter 9. Two of the sites, the eastern and western banks of lower Malibu Creek (sites B2 and B3, respectively), are not considered suitable for wetland restoration because they contain functional riparian habitat, a valuable and regionally scarce ecotype. Two additional sites, the "chili cook-off" area and vacant lots near the Civic Center, are not considered appropriate for restoration because they are isolated from the lower creek and lagoon. Although they are not strong candidates for wetland restoration per se, each of the four sites could accommodate treatment wetlands.

Eight alternatives were considered for the six viable wetland restoration sites. Two of these alternatives, Lagoon/Salt Marsh Restoration II and Salt Marsh Enhancement III, are considered low priority. Freshwater Wetland Enhancement and Bioengineerered Bank Stabilization are considered medium priority. The remaining four alternatives (Lagoon/Salt Marsh Restoration I, Salt Marsh Enhancement I, Salt Marsh Enhancement II, and Freshwater Wetland Protection) are all considered high priority.

Five of the six medium- and high-priority wetland restoration alternatives involve the same two sites. Freshwater Wetland Protection and Freshwater Wetland Enhancement would occupy site C1, the existing wetland near the intersection of Civic Center and Webb Way. Similarly, Lagoon/Salt Marsh Restoration I, Salt Marsh Enhancement I, and Salt Marsh Enhancement II would occupy site A1, the existing salt marsh in Malibu Lagoon. Since it is not possible to implement more than one alternative at each of these sites, selection of alternatives should be driven by the relative priority levels of the different alternatives (i.e., which alternatives would contribute the most to overall ecological health and integrity) and the likelihood of acquiring properties necessary to implement the different alternatives.

Choosing which alternative to pursue at site C1 is relatively simple because one of the alternatives, Freshwater Wetland Protection, is considered high priority and the other, Freshwater Wetland Enhancement, is assigned medium priority. This ranking reflects the fact that, unlike protection, enhancement would require artificial irrigation and might cause localized flooding. Furthermore, enhancement probably would require acquisition of parcels around site C1, while protection would only entail ensuring a conservation easement on the site itself.

Selecting a restoration plan for site A1 is more difficult because all three alternatives proposed for the site are considered high priority. Accordingly, selection should be based on the relative costs and benefits of each alternative and the feasibility of their implementation (Table 10-2). Lagoon/Salt Marsh Restoration I would contribute the most to overall ecological health and integrity since it would create a large area of open water and marsh habitat similar to what occurred in the pristine ecosystem. Salt Marsh Enhancement I and II are not considered as desirable because they would not result in a significant increase in wetland acreage. For this reason, Lagoon/Salt Marsh Restoration I represents the preferred wetland restoration alternative, and should be pursued if there are sufficient resources to purchase the properties from the owner of sites A2 and A3.

If acquisition of sites A2 and A3 is not possible, Salt Marsh Enhancement I or II should be pursued. Neither alternative would not require land acquisition, only DPR approval to proceed with enhancement of the existing salt marsh. Although they would not increase wetland acreage significantly, either alternative would improve the condition of wetland resources in the lagoon area. The decision of which of the two enhancement projects to pursue depends on the future availability of sites A2 and A3. Salt Marsh Enhancement I would involve minor changes to the configuration and topography of the existing salt marsh. Since it would be relatively inexpensive, implementation of this alternative would leave open the possibility of proceeding with Lagoon/Salt Marsh Restoration I in the future. Salt Marsh Enhancement II, on the other hand, would involve major changes to the configuration and topography of the existing salt marsh and, consequently, would be more expensive. Given the allocation of resources associated with the implementation of this alternative, it is unlikely that local authorities would want to proceed with Lagoon/Salt Marsh Restoration I in the future if Salt Marsh Enhancement

II were implemented.

Based on these factors, Salt Marsh Enhancement I should be seen as a short-term alternative that may be pursued if sites A2 and A3 cannot be acquired immediately, but may become available within the reasonable foreseeable future. Conversely, Salt Marsh Enhancement II should be viewed as a long-term alternative that may be pursued if acquisition of sites A2 and A3 seems unlikely in the reasonably foreseeable future.

10.5. Treatment Wetlands

Poor water quality is one of the most pressing environmental problems in the lower Malibu Creek watershed. Treatment wetlands represent one means of combating this problem. Although it is unlikely that they would eliminate water quality problems altogether, treatment wetlands have the potential to substantially improve water quality in the lower watershed if implemented in conjunction with the water resource management alternatives discussed above. Treatment wetlands would also provide ancillary benefits by serving as wildlife habitat and enhancing the overall aesthetic quality of the lagoon area.

Chapter 9 identified and evaluated six treatment wetland alternatives that could be implemented in the lagoon area. Three of these alternatives are assigned low priority because the sites they would occupy contain functional riparian habitat, or are not large enough to accommodate a treatment wetland. A fourth alternative (Alternative 1) that would occupy site A3 is considered medium priority. Lagoon/Salt Marsh Restoration I represents a more appropriate use of this site because it would provide a large benefit to overall ecological health and integrity. Nevertheless, site A3 might be an appropriate location for a treatment wetland if it, but not site A2, can be acquired, thereby precluding the implementation of Lagoon/Salt Marsh Restoration I.

Alternatives 5 and 6, which would occupy sites C2 and C3, respectively, are considered high priority. Both alternatives are equally attractive from a technical standpoint. Which alternative should be pursued depends on economics, logistics, and public preference vis-à-vis where a treatment wetland should be located (as well as plans for development of the different sites). The Civic Center site (C3) might be more reasonably priced than the "chili cook-off" site (C2) and might fit in better with the City of Malibu's zoning code and specific plan.

Finally, the realities of the availability of sites for water treatment should temper some of the recommendations made in Chapter 8. Even though treating creek flows is considered to be a high priority alternative, the reality is that there are few obvious locations to construct such a treatment wetland, particularly in the lagoon area. Even the areas that might be made available would most likely not be large enough to treat all creek flow. Thus, it may be difficult to implement this management alternative.

10.6. REFERENCES

Bell, G.P. 1995. Ecology and management of *Arundo donax*, and approaches to riparian habitat restoration in southern California. In J.H. Brock et al. (eds.). Plant invasions: studies from North America and Europe. Leiden, The Netherlands: Backhuys Publishers.

Manion, B.S. and J.H. Dillingham. 1989. Malibu Lagoon: a baseline ecological study. Report prepared for the County of Los Angeles and the California Department of Parks and Recreation. April, 1989.

Table 10-1. Contingencies related to implementation of different water resource management alternatives. Regardless of the approach chosen from this table, three alternatives (reduce nutrients in Tapia's discharge, eliminate Tapia's discharge during the dry season, and eliminate illicit discharges/connections) should be adopted.

	Implement BMPs	Reduce water use	Treat creek flows	Implement modified breaching	Divert excess creek flows offshore
1. Focus on source reduction. Flow reduction eliminates need for breaching	X	X			
2. Focus on source reduction. Flow reduction does not eliminate need for breaching.	X	X		X	
3. Focus on treatment.			X	X	
4. Focus on diversion.					X

Table 10-2. Contingencies related to implementing different wetland restoration alternatives.

	Lagoon/salt marsh restoration I	Salt marsh enhancement I	Salt marsh enhancement II	Freshwater wetland protection
1. Able to acquire A2 and A3 immediately.	X	X	X	X
2. Able to acquire A2 and A3 within reasonable period of time, but not immediately.				
(a) initial restoration		X		X
(b) later restoration	X			
3. Unable to acquire A2 and A3 within the reasonably foreseeable future.			X	X

Chapter 11: Concluding Perspective

Antony Orme

Chapter 11: Concluding Perspective

Antony Orme

The foregoing report has examined Lower Malibu Creek and its associated estuarine lagoon and barrier system from a physical and biological perspective with a view to environmental management and resource enhancement. A large body of data has been assembled and analyzed for the study period from August 1997 to August 1999. The analysis has also revealed the need for continued monitoring of the system in order to construct a more appropriate time series of variables for planning and management purposes, particularly with respect to water quality and public health issues.

In conclusion, a perspective is now presented on two principal themes, namely the constraints within which the present system functions and future objectives must be assessed; and the range of options available to those charged with the future planning and management of the system.

11.1 Constraints of the Malibu System

Lower Malibu Creek and its downstream estuarine lagoon and barrier system function at present within several constraints, some natural, some induced by human activity. A realistic awareness of these constraints is a necessary prerequisite for effective management and future planning of the entire basin. These constraints are explicitly discussed in the foregoing report and are outlined here for the purpose of evaluating the range of options available for management and planning.

- **Geology**

The 284-km^2 Malibu basin and adjacent coast exist within a tectonically unstable region characterized by massive transpression during Quaternary time and by episodic movement of the Malibu Coast fault zone which, from local evidence alone, must be considered potentially active. Future planning must accommodate the continued uplift of the Santa Monica Mountains, possible strike slip and reverse displacement in the fault zone, and subsidence at the coast. In human terms, uplift and subsidence are slow processes when averaged over Holocene time, but sudden co-seismic displacement of soft sediment and hard rock alike poses a potential hazard.

- **Mediterranean-type Climate**

The warm wet winters and warmer dry summers imposed by the strongly seasonal atmospheric circulation are felt throughout the Malibu basin, most significantly in hydrology and vegetation. Because predictability is not a strong feature of this climate, management and planning scenarios must accommodate high inter-annual and intra-annual variability in rain-producing storm events, exemplified by the very wet El Niño-related winter of 1997-98 and the unusually dry La Niña-related winter of 1998-99, and by variability within such winters.

- **Hydrology**

Responding to climatic forcing, surface flows, subsurface runoff and groundwater recharge also vary considerably within and between years. During wet periods, such as the 1997-98 winter, there is a high probability of frequent, high magnitude flood events characterized by high peak flows and steep rising and recession limbs to the hydrograph. During relatively dry years, with few if any large flood events, desiccation may be widespread and is translated into depletion of soil moisture and groundwater with implications for the physical and ecological character of the creek and its estuarine lagoon. Management and planning scenarios must accommodate this variability and further impacts on the hydrologic system imposed by human activity.

- **Marine environment**

The south-facing Malibu coast is relatively sheltered from most storm-wave activity but, when atmospheric conditions favor the onshore movement of storms from the southwest, storm waves can pose a hazard at the beach face. When storm waves are superimposed on super-elevated ocean levels and high tidal stages, as occurred during El Niño forcing in the 1982-83 winter but not in the El Niño event of 1997-98, serious beach erosion may occur. Southerly swells, most common during late summer, are generally constructive and, in the absence of river forcing, generally move the barrier beach onshore. Understanding of such forces should guide management of the estuarine lagoon and adjacent beaches.

- **Geomorphic Response**

The characteristic but highly variable watershed geomorphic cycle of drought, fire, mass movement, flood, erosion, sedimentation, and drought is strongly dependent on climate forcing through rainfall-runoff relationships.

With high tectonic relief, steep slopes, incompetent rocks, and flammable vegetation throughout much of the basin, this cycle is predictable in theory from year to year. In practice, the inter-annual variability of rainfall-runoff relationships makes prediction of future geomorphic responses difficult. However, high sediment delivery rates to downstream systems during and immediately after flood events are part of the natural system, accentuated by episodic fires within the basin and further complicated by human land-use practices. Such variability must be accommodated in management and planning scenarios.

- **Estuarine Lagoon**

Under natural conditions, estuarine lagoons like that at Malibu vary seasonally between open estuaries, restricted estuaries, and closed lagoons, the duration of each phase being a reflection of highly variable stream discharge and ocean forcing. Furthermore, over the longer term, such estuarine lagoons tend to fill with sediment, leaving just sufficient pathways for water and sediment fluxes during bankfull streamflow and tidal conditions. During floods, widespread but temporary inundation of adjacent wetlands is normal, with overbank deposition declining with distance away from flood pathways. Any barrier across the mouth of the system will likely be breached by flood events and/or by storm waves imposed on high tidal stages and superelevated ocean levels. Over the longer term, estuarine lagoons thus tend to be transient features, subject to erratic infilling until most of the sedimentary fill rises above normal tide and flood levels, although their existence may be prolonged by flushing during unusual flood events and by exceptional marine forcing. Any attempt to restore the natural system at Malibu must recognize the trend, even in the absence of human activity, towards net reduction of the estuarine-lagoon system over time.

- **Vegetation**

Despite the constraints of the Mediterranean-type climate on the hillslope vegetation within the Malibu basin, riparian habitats along lower Malibu Creek support unusually high levels of plant diversity. This is due to the availability of water adjacent to the creek, sufficient for plant growth and ecosystem services. However, the highly variable hydrology of the creek and estuarine lagoon imposes constraints on the biota, by generating rapid change during flood events and stress during prolonged drought. The ecosystem has also been significantly degraded over the period of human occupance and invaded by exotic plants, most notably in recent years by *Arundo donax* which accentuates fire incursions, reduces biodiversity, and alters hydrologic flows and sedimentation patterns.

- **Fauna**

The Malibu riparian and estuarine system also favors faunal biodiversity, subject under natural conditions to the opportunities and stresses imposed by streamflows, tidal forcing, erosion, sedimentation, and nutrient delivery and eutrophication. Because many species use the estuarine lagoon during at least part of their life cycle, the temperature and chemistry of these waters are especially important. Most organisms thrive within a preferred range of salinity, dissolved oxygen, ammonia, nitrate, nitrite and sulfide. These are subject to natural variation attributable to the frequency and magnitude of streamflows and ocean-water incursions, the latter especially dependent on the status of the barrier beach across the mouth of the estuarine lagoon. Management of faunal resources must accommodate both the preferred range of habitat conditions and recognize the system's inherent variability.

- **Eutrophication**

Eutrophication is a natural process within estuarine lagoons, such as that at Malibu where nutrient loading is favored by stream discharge during wet winters. The effect of these inputs, particularly of nitrogen and phosphorus, is accentuated by transformation of the estuary into a closed lagoon by barrier construction, usually during summer months following winter breaching. Even under natural conditions, some degree of algal bloom activity occurs typically within closed lagoons, normally but not exclusively during the summer. Some eutrophication also occurs, particularly in backwater areas, when the hydrologic flux and tidal forcing within the estuary are curtailed by natural constriction of its mouth. Under the influence of human activity, eutrophication is commonly accentuated.

- **Human Impacts**

The several forms of human impact that act as constraints on the Lower Malibu Creek and estuarine lagoon system may be grouped between those derived from the upper basin and those occurring within the lower basin.

The widespread urbanization of the upper basin over the past 40 years has generated inputs to the lower basin comprising increased storm runoff and increased low flows from impermeable surfaces, increased nutrient loading from land-use practices, increased contamination of waters from fecal waste, domestic wastewater, and petroleum hydrocarbons, and increased inputs of pathogenic protozoan parasites and enteric viruses, including *Giardia* and *Cryptosporidium*. The Tapia wastewater treatment plant is responsible for treating that portion of these inputs related to sewer systems in the upper basin and is a readily identifiable point source for certain outputs to the lower basin. However, there remains an unquantified but probably significant volume of material that enters the upper basin from direct surface and subsurface runoff, groundwater seepage, septic tank drainage, and aerosols. Increased soil erosion resulting from land clearance, especially during the construction phase, from conversion of native vegetation communities to grassland, and from changed frequencies of fire in the basin, also feed sediment downstream. Collectively these materials contribute to sedimentation and nutrient loading in the estuarine lagoon and to pathogen occurrences there and in the adjacent surf zone, although these effects may be offset to a greater or lesser degree by the flushing activity of winter stormflows and by dispersal by nearshore current systems.

The lower basin is very small in size and impact compared with the upper basin, the area below the confluence of Malibu Creek and Cold Creek amounting to only 4% of the entire basin. Here, the relatively natural system inherited from the nineteenth century was altered substantially during the twentieth century. Over the past 50 years in particular, it has experienced significant urbanization and other construction, much of it somewhat irrational, which have created major problems within the lowland and compounded those derived from the upper basin. Initially, ranching and cultivation significantly modified the area's ecology, replacing indigenous species with aggressive exotic plants and accelerating erosion and sediment delivery from grazed hillsides. Later, railroad and, more importantly, highway construction occurred with minimal concern for the drainage needs of the natural system. Development of the Malibu Colony from the 1920s onward has more or less stabilized most of the barrier beach. Provision of a commercial infrastructure infringes on normal functioning of the lowermost creek and estuarine lagoon. And, associated with both past and projected developments, a vast quantity of artificial fill has been placed across the lowland, in places 3 m thick, effectively constraining areas that at least seasonally once functioned as wetlands. Overall, there has been a significant net loss of the types of prime habitat normally associated with estuarine lagoons, while natural processes have been invited by human activity to operate within an increasingly constrained and dysfunctional system.

11.2 Options for the Future

Lower Malibu Creek and its estuarine lagoon are presently dysfunctional in as much as they are adjusting to processes whose nature, magnitude and frequency have been significantly modified by human activity over the past century. Any desire to modify the system as it presently exists, to develop the area further or to restore portions of the system to its former state, must be tempered by reality, by the economic, political and legal consequences of seeking to impose change. We, the scientists responsible for this report, can present appropriate information necessary to the decision-making processes and we can advise on management and restoration options, but we cannot make decisions that are correctly left, to other agencies. The concluding observations discussed below are presented in that context.

In essence there is a spectrum of options available for the future management of Lower Malibu Creek and its estuarine lagoon. This spectrum ranges from the "Do-Nothing Option" to the "Return-to-Nature Option", with a variety of intermediary alternatives.

♦ The Do-Nothing Option

This option implies that Lower Malibu Creek and its estuarine lagoon should be maintained with their present characteristics, exposed to physical, ecological and human forces presently operating within the basin, and subject to existing economic, political and legal controls over land-use policy. It also implies accepting a large number of past accomplishments such as the leaving the Rindge Dam in place, leaving fill plastered across much of the coastal basin, accepting widespread loss of prime habitat, and permitting continued inputs of deleterious waste to the system.

For we investigators to recommend the Do-Nothing Option for the entire system would be contrary to the purpose of our brief which was to submit recommendations for the future management and restoration of the system. It would also be contrary to informed common sense which commands that responsible agencies, landowners and informed citizenry should seek to enhance a system that has become peculiarly dysfunctional through human mismanagement.

This does not mean that the Do-Nothing Option is wholly irrelevant. There are some parts of the system where to interfere at this stage might only cause further negative impacts. For example, the provision of a permanent drainage outlet through the barrier, designed to alleviate ecological stress within the lagoon, when it exists, might aggravate problems of lagoon behavior, beach stability, nearshore ecology, and simple recreation. Such a structure could also be costly in construction and maintenance. There is a long litany of human interference at lagoon-beach-ocean interfaces that should serve to caution against tampering permanently with such systems.

♦ The Return-to-Nature Option

This option could be proposed by those who seek to eliminate human impacts from the entire area and return the system, at a minimum, to its status at the commencement of the historic period, locally a little more than 200 years ago. This implies removing the human population from the entire Malibu drainage basin. The mind boggles at the logistic, political, economic and legal implications of such a move. We investigators cannot entertain such an option.

However, as above, this does not mean that some return-to-nature is not locally possible with respect to specific areas or themes. For example, the elimination of alien plant species, especially the aggressive and troublesome *Arundo donax*, from the lower creek and estuarine lagoon could be undertaken in an attempt to return to a more natural riparian system. There are several other possibilities, some of which may seem attractive but carry many uncertainties. The removal of the Rindge Dam in Malibu Canyon would be an example of the uncertainty surrounding a return-to-nature, although we have not elaborated on this theme because another agency is presently undertaking such a study.

♦ The Do-Something Option

Most interested and informed parties would support some attempt to manage the Malibu system better, to enhance a decaying and dysfunctional ecosystem, and to improve the human experience of this valuable resource. But what? A conservationist might see innumerable opportunities to restore portions of the natural system. A land developer might see alternative opportunities for enhancing the human experience through further construction. Architects, engineers, recreationists, surfers and others all have a perspective, often several perspectives, on what might best be done.

For these reasons, we have presented in this report a reasoned series of management objectives and restoration scenarios, with an assessment of feasibility, cost, effectiveness and environmental impact. We recognize that some of these recommendations are controversial. To some they may not go far enough; to others they may go too far. They are provided to establish an intelligent forum for further debate based on our present scientific understanding of the system. We are not economists, politicians or lawyers, but scientists who have a sincere interest in discovery and applying those discoveries to useful purpose.

There is a real need for the Do-Something Option with respect to issues of water quality and public health. A stagnant lagoon replete with human waste and pathogens is not an attractive resource. There is also a real need for this option with respect to the vitality of the biological system generally, for habitat improvement and restoration. The existing wetland immediately west of the present lagoon, restored in 1983, is simply not functioning as such and should be redesigned to incorporate a more realistic ecosystem with improved water circulation, ideally in conjunction with adjacent former wetlands farther west. Such a proposal is scientifically feasible.

Could we go further? Yes and no! Individually, we scientists may have different perspectives as to what is feasible and, to a greater or lesser extent, we can all envisage and design improvements over the present system. From the hydrological perspective, for example, it is reasonable to suggest that all land from Malibu Creek west to Cross Creek Road, and from Pacific Coast Highway south to Malibu Colony Road, might be restored to become a more effective estuarine lagoon and creek system, with improved riparian and wetland habitat, and attractively landscaped buffer zones and recreational opportunities. Such a restoration would be even more effective if the Pacific Coast Highway bridge were lengthened at either end to provide for better water circulation. Such changes, however, ignore the costs involved in compensation and relocation, even if agreement on policy could be reached. Conversely, also from a hydrological viewpoint, it is less feasible to restore areas north of Pacific Coast Highway and west of Cross Creek Road to their quasi-natural state because, apart from existing infrastructure, water circulation would be truly problematic, even after the widespread artificial fill was removed. Prior to its partial development, the area was already well advanced towards supratidal habitat subject, as in March 1938, to occasional incursions of floodwaters. Road construction did much to impede drainage into and out of this area, indeed creating the small extant freshwater wetland north of the highway ramp. However, functioning coastal wetlands and estuarine lagoons need a reliable circulation of tidal waters and periodic flushing by tidal currents and streamflows if they are to provide prime habitat. Such circulation would be difficult to achieve without severe disruption of existing infrastructure, including the Pacific Coast Highway.

In retrospect, we scientists may understand how, when, and where Lower Malibu Creek and its estuarine lagoon system became dysfunctional. We may also understand the problems associated with the present system. But, for economic, political and legal reasons rather than scientific feasibility, it may be less easy to implement procedures for the effective management of the system and the restoration of selected components towards their former state. We present our observations with a humility that derives from our scientific understanding.