# MALIBU LAGOON
## RESTORATION & ENHANCEMENT PLAN

Prepared for

California State Coastal Conservancy

California State Department of Parks and Recreation

Prepared by: Moffatt & Nichol

In Association With: Heal the Bay

June 17, 2005 M&N File: 5381

# FINAL MALIBU LAGOON RESTORATION AND ENHANCEMENT PLAN

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**Moffatt & Nichol**

3780 Kilroy Airport Way, Suite 600

Long Beach, California 90806-2457

In Association With:

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# EXECUTIVE SUMMARY

This Malibu Lagoon Restoration and Enhancement Plan presents detailed information to implement and monitor the preferred restoration alternative. The preferred alternative is Alternative 1.5, as specified in the Malibu Lagoon Feasibility Study Final Alternatives Analysis. Implementation details are provided in the form of plans for water management, habitat management, access, and monitoring to facilitate implementation of the monitoring program and subsequent environmental review and permitting. This document is intended to serve as a "living" document that is regularly updated as monitoring, planning and phased implementation proceed and new information is generated. It may be continually updated into perpetuity as monitoring and adaptive management occur.

Significant impairments currently exist at the lagoon primarily due to uncontrolled inflow of water from outside of its boundaries contributing pollutants and nutrients to the system, and poor circulation within its boundaries. The water management plan outlines restoration measures intended to control local outside inputs, such as storm drainage from the parking lot and irrigation from perimeter areas, as well as promote circulation of water within the lagoon. Storm drainage is to be managed by increasing percolation and drainage away from the lagoon. Measures include sloping the parking lot away from the lagoon to drain toward Pacific Coast Highway, using permeable pavement at the parking lot and entrance roads and vegetated swales along the parking lot perimeter. It may also be possible to divert and treat runoff by connecting to the City of Malibu storm drain force main to be installed in the near future. Circulation will be enhanced by reconfiguring the west lagoon to promote maximum tidal circulation during open conditions and maximize wind driven circulation during closed conditions. Circulation will be assessed by continuously monitoring and evaluating water movement within the lagoon to identify needed adaptive management improvements. Open and closed lagoon conditions are addressed, and the use of continuously monitoring gauges is specified. The plan includes performance criteria and adaptive management options so the plan can be revised if needed to ensure long-term restoration integrity and success.

Malibu Lagoon also experiences degraded habitat and invasion by non-native species due to anthropogenic disturbance and encroachment on the sensitive ecosystem of plants and animals. A Habitat Plan is provided specifying implementation practices and maintenance requirements for enhancement and management of the restored ecosystem. The plan defines vegetative communities that will be established and/or enhanced as part of the restoration process. Details are provided for slopes and drainage, topsoil salvage and management, planting and establishment, and maintenance for short- and long-term conditions. The plan utilizes an adaptive management framework to ensure long-term restoration integrity and success.

A Public Access, Education and Interpretation Plan is provided including a list of access options and creative ideas for implementation and management to enhance the educational and recreational user experience as determined from stakeholder input. The plan specifies a perimeter access plan at grade along the western edge of the western arms at the location of the existing vehicle access route. Multiple interpretive nodes and areas suitable for educational programs are identified, and multiple length interpretive loops are provided to allow for a variation of docent led activities with exposure to multiple habitat types. A significant element of the plan is the relocated parking area, moved back and elevated to a position along the Pacific Coast Highway to be acoustically and visually buffered by a proposed extension of the “Adamson wall.” Amenities of the access plan consist of a non-intrusion platform near the parking lot and Pacific Coast Highway, a view and access dock at the Adamson House, and a combination viewing and interpretive area called the “thick wall and duck blind” near the southwest perimeter to enable passive interaction without disturbance.

A detailed monitoring plan is provided setting out a program of field observations and monitoring to be undertaken prior to, during and following implementation. Specific monitoring tasks and decision-points are specified to feed into an adaptive management framework to ensure long-term restoration integrity and success. The Monitoring Plan will be used to assess floral and faunal assemblages, protect existing habitat, minimize impacts during restoration activities and document resource changes for application in future adaptive management programs. To achieve these objectives, the Monitoring Plan includes provisions for monitoring physical, chemical, and biological components. Required monitoring equipment, manpower, costs and schedules are provided in matrices at the end of this report.

Future tasks to be completed for restoration include monitoring, environmental review, permitting, final restoration design and phased restoration implementation. Specific stages consist of:

- Pre-restoration monitoring;
- Environmental review that will include additional data collection (includes public comments and hearings);
- Permitting by appropriate resource agencies (includes public comments);
- Final design for the restoration program that will likely include additional data collection and analyses;
- Phased restoration implementation; and
- On-going monitoring and adaptive management activities.

# 1.0 INTRODUCTION

Southern California has lost approximately 95% of its historic coastal wetlands. Previously viewed as poor quality habitats, the ecological importance of coastal estuaries and wetlands has recently been recognized. The highly urban setting of Southern California significantly limits coastal wetland creation, restoration and enhancement opportunities and Malibu Lagoon represents a unique opportunity to restore a valuable coastal wetland. The Malibu Lagoon Restoration and Enhancement Plan presents a comprehensive approach to restore and enhance the ecological structure and function of Malibu Lagoon, as well as to enhance the visitor's experience through improvements to access and interpretation. This plan is the result of two years of planning, design and evaluation and represents ecological solutions for this unique and valuable ecosystem. The Lagoon Technical Advisory Committee, California State Department of Parks and Recreation (State Parks), State Coastal Conservancy, and Lagoon Restoration Working Group have worked together to design a restoration alternative to restore the biological and physical functions to the lagoon while minimizing impacts to the existing system. Details of the restoration are described in this Restoration and Enhancement Plan that includes plans for management of water, habitat, and access, as well as a comprehensive monitoring plan.

## 1.1 BACKGROUND

Malibu Lagoon is a 31-acre shallow water embayment occurring at the terminus of the Malibu Creek Watershed, the second largest watershed draining into Santa Monica Bay. Malibu Lagoon empties into the Pacific Ocean at world famous Malibu Surfrider Beach. World renowned as a surfing and recreational destination, Surfrider Beach receives approximately 1.5 million visitors every year.

Anthropogenic activities have significantly altered the physical configuration of Malibu Lagoon. The existing lagoon is only a very small portion of its historic area. Urban encroachment has occurred on all sides. The Pacific Coast Highway (PCH) Bridge has dissected and constricted the lagoon surface area, and a significant portion of the once low-lying tidally influenced areas near the mouth of the Malibu Creek were filled in the 1940's and 50's.. By the late 1970's the site was completely filled and housed two baseball fields. Urbanization upstream in the Malibu Creek Watershed has increased the volume of water transported into the lagoon and urban pollution has significantly diminished the quality of that water through inputs of nutrients, sediments, and pollutants.

In 1983, the California Department of Parks and Recreation initiated a restoration of the lagoon. The restoration involved the excavation of three distinct channels (designated as A, B and C Channels) in the western portion of the lagoon, oriented perpendicular to the natural flow path of the Creek as shown in Figure 1. The channels were seeded with salt marsh plants and series of boardwalks were created to allow access by the public. In 1996, the California Department of Transportation (Caltrans) funded a successful restoration program to mitigate for impacts incurred during the Malibu Lagoon Bridge Replacement Project. Specific restoration measures, coordinated by the Resource Conservation District of the Santa Monica Mountains and (State Parks, included the very successful tidewater goby habitat enhancement project and the


| **Final Malibu Lagoon Restoration and Enhancement Plan** | Existing Lagoon Conditions | **Figure 1** |
|---|---|---|

revegetation of areas disturbed by construction activities with native species, including extensive removal of non-natives.

Despite these restoration efforts, the ecosystem of Malibu Lagoon remains degraded and in the late 1990's the California State Coastal Conservancy funded a study by UCLA (Ambrose and Orme 2000) to: 1) identify impacts to the ecological health and water quality in the lower creek and lagoon ecosystems and 2) provide recommendations on how to best manage these impacts. The study produced three categories of recommendations: 1) the installation of best management practices (BMPs) to improve water quality; 2) the creation of treatment wetlands to enhance the water quality of stormwater runoff; and 3) restoration of existing wetland habitat to enhance their ecological functioning.

Following a year long facilitation process, the restoration of the existing lagoon area and small parcel on the east side of the creek adjacent to the Adamson House was identified as the highest priority Short Term project by the Malibu Lagoon Task Force.

The restoration goals for Malibu Lagoon as identified by the Malibu Lagoon Task Force consist of:

- Salt Marsh Enhancement at Site A1 (West Arms)
    - Increase tidal flushing
    - Improve water circulation
    - Increase holding capacity
    - Reduce predator encroachment

- East Lagoon Restoration at Site A4 (Adjacent to Adamson House)
    - Regrade to restore typical salt marsh hydrology
    - Create nesting island for least terns and Snowy Plovers
    - Create channel connections to the lagoon

Based on the results of the Final Alternatives Analysis for the Malibu Lagoon Restoration Feasibility Study, the Lagoon Technical Advisory Committee, State Parks, and the State Coastal Conservancy, with substantial input from the Lagoon Restoration Working Group, recommend Alternative 1.5, the Modified Restore and Enhance Alternative shown in Figure 2, as the preferred restoration design for Malibu Lagoon. This restoration alternative is expected to most readily achieve the goals of restoration while introducing the least amount of impact to the existing lagoon ecosystem. Restoration efforts may be performed in succinct stages to minimize impacts to the existing wetland habitat and to provide refuge for species displaced by construction activities. A phased restoration implementation and long-term adaptive management approach will be implemented to maximize the ecosystem benefits of this project.


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April 2005
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| Final Malibu Lagoon Restoration and Enhancement Plan | Alternative 1.5 Concept Plan | Figure 2 |
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Details of Alternative 1.5 and how this design is best suited to meet the goals of the restoration program are available in the Malibu Lagoon Restoration Feasibility Study Final Alternatives Analysis. This document is available online at http://www.healthebay.org/currentissues/mlhep/default.asp. Major components of this design are described below.

Parking Lot and Staging Lawn

The existing parking lot will be relocated to the north and west to be adjacent to PCH, the current parking lot entrance from PCH and Cross Creek Road, and the current western property line. The new parking lot and staging area will be created with runoff treatment controls, including permeable pavement or other similar substances, appropriate native vegetation, and will include a staging area to enhance existing educational and recreational uses of the site. The new parking lot will maximize the use of Best Management Practices (BMP) to minimize or eliminate runoff to enhance water quality in the Lagoon. The current number of parking spaces will remain and new interpretative displays and panels will be installed.

Main Channel

The Main Channel will remain substantially "as is." The western edge of the main lagoon at the interface with the western arms complex will be reconfigured in the form of a naturalized slope to provide a degree of separation between the main lagoon and west channel system. All efforts should be made to allow the barrier berm to open and close naturally. Driving across the berm should be minimized and it is recommended that management of a section of the lagoon side of the berm be maintained to protect avian species from anthropogenic impacts during closed conditions.

East (A4)

The existing boat house channel will be deepened and recontoured to create a new avian island along the eastern bank of the Adamson House grounds. This work is expected to have a minimum impact on the existing habitat, will create additional mudflat habitat and promote additional water circulation around the new island.

West Lagoon Complex

A new channel will be created along the southern edge of the west lagoon to create a single main entrance and exit for water conveyed into and out of the west lagoon. This channel may be optimized to overlie the existing "C" channel to minimize the impact to existing habitat and will be designed to enable a future connection to the "golf course" parcel located adjacent and to the west of the lagoon. A naturalized slope separating the main channel from the west channel, with minimum elevation change, will be created using lagoon materials displaced by dredging of the new main west channel and those that currently exist along this edge. The main west channel will possess a natural dendritic planform to maximize tidally-influenced water inundation to the west channel and its fingers. Isolated bird islands will be created to provide refuge for foraging and/or loafing birds. These islands will be optimized to maximize the use of the existing wetland habitat to minimize impacts to the existing system.

## 1.2 PURPOSE OF THIS DOCUMENT

The Restoration and Enhancement plan is developed specific to the preferred alternative to facilitate the initiation of monitoring, environmental review, permitting, final restoration design and phased restoration implementation. These specific stages will include:

- Pre-restoration monitoring;
- Environmental review that will include additional data collection (includes public comments and hearings);
- Permitting by appropriate resource agencies and responsible permitting agencies (includes public comments);
- Final design for the restoration program that will likely include additional data collection and analyses;
- Phased restoration implementation; and
- On-going monitoring.

Under a Proposition 13 grant from the State Water Resources Control Board, the State Coastal Conservancy has secured funds to complete the initial stages of the project. The Resource Conservation District of the Santa Monica Mountains has been contracted to administer the project on behalf of State Parks, and will continue to work closely with the State Coastal Conservancy, the Lagoon Technical Advisory Committee and the Lagoon Restoration Working Group. The restoration design will evolve and be further optimized as it proceeds through the subsequent stages of permitting, final design, and phased implementation. The public will have opportunities to comment and provide input throughout the permitting and restoration design optimization stages.

To efficiently achieve the stages listed above, the Malibu Lagoon Restoration and Enhancement Plan specifies the following components:

1. Water Management Plan
    - A water management plan is specified to manage drainage from the parking lot and public use areas to restored habitat areas. It includes Best Management Practices to enhance water quality in the lagoon.
    - Circulation of water within the lagoon will be closely monitored and evaluated. The Water Management Plan includes performance criteria and adaptive management options so the plan can be revised if needed to ensure long-term restoration integrity and success.
2. Habitat Plan - A detailed habitat enhancement and management plan specifies implementation practices and maintenance requirements. The Habitat Plan defines vegetative communities that will be established or enhanced as part of the restoration process. This plan addresses the establishment or enhancement of habitat for rare, endangered and regionally uncommon plants and animals that are appropriate for this site

and uses an adaptive management framework to ensure long-term restoration integrity and success.

3. Access, Education, and Interpretation Plan - A public access, education and interpretation plan is provided including a list of access options and creative ideas for implementation and management to enhance the educational and recreational user experience. The access plan considers stakeholder input, educational and recreational users of the site.

4. Monitoring Plan - A detailed monitoring plan is provided setting out a program of field observations and monitoring to be undertaken prior to, during and following implementation. Specific monitoring tasks and decision-points are specified to feed into an adaptive management framework to ensure long-term restoration integrity and success. The Monitoring Plan includes:
   - Habitat – flora and fauna;
   - Water quality – during both open and closed conditions;
   - Sediment Quality – sampling of grain size; and
   - Bathymetry – Lagoon topography.

# 2.0 WATER MANAGEMENT PLAN

The objectives of the water management plan are to eliminate all point source discharges to the lagoon to maximize lagoon water quality, and to improve and maintain circulation within the lagoon under all conditions. Direct surface discharges to the lagoon can occur from storm water and from irrigation. Circulation is influenced by hydraulic conditions at the lagoon. These processes are discussed below.

As this project site is high-profile, it is an opportunity to provide a widely-viewed water quality demonstration project for the public. The experience and information gained from this demonstration project site (i.e., in the form of tours and available educational materials) can be used by the fields of education, public works, restoration, and others for improvement of water quality at other locations.

## 2.1 STORM WATER MANAGEMENT

In the wet season, storm water runs off the existing surface of the parking lot, entry road, turf area and kiosk, and eventually flows toward the lagoon, as shown in Figure 3. Storm water can be better managed to minimize or even eliminate direct runoff to the lagoon. Several suggestions to improve storm water management are provided below. For each item below, water quality benefits are increased percolation of storm drainage and possibly more efficient conveyance to a drainage system to the future City treatment plant, both resulting in less direct runoff to the lagoon. Less runoff will reduce the inputs of pollutants to the lagoon such as metals, bacteria, total petroleum hydrocarbons, nutrients, oils and grease, and possibly others thereby maintaining higher lagoon water quality than currently exists.

### *2.1.1 Increased Permeable Surfaces*

Permeable Pavement

Permeable pavement is available for constructing a parking lot and entrance road that are more permeable than the asphalt and concrete that presently exist at the site. Figure 4 shows the recommended location for permeable pavement. Materials used to create this feature are permeable interlocking concrete pavements. These surfaces are constructed of individual paver stones interlocked, and shaped to provide gaps to allow infiltration between the stones into a porous base.

The paver stones are placed over an 8 inch thick base layer of ½ inch crushed aggregate, under a 1 inch thick setting bed layer of 3/8 inch crushed rock chips. The crushed rock chips are also poured into the gaps between paving stones after the stones are laid. Storm water infiltrates through the gaps in the surface layer, and percolates through the coarse bedding material into the underlying soil and eventually the groundwater zone as shown generically in Figure 5, and for site-specific conditions in Figure 6.

One type of stones are manufactured by a company named Uni Eco-Stone, and sold locally by Acker Stone in Ontario, California. Other types of stones were investigated but this particular


| Final Malibu Lagoon Restoration and Enhancement Plan | Conceptual Area of Permeable Pavement | Figure 4 |
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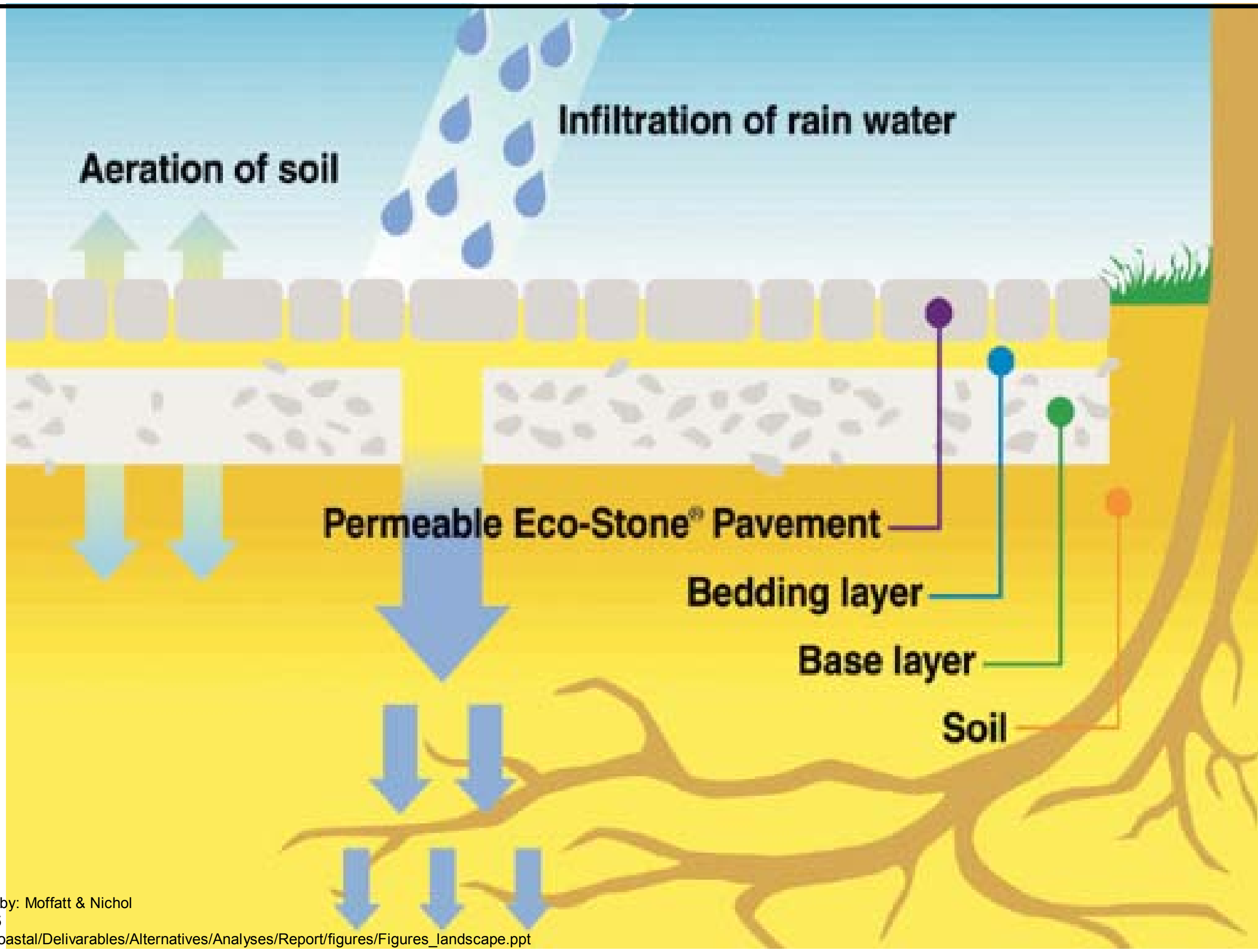


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| Final Malibu Lagoon Restoration and Enhancement Plan | Concept Cross-Section of Permeable Pavement | Figure 5 |
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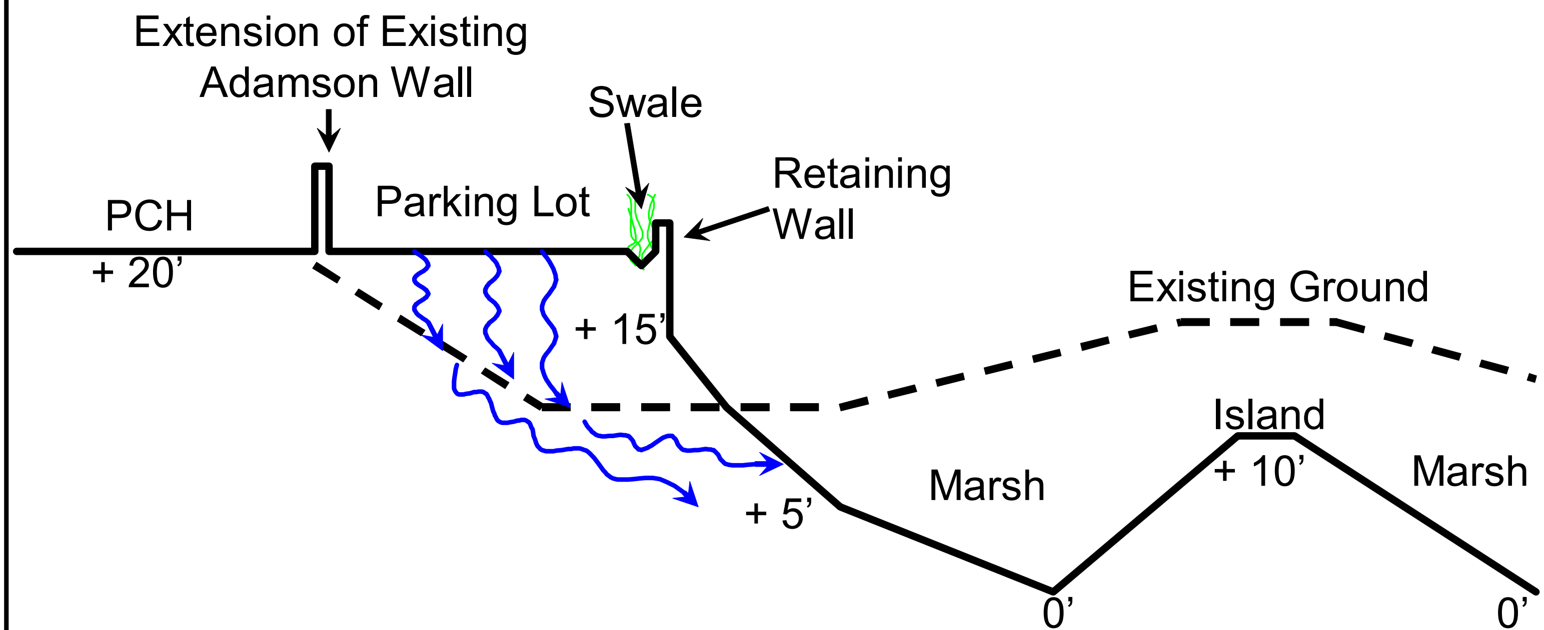


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| **Final Malibu Lagoon Restoration and Enhancement Plan** | Proposed Parking Lot Cross-Section Looking East | **Figure 6** |
|---|---|---|

brand was most suitable for parking areas and is able to support the weight of buses and large vehicles. Guidelines for use of this material are provided in Appendix A.

The performance of the permeable pavement also depends on the quality of construction, and the extent of maintenance. Maintenance is required to reduce clogging of the coarse rock bed between and below the pavers by regular street sweeping. Sweeping at a frequency of every six months will prolong the life of the pavement.

The permeable pavement can percolate significant storms, depending on storm intensity. The manufacturer indicates that severe storms of up to the 50-year storm can be captured. Assuming that storm intensities will likely exceed the infiltration capacity of the permeable surface, additional measures to capture storm water are addressed below. The life of the permeable pavement is estimated to be approximately 15 years, based on construction, maintenance, and environmental conditions. When they no longer become effective, they should be entirely replaced rather than repaired.

Permeable pavements cost approximately double the cost of standard asphalt concrete parking lot surfaces. Standard parking cost $5 per square foot to construct, and permeable pavement areas cost $10 per square foot maximum to construct. The new parking lot at Malibu Lagoon as shown in Alternative 1.5 may be approximately 1 acre in area, or 45,000 square feet. Thus the cost to construct a standard new parking lot is approximately $225,000 while the cost to construct a permeable pavement parking lot is approximately $450,000 as shown in Table 1.

**Table 1 - Malibu Parking Lot Construction Material Options**

| CONSTRUCTION MATERIAL OPTIONS | UNIT COST PER SQUARE FOOT | AREA IN SQUARE FEET | TOTAL CONSTRUCTION COST IN 2005 DOLLARS |
|---|---|---|---|
| Standard Asphalt/Concrete | $5.00 | 45,000 | $250,000 |
| Permeable Pavers | $10.00 | 45,000 | $450,000 |

Drainage Swales

Another method of controlling and filtering drainage is use of drainage swales to promote infiltration and provide for additional habitat at the site. Drainage swales can be installed along the perimeter of hardscape areas such as the parking lot to intercept surface runoff that is not infiltrated into the parking lot.

A concept layout for swales is shown in Figures 7 and 8. The conceptual cross-section of the swale is shown in Figure 9, and is 3 feet deep and 9 feet wide with in a V-shaped cross-section. The side slopes are at 33 degrees, with changes of 1 foot vertically to 1.5 feet horizontally. These dimensions are applicable to future bioswales at the site for scenarios of the parking with and without permeable pavement. The bioswales are beneficial in either case and do not occupy a significant amount of surface area so they do not preclude other hard- or softscape from being installed at the parking lot area. The two layouts for bioswales depend on the slope of the parking lot surface. Swale scenario 1 is a relatively flat parking lot or one sloping slightly downward toward the south (lagoon-side) outfitted with swales running along the south and west perimeters of the site and within the turnabout. Swale scenario 2 is a parking lot sloping downward to the north away from the lagoon. The swales would be located along the north lot edge and within the turnabout.

The drainage swales are intended to be large enough to hold runoff from the 100-year storm before it begins to overflow. Water retained within the swales would gradually percolate. Habitat formed within the swales would be designed to be complementary to the wetland. Specific vegetation types will be determined upon final swale design.

Both swales and permeable pavement would be used in compliment with permeable surfaces around the parking area consisting of decomposed granite and native California bunchgrasses, rather than hardscape access areas such as sidewalks and turf as exists today. Figure 10 shows possible locations of these softscape features.

The costs of swales are less expensive than parking lot hardscape, as the cost is mainly attributed to earthwork and landscaping. Maintenance is required for weeding, removal of exotic specifies, and replanting of dead natives. Overall the costs of swales should be less than parking area hardscape (on the order of $10,000 or less to install) and the benefits may be greater as both infiltration and habitat are enhanced.

### *2.1.2 Redirection of Storm Water Away From the Lagoon*

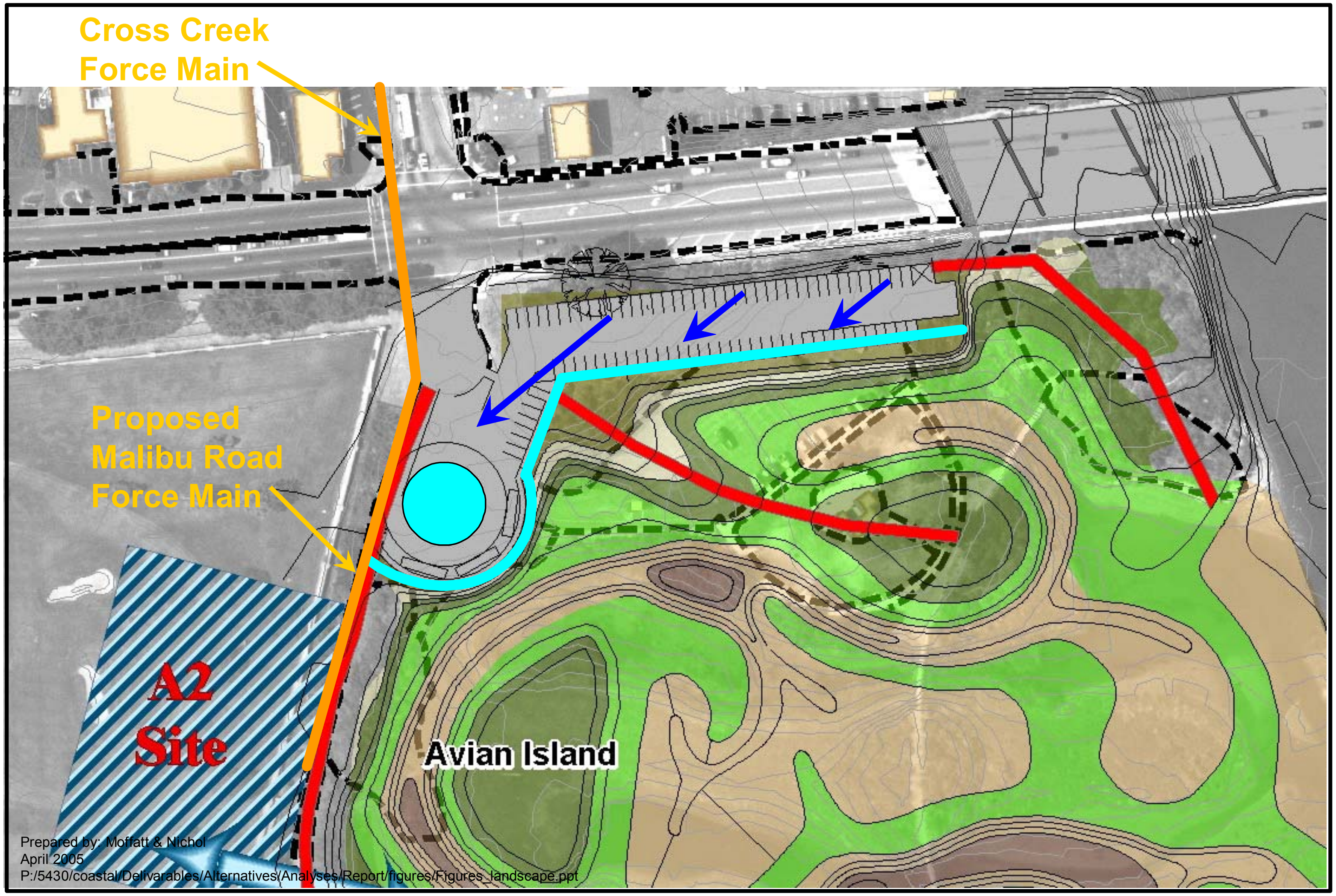
In addition to creating greater impervious surfaces for storm water management, redirecting storm water away from the lagoon and toward other appropriate drainage facilities is an option to supplement the installation of permeable surfaces. Two options are described below and many more could be conceived.

<u>Slope the Parking Lot Toward PCH</u>

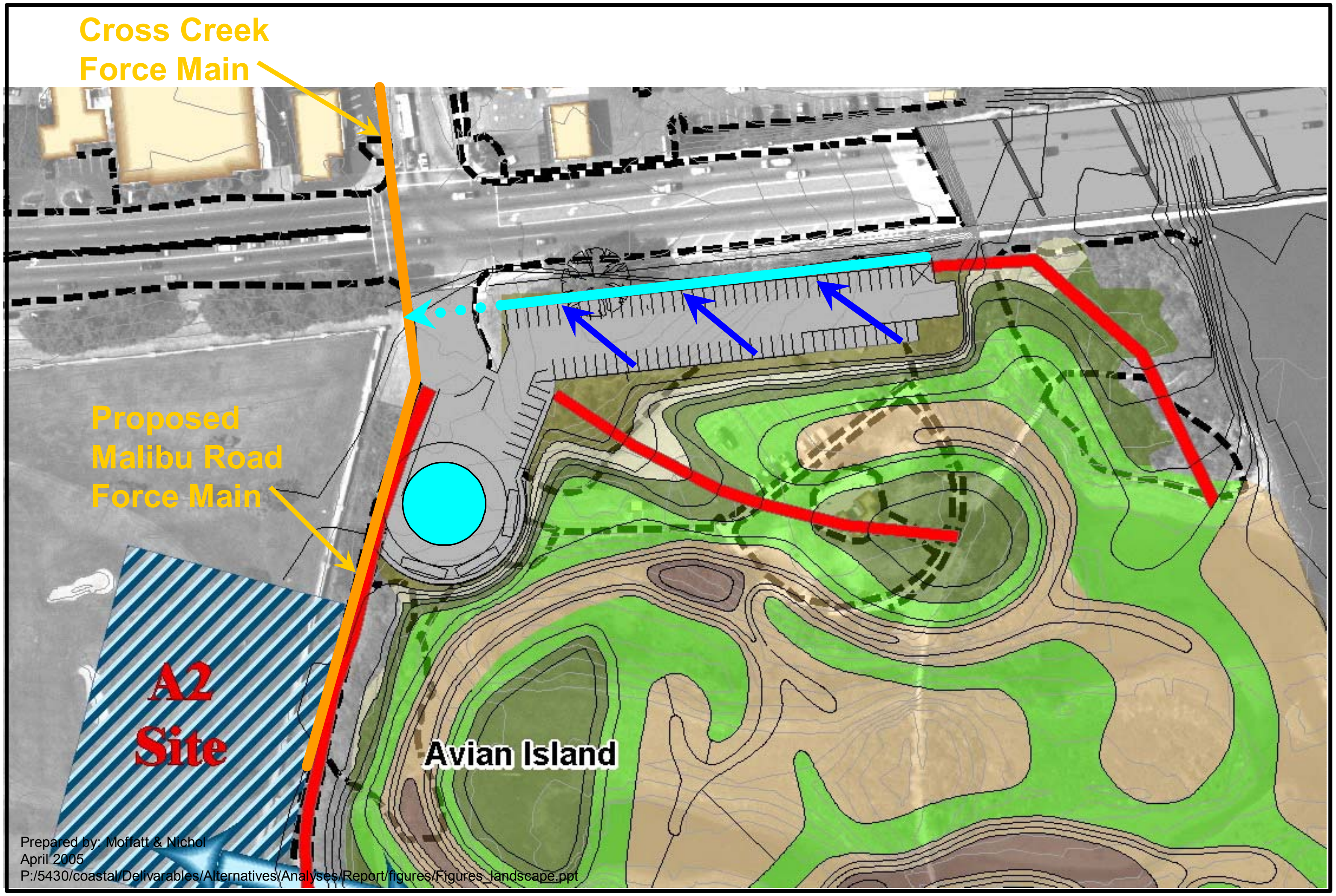
The lagoon State Park parking lot could be sloped downward toward the north to promote drainage away from the lagoon rather than toward the lagoon as presently occurs. As shown in Figure 8, such drainage could be conveyed to a swale or other conveyance feature (trench or pipe) and conveyed farther away from the lagoon.

<u>Route Parking Lot Drainage to the Future City Drainage System</u>

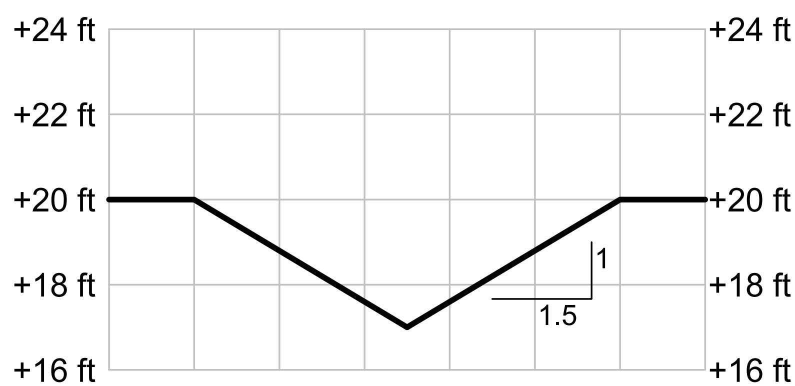
Another option for managing storm water at the State Park is to route drainage westward toward the collection sump for the City’s future force main line along Malibu Road. The City intends to install a treatment plant for storm water and dry weather flow near Cross Creek Road and Civic Center Way, with a force main line pumping water from near the Malibu Colony north to the plant, bypassing the State Park parking lot. Drainage off the future parking lot could be routed to the sump near Malibu Colony at the south end of the future force main line, and then be included in water pumped upstream toward the future treatment plant. The City indicated sufficient capacity exists to accommodate the parking lot drainage (Yugall Lall, Personal Communication, May 13, 2005)




**Final Malibu Lagoon Restoration and Enhancement Plan** | Concept Drainage Bioswales at South Parking Lot Perimeter | **Figure 7**




**Final Malibu Lagoon Restoration and Enhancement Plan** | Concept Drainage Bioswale at North Parking Lot Perimeter | **Figure 8**

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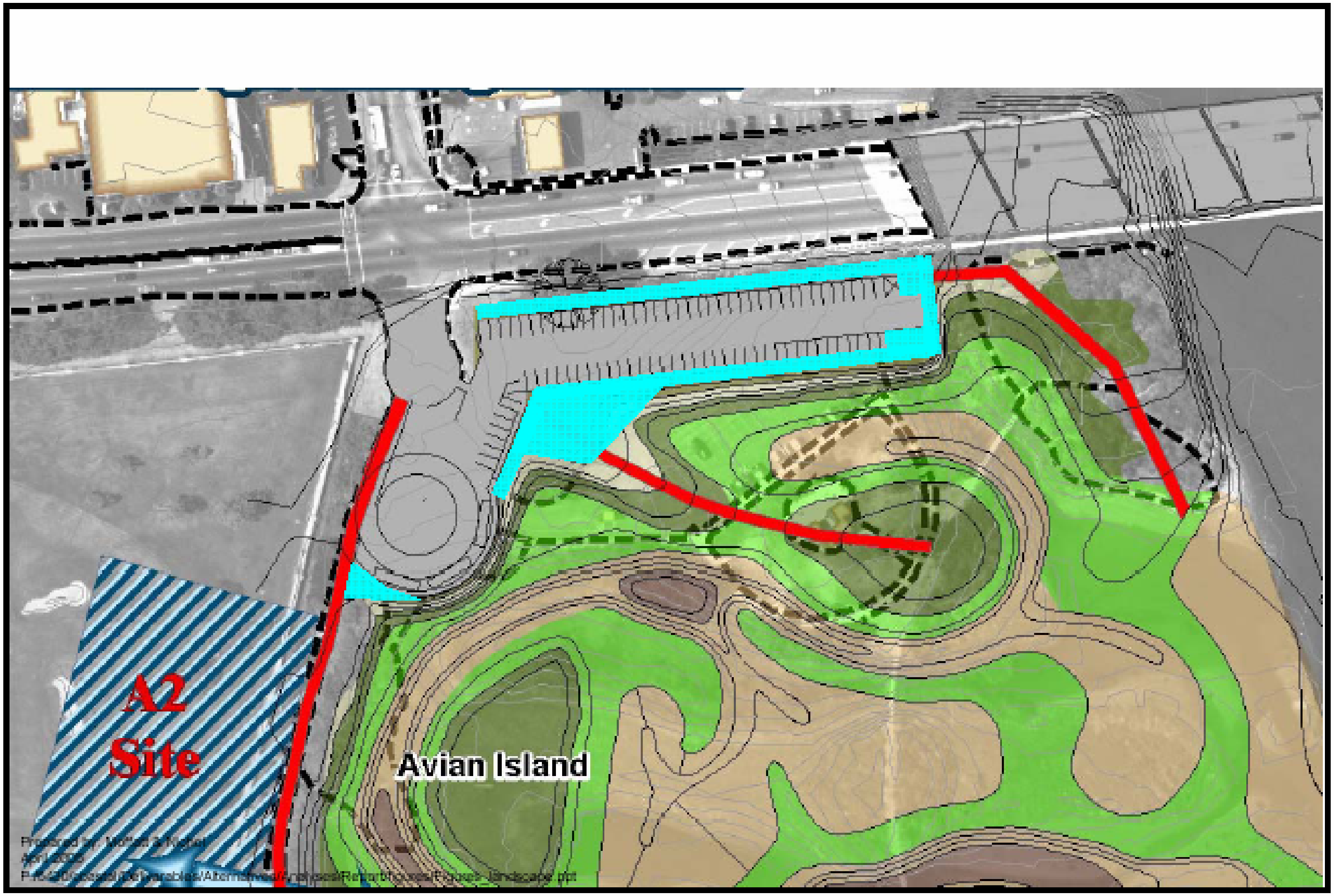
| **Final Malibu Lagoon Restoration and Enhancement Plan** | Cross-Section of Concept Bioswale | **Figure 9** |




Final Malibu Lagoon Restoration and Enhancement Plan

Softscape Areas of Decomposed Granite and Native Growth

Figure 10

## 2.2 IRRIGATION

Nuisance water can also be inadvertently contributed to the lagoon by temporary and permanent irrigation of plantings at landscaped areas. As a natural habitat area, permanent irrigation should not be installed or used ever. In some instances supplemental irrigation is warranted to assist in the establishment of plants. The form of supplemental irrigation may be passive or active depending upon the final restoration design, seasonality of restoration work, and extent of habitat and anticipated duration of required irrigation. Active irrigation would include the implementation of a temporary irrigation system (overhead spray, drip, tended hand watering, or a combination of these methods) to assist in establishment of plant materials. For a passive system, a hydrophilic amendment would be used in the planting soils or as a binding agent for seed. Given the coastal location of the project site, coastal fog and high humidity provides adequate atmospheric moisture to support seed germination and surface soil moisture levels necessary for plant establishment during most portions of the year. This may be a viable alternative to installation of an irrigation system at the site. Use of turf at the site is also not recommended.

1. All temporary irrigation must be installed in shallow buried areas along the ground surface to avoid disturbance to wetland habitat yet still remain hidden.
2. Temporary irrigation should be automated, utilizing control clocks of current technology with multiple program and cycle features with battery backups.
3. No manual unattended irrigation should occur either with portable irrigation heads or manual control valves, except where a manual control valve also includes an automatic shut off timing device. Watering by hand-held hose should be permitted in all areas.
4. Temporary irrigation should include the following equipment:
    a. High flow shut off valve or breakaway shut off valves;
    b. Automatic Irrigation system;
    c. Rain shut-off device;
    d. Anti-drain valves to eliminate low head drainage; and
    e. Master control valve located at the point of connection.
5. Approved backflow prevention devices should be required for all new temporary irrigation systems.
6. Minimize or eliminate the use of herbicides and pesticides to protect habitat. An integrated pest management (IPM) program should be developed and implemented to wholistically address the problems of pests and weeds.
7. Only apply pesticides/herbicides, if needed, consistent with State-wide policy regarding pest control in all State parks. This may be found on the State intranet website http://search.parks.ca.gov/ and following on to "Department Policies" and then on to DOM (Department Operations Manual), and then to section 0700 "Pest Control."

8. All temporary irrigation must be inspected regularly to ensure appropriate function.
9. No reclaimed water may be used for temporary irrigation within the wetland.
10. Consider applying salt water irrigation to salt-tolerant habitat areas susceptible to weed infestation by non salt-tolerant weed species.
11. A contingency irrigation plan should be prepared prior to revegetation activities to facilitate rapid installation if the need arises.

## 2.3 CIRCULATION

Water within the lagoon needs to circulate to remain of suitable quality for use as habitat. Improvements to circulation from existing conditions are an important project objective and this plan sets forth steps to verify that circulation has improved and signals to indicate the need for system modifications to maintain improved conditions. Target circulation improvements are detailed for winter, summer open and closed lagoon conditions. Verification of circulation improvements requires monitoring that is addressed in this section, and in more detail in Section 5.0 of this document. The monitoring parameters specifically address the spatial and temporal variability of circulation within the lagoon and provide performance targets to facilitate future adaptive management modifications.

### *2.3.1 Open Conditions*

Circulation improvement under open lagoon conditions will require comparison of existing conditions with expected restored conditions. There are two main approaches to this that can be implemented separately or together, depending on the desires of the landowner. One approach is to quantify tidal flushing and resulting water quality conditions. Another approach is to directly measure flow velocity continuously. Both approaches are described below.

<u>Quantify Tidal Flushing and Resulting Water Quality</u>

The effort to quantify tidal flushing and resulting water quality will directly relate circulation with water quality, and require more intensive analyses. This method consists of the following steps outlined below.

1. Create a rating curve that provides an estimate of the water depth to lagoon volume. This can be done using depth data from a stationary data logger (suggested to be the YSI 600XL or equivalent) at the western arms and the main lagoon, and using topography/bathymetry data recorded as periodic surveys of the lagoon. Both the use of the data loggers and surveys are addressed in more detail in Section 5.0, Monitoring Plan, of this document.
2. Create a simple water budget from the rating curve and other data (described below) that yields the volume of daily tidal exchange and the flow velocity. Daily tidal volume exchange indicates the rate of tidal flushing and water residence time in the lagoon. This volume of tidal turnover can be estimated for existing conditions and then compared to restored conditions to quantify the change in water turnover and relative age. Tidal flow velocity is a direct indicator of the scour of the tidal channels and resulting grain size. One project objective is to increase bed scour and grain size to reduce the sequestering of

nutrients and therefore improve water quality. The water budget and pertinent parameters can be estimated using the approach below.

- Track water volume changes over time (using depth and topography/bathymetry data) and plot relative to the tidal cycle at the mouth (using a tidal time series program such as WXTides or an equivalent).
- Estimate flow velocities at certain locations using bathymetric channel cross-section data and volume changes over time from the real time water depth data. Alternatively, tidal flow velocities can be measured continuously using a meter located within the western arm. The meter could be one of several available from Sontec (see Appendix B for more information) or an equivalent supplier and described in more detail in Section 5.0. The advantage to their use is that flow velocities would be provided continuously and not have to be calculated by staff but would be directly provided by the gage, and that data are improved in quality compared to what can be estimated indirectly from other data. The drawback to their use is their relatively high cost, and the problem of securing the gage from theft, damage, and vandalism in this exposed public location. The gage can be insured against damage and theft, and could likely be secured and camouflaged to a certain extent to reduce public interest. The gage would also require regular monthly maintenance and data management. Other gages were investigated such as those by Marsh-McBirney but that supplier indicated they are not continuously recording gages and may not meet the measurement objectives, but could be used for periodic spot checks of velocity to supplement any calculations made by staff. Their gage information is in Appendix C.

3. Identify the extent of penetration of saline, oxygenated, and cooler (oceanic) water exchange in the western arm sites at various tide levels using water quality data loggers such as the YSI 600XL or equivalent described in Section 5.0.
4. Quantify the critical tidal elevation that induces flushing of the western restored areas and the frequency of that tidal elevation.
5. Determine the acceptability of the flushing condition based on water quality data collected as part of the monitoring program specified in Section 5.0.
6. Install the monitoring system at least 1 year prior to restoration activities for data to compare to post-restoration conditions. Alternatively, the system could be installed after restoration, and conditions in restored areas compared to those in the main channel for the same time periods to enable inferences of acceptable differences between the two locations. This second option is less desirable than the option of installing a system prior to restoration.

#### *2.3.2 Closed Conditions*

Circulation under closed lagoon conditions will be more difficult to estimate due to the relatively low magnitude velocity of water motion. Circulation can be measured directly by various methods, or ascertained indirectly by measuring water quality parameters that are a function of circulation and other variables.

Direct measurement of water movement can be measured using either a stationary continuously-reading velocity gage or hand-held instruments or both, or visually estimated using floats (such as fruit drops done for the Malibu Lagoon Feasibility Study). Circulation will be very slow and thus any sensor used will have to be very sensitive to make accurate measurements.

A suitable stationary sensor would be one of those offered by Sontec and described in Section 5.0 and Appendix B. It should be mounted within a suitable location within the western arms, such as the location used to estimate tidal flow velocities under open conditions. The initial location considered suitable is near the downstream end of existing C Channel. This location will also be the similar downstream end of the future channel.

Hand-held instruments can be obtained from similar suppliers (such as Marsh-McBirney) and even forestry supply stores. They are small meters suspended into the water by a line held by the user. These gages are fairly reliable and can be used to supplement data collected by a stationary continuous data logger.

Float-tracking studies can be used to estimate circulation in a rough fashion during certain events. They can supplement stationary measurements and even hand-held instruments by providing a synoptic view of lagoon water movement (simultaneously over the entire lagoon) over a relatively short time-frame such a one day. Float tracking is not as accurate as direct metered measurements, but can give a "big picture" view of the system and is therefore useful.

Indirect estimates of circulation can be obtained by measuring water quality parameters influenced by circulation such as dissolved oxygen (DO), water temperature, oxygen-reduction potential (ORP), and salinity throughout the water column and particularly within the bottom of the water column. These data will not provide direct indication of circulation, but their indicator status of the process of water exchange will confirm conclusions generated from measured data.

Improved circulation over time at the western arms compared to existing conditions can be inferred based on criteria such as the number of days at a given sample location and depth where:

- Dissolved oxygen is less than 3 milligrams per liter (mg/l);
- Water temp > 25°C; and
- ORP is < -100.

Alternatively, a relative comparison of the same parameters of water quality conditions in the western arms and in the main channel may be a better comparison as it will account for seasonal differences. This comparison also places the restored western arms area into context with the main channel.

**It is important to note that until source reduction efforts are implemented, reductions of the magnitude and duration of eutrophic conditions within the closed Malibu Lagoon will be limited.**

# 3.0 HABITAT PLAN

The Habitat Plan addresses the initial enhancement and establishment of habitats within the restored lagoon system as well as the on-going maintenance and management activities required to ensure that restoration habitat objectives are achieved. Adaptive management is an anticipated element of the Habitat Plan. Adaptive management will be required to respond to variability in the physical and chemical conditions manifested under the lagoon restoration plan.

## 3.1 HABITAT DESIGN

### *3.1.1 Slopes and Sediment Types*

Habitat restoration within the restored lagoon is highly dependent upon development of suitable hydrologic and soil conditions and the availability of desirable reproductive plant materials to colonize the restoration areas. To accomplish the desired restoration, it will be necessary to design the site with appropriate consideration of elevations, slopes, and sediment characteristics. Table 2 outlines the general design slope, elevation, and sediment criteria of the habitats to be targeted in the project development. These criteria are provided at this stage to provide a design context, however further refinement will be required in project design and engineering in order to achieve habitat objectives.

**Table 2 – Habitat Colonization Criteria**

| HABITAT TYPE | ELEVATION (FT. MSL) | SLOPE GUIDELINES | SEDIMENT CONDITIONS |
|---|---|---|---|
| Subtidal Gravel/Sand Bar | -2 to -1 | Any slope, slopes will be dictated by the natural angle of repose following storm events and tidal action | Coarse sand and gravel typically greater than 2 mm grain size. |
| Intertidal Gravel/ Sand Bar | -1 to +4 | Any slope, slopes will be dictated by the natural angle of repose following storm events and tidal action | Coarse sand and gravel typically greater than 2 mm grain size. |
| Sand Beach | +4 to +6 | Any slope, slopes will be dictated by the natural angle of repose following storm events and tidal action | Sand typically between 0.1 mm and 2.0 mm grain size. Sands may be substantially derived from coastal beach sources |
| Subtidal Softbottom | -2 to 0 | Any slope, slopes will be dictated by the natural angle of repose following storm events and tidal action | Muds to sands typically ranging from 0.001 to 2.0 mm. Coarser materials will be present in higher energy environments along the main channel through the lagoon |

| HABITAT TYPE | ELEVATION (FT. MSL) | SLOPE GUIDELINES | SEDIMENT CONDITIONS |
|---|---|---|---|
| Mudflat | 0 to +3 | Shallow slopes typically less than 25:1. Within the western lagoon slopes may be steeper along channel fringes. | Sediments are anticipated to be very fine sands to muds (0.001 to 0.08mm). Areas are typically depositional with sediment of both organic and mineral origin being represented. |
| Marsh | +3 to +5 | Shallow to moderate slopes typically less than 5:1. Where slopes are shallower than approximately 50:1, increased tidal channels may be required to reduce sediment saturation. All marsh areas must have positive drainage such that water does not pond at low tides to cause absence of vegetation (mudflat). | Sediments are muds to fine sands with moderate to moderately poor drainage. Grain size should average between approximately 0.01 mm and 0.08 mm. |
| Nontidal Southern Coastal Salt Marsh (Alkali Meadow) | +5 to +7 | Shallow slopes typically less than 10:1. All areas must have positive drainage. | Sediments are muds to fine sands with moderate to moderately poor drainage. Grain size should average between approximately 0.01 mm and 0.08 mm. |
| Riparian | varies | Shallow to steep slopes typically between 2:1 and 10:1 located where consistent freshwater groundwater influence is found. | Sediments are well drained fine to coarse sands at freshwater inputs, including seeps. |
| Coastal Dune/Bluff Scrub | +7 to +9 | Slopes vary considerably however for design, slopes should be designed between 4:1 and 10:1 for establishment, lower erosion, and maintenance. | Non-saline sands and low silt content sandy loam soils. |

Design conditions are to be developed during final design using the general elevation, slope, and sediment criteria outlined above, along with a verification of the typical hydroperiod for the lagoon under the restored conditions and consideration of habitat transition and slope transition characteristics at a suitable design scale.

### *3.1.2 Topsoil and Sediment Salvage and Management*

In developing habitat designs, it is anticipated that stockpiling and reusing suitable sediments will be necessary to obtain the physical and chemical conditions necessary to support desired biological communities. These aspects of the design must be integrated into the project engineering construction documents, and grading activities.

Because of the highly variable sediment conditions within Malibu Lagoon, it would be very easy to restore the desirable lagoon contours and fail to establish suitable conditions within surface sediments that are necessary to support desired habitats. For this reason, it will be necessary to closely monitor sediment conditions, stockpile desirable surface sediments, and place surface materials within appropriate habitat types as the site grading is finalized. To aid in the salvage and replacement of sediments for surface caps within the various habitat types, the total volume of sediment necessary to create a 1-foot thick cap of each type of sediment required to achieve the desired habitat conditions has been determined based on preliminary site designs as shown in Table 3.

**Table 3 – Volume of Earth Material Needed for Planting**

| HABITAT TYPE | ACRES | SEDIMENT TYPE | CU. YDS. |
|---|---|---|---|
| Sand Beach | 4.45 | $D_{50}$ between 0.1 mm and 2.0 mm. Sands may be substantially derived from coastal beach sources | 7,200 |
| Mudflat | 5.59 | $D_{50}$ between 0.001 to 0.08mm. High organics are okay. | 9,000 |
| Marsh | 5.08 | $D_{50}$ between 0.01 mm and 0.08 mm. | 8,200 |
| Alkali Meadow | 3.28 | $D_{50}$ between 0.01 mm and 0.08 mm. | 5,300 |
| Coastal Dune/Bluff Scrub | 1.22 | Non-saline sands and low silt content sandy loam soils. | 2,000 |
| **TOTAL** | | | 31,700 |

While it is not necessary that all surface sediments be removed and replaced to construct suitable habitat areas, the volume of material required to achieve the desired surface sediment conditions should be tracked through construction to ensure that valuable and necessary sediments are not exported inadvertently.

Following final grading, it is likely that it will be necessary to adjust the drainage conditions of vegetated habitats to ensure positive drainage. It is likely that some delay will be required between grading and planting. Depending upon soil salinities, it may be necessary to leach soils prior to planting. This may be accomplished either by delaying planting through the rainy season or using irrigation.

Similarly, for habitats that are to be maintained as alkaline environments, it may be necessary to raise soil salinities to minimize invasion by undesirable weedy species. This may be accomplished through application of saltwater irrigation or retarding surface drainage and irrigating with brackish or freshwater at a rate that allows for high evaporative water loss.

### *3.1.3 Restoration Planting and Natural Establishment*

The restoration of Malibu Lagoon is anticipated to rely heavily on natural recruitment into the desired habitat zones combined with directed revegetation. This has become a standard approach to large-scale coastal habitat restoration in Southern California. The effectiveness of restoration using natural recruitment is dependent upon a number of factors. These include the availability of desirable reproductive plant materials within the system, the extent of undesirable reproductive plant material that may recruit, the suitability of the site to support consistent recruitment, the anticipated rate of habitat colonization and the acceptability of anticipated species distribution and ratios if natural colonization occurs. Within Malibu Lagoon, the process, rate, and outcome of natural vegetation colonization will vary by elevation and habitat type. For this reason, directed restoration is anticipated to be required in a number of areas. Directed restoration will rely on container plantings, salvage and replacement of desirable plants presently found in the lagoon, and application of seed.

For plan development, the anticipated approaches to vegetated habitat restoration are outlined in Table 4, reflecting the most likely restoration approaches contemplated at this time. During final design and engineering, further consideration of approach will be undertaken and methods may change.

**Table 4 – Approach To Vegetated Habitat Restoration**

| HABITAT TYPE | RESTORATION APPROACH | IRRIGATION METHODS | LEADING FACTORS IN APPROACH |
|---|---|---|---|
| Marsh | Natural recruitment and salvaged plant transplants (below +4)<br><br>Salvage plant and container planting (+3 to +5) | Natural hydrology | Low elevations will receive high seasonal inputs of marine water and saline toxicity may be expected to control cattail spread and promote dominance by native halophytes. At higher elevations, freshwater discharge may be expected to dominate even during winter periods and cattail marsh may persist throughout the year. Increased effort to plant halophytes and brackish marsh emergent species will allow establishment adequate to preclude cattail monocultures.<br><br>Under both open and closed conditions adequate soil moistures are anticipated to support both recruitment and establishment of target vegetation. |

| HABITAT TYPE | RESTORATION APPROACH | IRRIGATION METHODS | LEADING FACTORS IN APPROACH |
|---|---|---|---|
| Nontidal Southern Coastal Salt Marsh (Alkali Meadow) | Salvaged plant transplants Container plantings and seeding | Hydrophilic amendments Intermittent summer saltwater irrigation | Areas are subject to upland weed species invasion if salinities are low and primary space is available. Although positive drainage is required, relatively poor soil drainage caused by very flat slopes and fine-grained sediments will increase soil salinities to a point that will promote halophytes and kill weeds. Areas above regular inundation levels will receive poor recruitment by wetland plants predominantly dependent upon hydro-dispersal or wind dispersal to saturated soils. For this reason natural recruitment of target vegetation will be slow and weed recruitment will be high. |
| Riparian | Natural recruitment | Natural hydrology | Riparian vegetation is not specifically targeted in the restoration efforts but will be a resultant habitat where freshwater discharges occur along the wetland fringes above the higher tide lines. Natural recruitment of native willows and mulefat vegetation will occur where hydrology is acceptable. Promotion of hydrology will not foster long-term vegetation establishment since deeper rooting at the lagoon fringe will result in saline toxicity of plants once supplemental water is removed. |
| Coastal Dune/Bluff Scrub | Seeding and container planting | Hydrophilic amendments and potentially spray irrigation | Upland plant salvage and transplant is not typically efficient on a large restoration scale. Seeding of habitat is a proven technique for these habitat types, although container species often can be used to promote diversity through introduction of species that are poor recruiters from seed or which are typically out competed by dominant species of the habitat. Hydrophilic amendments may be adequate to establish upland habitats, however overhead irrigation may be required if sediments are saline. |

Many of the desired species presently exist in the lagoon habitats that would be impacted by the proposed work and significant salvage and transplants may be undertaken to minimize the need for new plantings and to optimize the use of site native materials. A temporary on-site nursery area should be considered for the project. This would require the installation of a temporary overhead irrigation system using potable water. The system would be operated as needed to keep salvaged plants healthy until received sites are made available. Plant materials recommended to be used in the restoration of the lagoon are outlined in Table 5 below along with the preferred application methods. Container size will vary depending on species, season of planting and location within the restored wetland.

**Table 5 – Recommended Plant Pallete for Malibu Lagoon Restoration**

| PLANT NAME | HABITAT | PLANTING METHOD |
|---|---|---|
| Pickleweed (*Salicornia virginica*) | SCSM | seed & salvaged plant material |
| Parish's glasswort (*Salicornia subterminalis*) | SCSM | seed & salvaged plant material |
| Dwarf glasswort (*Salicornia bigelovii*) | SCSM | seed |
| Marsh jaumea (*Jaumea carnosa*) | SCSM | container |
| Saltwort (*Batis maritima*) | SCSM | container |
| Sea lavender (*Limonium californicum)* | SCSM | container |
| Alkali heath (*Frankenia salina)* | SCSM, AM | flat |
| Southwestern spiny rush (*Juncus acutus*) | SCSM, AM | container & seed |
| Salt-cedar (*Monanthoschloe littoralis*) | SCSM, AM | flat |
| Saltgrass (*Distichlis spicata*) | SCSM, AM | salvaged plant material |
| Salt marsh fleabane (*Pluchea odorata*) | AM | container |
| Purple sand verbena (*Abronia umbellata)* | CD/BS | seed |
| Silver beach bur (*Ambrosia chamiisonis)* | CD/BS | seed |
| Beach primrose (*Camissonia cheiranthifolia*) | CD/BS | seed |
| Beach morning glory (*Calystegia soldanella*) | CD/BS | seed |
| Extuary sea-blite (*Suaeda esteroa*) | CD/BS | container |
| California box-thorn (*Lycium californicum*) | CD/BS | container |
| Dune buckwheat (*Eriogonum parvifolium*) | CD/BS | seed |
| Coyote bush (*Baccharis pilularis*) | CD/BS | seed |
| Bladderpod (*Isomeris arborea*) | CD/BS | container |
| Lemonadeberry (*Rhus integrifolia*) | CD/BS | container |

SCSM-Southern California Coastal Salt Marsh; AM-Alkali Meadow; CD/BS-Coastal Dune/Bluff Scrub

## 3.2 INITIAL HABITAT RESTORATION

### *3.2.1 Maintaining Unvegetated Habitat Areas*

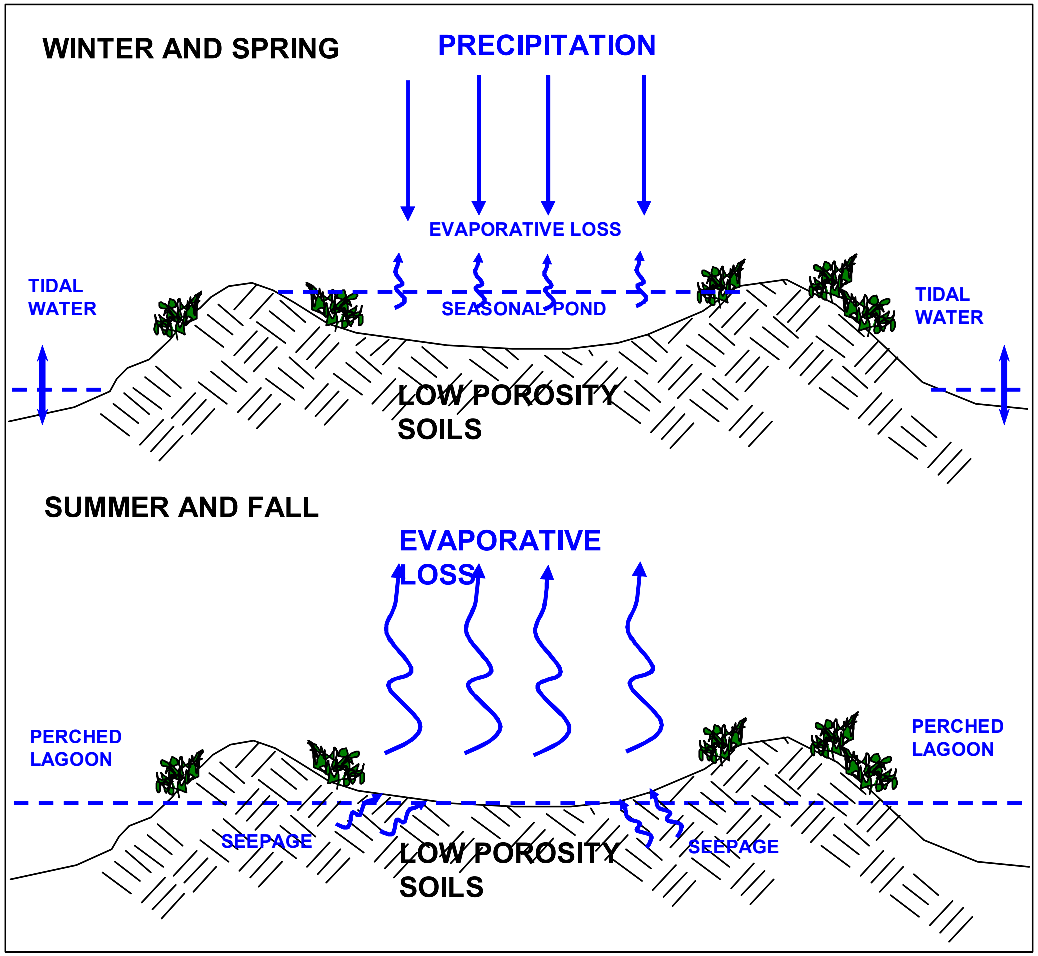
The Malibu Lagoon restoration program incorporates both vegetated and unvegetated habitat areas. Included among the unvegetated habitat areas are frequently submerged habitats such as mudflats and channels as well as exposed avian islands, beaches, and dunes. The highest functionality of these habitats depends on maintaining their open nature. For frequently submerged habitats, this is accomplished naturally by maintaining very low oxidation-reduction potential (ORP) or high scour. However, for habitats located in areas of lower inundation frequency, opportunistic vegetation often consumes open ground rapidly. To combat the expansion of undesirable vegetation into the naturally open habitat areas, there are several approaches that may be taken.

For beach and dune habitats it is important to minimize the accumulation of fine sediments that retard water and nutrient drainage and impart sediment stability. Desirable dune vegetation is tolerant of very low nutrient supplies and shifting sediment conditions. Where sediments are stabilized, opportunistic and often invasive annuals and herbaceous perennial plants often become established. For this reason, development of dunes will only be highly successful in areas where fine sediments are not accreted, nutrient supplies are kept low, and sediments are unstable. Regular seasonal lagoon breaches and natural closure frequencies are suitable to maintain unvegetated beaches along the coastal fringe. For dunes, the lagoon breaches are too frequent for regular dune development along the barrier beach. Adjacent to the Malibu Colony fence line, the stability of the beach is high and it may not be possible to maintain the open vegetation of a natural dune system. This site may be suitable for development of a transitional upland area. However, there may be greater opportunity to support desirable conditions at the eastern end of the beach where a degraded dune system presently exists.

For avian islands it is desirable to maintain sparsely vegetated or unvegetated areas. This can be accomplished through two recommended methods. The first is to develop a site that lacks soil by using well-drained cobble and gravels with no fine sediments. An example of such an island is the mid-lagoon shoal that often forms as a result of major storm events. Over time, these islands eventually trap finer sediments and debris as well as receiving considerable nutrient inputs from bird wastes. As fine sediments and nutrient levels rise, sparse opportunistic vegetation becomes established. Over time, the islands will eventually be consumed by vegetation unless they are flushed of fine sediments either by storm flows, high water volume rinses, or mechanical reworking of the cobble and gravels on an as-needed basis. Such island cleaning may be required on a 2 to 10 year maintenance frequency. The second recommended approach to maintaining unvegetated or sparsely vegetated areas for avian islands is to reduce soil and surface drainage thus reducing sediment ORP and increase soil salinity. Following this approach, poorly drained soils are used to create the island surface and the top of the island is made to be slightly concave so that it holds water when flooded either by natural rainfall, artificial pumping, or infrequent inundation, generally through a controlled structure. By creating an internal basin, water loss principally occurs through evaporation and thus salts are concentrated on the island surface. This creates a salt panne environment that is sparsely vegetated by halophytes that are generally concentrated along the ponding edges.

Operationally, the salt panne basins are seasonally flooded during the winter and spring periods and dry during the summer and fall periods. Such ponded areas are often used as foraging areas by small shorebirds because of the controlled shallow depths and the often high concentration of brine flies and other insect prey species. During the dry summer season these areas are often used as nesting sites by such species as avocets. Examples of these types of salt pannes often exist in areas of hydraulic fills around bays and estuaries of Southern California. They are also a common feature in natural flood deltas of estuaries where major storms have scoured out depressions in the high marsh plains (Tijuana River Estuary, Sweetwater River Marsh), however most of these historic deltas have been lost from the region and natural examples are limited today. Figure 11 below shows a conceptual salt panne.

To maintain low vegetation cover within the salt pannes, it may be necessary to seasonally pump salt water into the basins on an infrequent basis to increase salinity levels. This should not require annual actions and can be accomplished during periods of tidal opening with a small (1 or 2-inch) gas powered pump. An alternative approach would be to lower the basin floor to an elevation that exists at or below the normal high water level of the lagoon so that natural evaporation of seepage increases salinity levels in the basin. The schematic in Figure 11 below illustrates these concepts around the salt panne avian island configuration.

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April 2005
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| Final Malibu Lagoon Restoration and Enhancement Plan | Concept Salt Panne | Figure 11 |
|---|---|---|

### *3.2.2 Minimizing Habitat Losses from Seasonal Inundation*

The same low oxidation-reduction potential that can be used to limit vegetation growth where it is undesirable, will also be of concern in vegetated habitats. Because of the long-term seasonal inundation of much of the lagoon habitat during the summer months, vegetation dieback can be expected in these areas. While it is not fully possible to correct the problems associated with long-term inundation on vegetation communities, it is possible to reduce the effects by taking the following steps:

1) Develop an undulating topography within the seasonally inundated habitats in order to ensure that the extent of inundation is varied across the terrain. This will ensure that not all vegetation is subject to the same potential risk of loss;
2) Incorporate vegetation that tolerates prolonged exposure to anoxic soil conditions into restoration efforts. Such species include: *Jaumea carnosa, Batis maritima,* and *Spartina foliosa*
3) Incorporate vegetation into restoration efforts that rapidly expands into unvegetated areas by seedling recruitment. Such species include: *Salicornia virginica and Salicornia bigelovii.*
4) Promote increased oxygenation of waters during inundation periods.

Lagoon water levels typically rise to a maximum elevation at the very end of the closed lagoon period. Water level data from others (M&N, 2005) indicates water levels stabilize at approximately +5 feet above mean sea level (msl) for the summer, then rise another one to two feet for approximately the last two to four weeks of the closed period water levels. This last short term rise in water level is caused by releases from upstream water impoundments such as the Tapia Plant. The lagoon habitat vegetation mosaic is adapted to maximum water levels at +5 feet msl. The short-term period of super water level elevations is too short to affect the distribution of vegetation and should not cause significant or long-term variations of lagoon habitat. No planning or design features are needed to address this condition.

## 3.3 ESTABLISHMENT MAINTENANCE

During early establishment of the restoration, it will be necessary to conduct maintenance that promotes the effective development of target habitats while preventing the establishment of non-target vegetation. Specifically, it is anticipated that it will be necessary to conduct focused invasive species removal from restoration areas. It may also be necessary to augment plantings of desirable target vegetation or conduct increased levels of maintenance to promote plant establishment or address identified problems.

In addition to normal establishment maintenance, adaptive management may be required to foster effective habitat development. It may be necessary to alter site topography or drainage, modify plant palettes to fit specific site conditions, or direct habitat restoration of a differing habitat zone. Adaptive management actions will be based on results from habitat monitoring, described later in Section 6.0.

## 3.4 LONG-TERM HABITAT MAINTENANCE

Malibu Lagoon is a system naturally characterized by alternate states of open tidal influence and closed brackish/freshwater pond conditions. As a result of the highly variable environmental conditions occurring within the lagoon, the lagoon is at great risk of invasion by opportunistic exotic species and the degradation of fringing habitats absent vigilant maintenance. Maintenance within the lagoon will require on-going exotic plant control efforts. The extent of such maintenance in the lagoon may be reduced if highly invasive exotic plants are controlled effectively in the watershed.

In addition to exotic species invasions within the lagoon, it is anticipated that high nutrient loading within the lagoon will continue to promote growth and expansion of opportunistic algae and fast growing vascular vegetation such as cattails over other species. The proliferation of ephemeral macroalgae and microalgae will further adversely effect oxygen levels within the lagoon and adversely impact aquatic animal communities as well as less competitive plants. The effective development of target aquatic habitats and associated communities is dependent upon both the improvement of existing lagoon environments and curtailing degradation from external sources, particularly the inputs of nutrients and control of exotic species in the watershed. Improvements to these external factors should be made a priority in a parallel effort to the lagoon restoration.

# 4.0 ACCESS, EDUCATION, AND INTERPRETATION PLAN

The access, education, and interpretation plan is shown in Figure 12. This plan provides for access at grade along the perimeter of the western arms complex at the location of the existing vehicle access route. Multiple interpretive nodes and areas suitable for educational programs have been identified, and multiple length interpretive loops provided to allow for a variation of docent led activities with exposure to multiple habitat types.

The most important element of the plan is the relocated parking area, moved back and elevated to a position along PCH that will be acoustically and visually buffered by a proposed extension of the "Adamson wall." This move will:

- Expand the area available for habitat, and if stepped retaining walls at the south and east are provided along that edge, it will allow for an even greater area of shallow-slope wetland margins;
- Allow more ground surface area to be available for wetland habitat restoration, including installation of potential adaptive management options such as the North Channel, if needed in the future depending on the footprint of slopes shown in the plans;
- Make it possible to implement the best management practices in the construction of the new lot as discussed above;
- Create a new bus drop and parking zone in addition to providing car capacity equal to that of the existing lot;
- Provide an elevated platform for initial orientation (designed to be sufficiently sturdy to not shake under average wind conditions for stable bird viewing with telescopes);
- Make access to the PCH bridge easier and more clearly defined; and
- Make possible the installation of an ADA accessible viewing tower at an elevation above PCH bridge in order to experientially re-integrate the full tidal/lagoon system of Malibu Creek that is currently bisected and fragmented by the PCH bridge.

The access plan provides for different experiential, teaching and management opportunities, with a number of "add alternate" components.

## 4.1 PERIMETER ACCESS

This plan, shown in Figure 12, will provide a primary beach access trail that is directly accessible from the Cross Creek Road intersection and bus drop-off zone. This approach provides for three primary interpretive nodes near the parking area, and optional locations for additional nodes for instructive features, benches for wildlife viewing, picnicking, painting, etc.

Access to the interior of the system in this alternative is limited to a single path along the axis of the entry/drop-off zone along a gently sloping peninsula (area "2") where the primary teaching can take place on picnic tables aligned along the trail, or in the optional amphitheater seating (north of trail axis at area "2"). The access continues across a short span, that could if designed as a drawbridge to allow for a seasonal island in the approximate location of the existing turf/interpretive kiosk zone at closed lagoon conditions. While this interpretive node is envisioned as a cleared gathering area within a dominant restored wetland habitat, the grading of the island could allow for some of the existing sycamores to be retained for shade within a small upland component. Figure 13 shows the overlook that could be created for minimal intrusion.

Additional features of this plan include:

- Storage and restroom facilities near entry parking circle;
- Orientation and interpretive node at perimeter trailhead (area "1");
- Optional storage/restroom location built into "Adamson wall" at Lagoon Loop Trail gateway at east end of parking lot;
- Enhanced "Lagoon Loop Trail" access to the east lagoon over PCH bridge with interpretive signage and graphics;
- An underpass at the east abutment to provide improved access to the riparian habitat north of PCH and west of Serra Road;
- A loop trail extension arcing along the upland margin along the Adamson property (existing chain link is proposed for removal to allow for restoration and access);
- An interpretive overlook at a restored Adamson House dock shown in Figure 14 and boat house to introduce cultural tourists to the features of the nearby habitat island and lagoon system from the eastern vantage point;
- A continuation of the Lagoon Loop Trail to the beach below the Adamson House; and
- A possible mural wall separating the Colony properties from the perimeter trail as shown in Figure 15, including a "thick wall" element with integrated benches, interpretive displays including possible dioramas, and additional storage for teaching and testing equipment. The wall will arc toward the wetland margin to define a node within the access path defined on the opposite side by:
    - an "interpretive blind" concealing observers from the wetland complex and framing particular instructive views with integrated interpretive graphics (see sketches);
    - additional alternative Interpretive Activity Zone sites as appropriate to the docent led programs and to provide for expected user capacity for passive recreation (picnics, painting, study, etc); and
    - an improved self-contained restroom facility with vehicular access for servicing at the edge of the beach/upland area.


Prepared by: Moffatt & Nichol
April 2005
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**Final Malibu Lagoon Restoration and Enhancement Plan**

Perimeter Access Plan

**Figure 12**


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| Final Malibu Lagoon Restoration and Enhancement Plan | Non-Intrusion Platform Option | Figure 13 |
|---|---|---|


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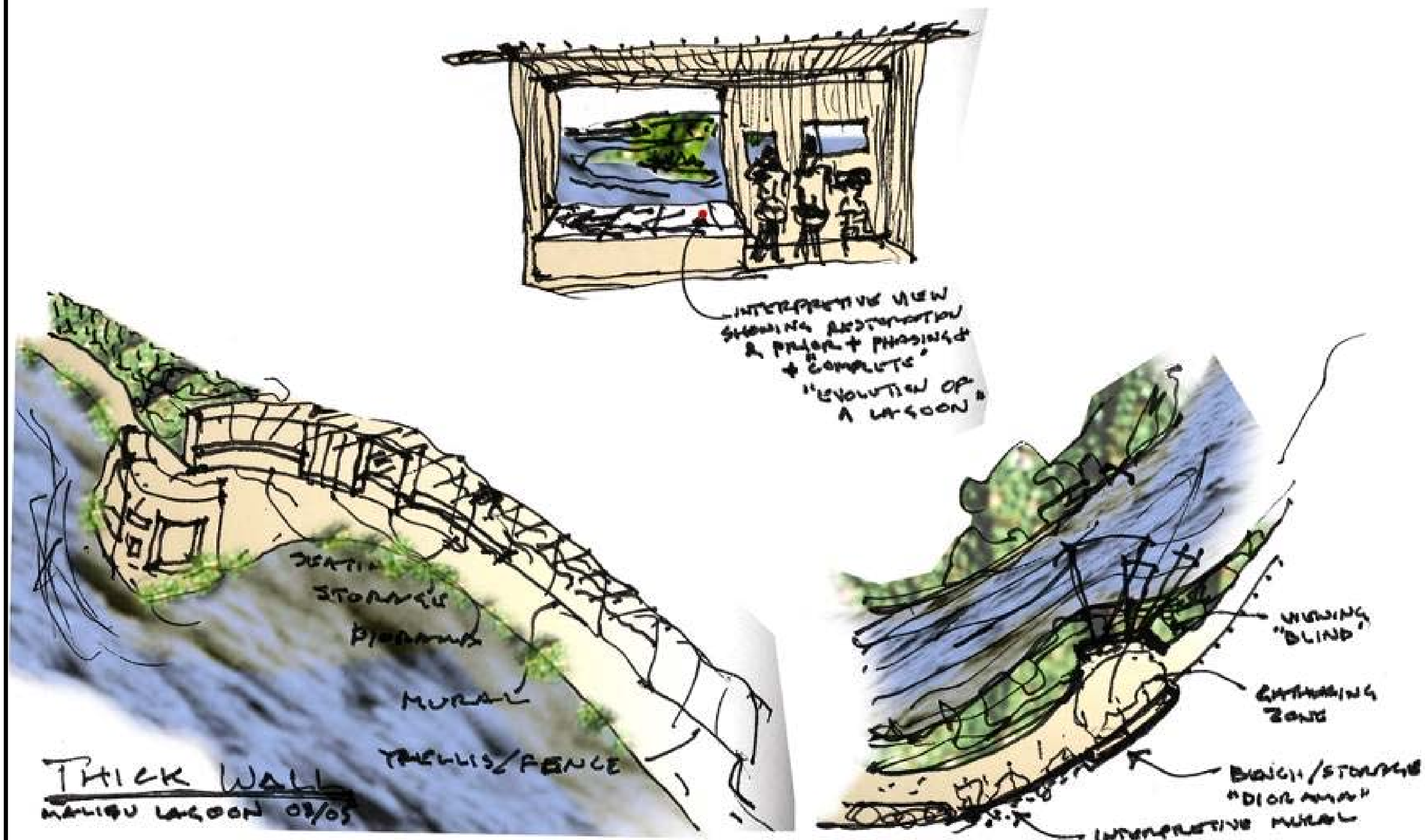
| Final Malibu Lagoon Restoration and Enhancement Plan | Adamson Dock View | Figure 14 |
|---|---|---|

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| **Final Malibu Lagoon Restoration and Enhancement Plan** | The Thick Wall and the Duck Blind | **Figure 15** |
|---|---|---|

# 5.0 MONITORING PLAN

## 5.1 PURPOSE OF THE LAGOON MONITORING PROGRAM

The Malibu Lagoon monitoring program will be used to assess the existing floral and faunal assemblages at the lagoon, protect existing habitat, minimize impacts and document resource changes for application in future restoration programs. The primary monitoring program objectives are as follows:

- Set the baseline of biological, physical and chemical conditions for analysis of the project under the California Environmental Quality Act (CEQA) to minimize impacts to existing habitat and to evaluate future restoration success;
- Facilitate an evaluation of the effectiveness of the restoration to provide habitat for fish and wildlife;
- Assess progress towards restoration goals;
- Document changes in the ecology of the lagoon environment over time;
- Provide timely identification of any problems with the physical, chemical, or biological development of the lagoon, and;
- Assist in providing a technical basis for resource management of the lagoon system by documenting maintenance needs and enhancement opportunities.

## 5.2 ANNUAL REPORTING

The lagoon-monitoring program consists of annual sampling activities completed during each year prior to and following lagoon restoration activities. The monitoring program has been tailored to provide useful information to assess restoration and make sound management decisions. The annual report provides a data presentation and analysis format for assessing the status of the restoration project and evaluating changes in the site over the course of the program. Each annual report is to include a compilation of information collected for the specific year of sampling as well as a cumulative reporting for all prior monitoring years. The report shall further provide an analysis of data for the specific year and a cumulative analysis of change in the system, making use of information from preceding years. The annual reports are to accomplish the following:

- Identify the investigations or sampling completed for the specific report year;
- Document studies and surveys conducted and summarize sampling methods;
- Summarize information gathered during the year and provide aggregate information on sampling completed to date;
- Summarize restoration activities conducted during the prior year and provide an outline for future restoration work to be completed;
- Present an analysis of the data collected and provide an evaluation of the ecological development of the lagoon system;
- Document habitat values achieved through restoration efforts, and;

- Make recommendations regarding beneficial changes and/or additions to monitoring methodology and data collection and analyses.

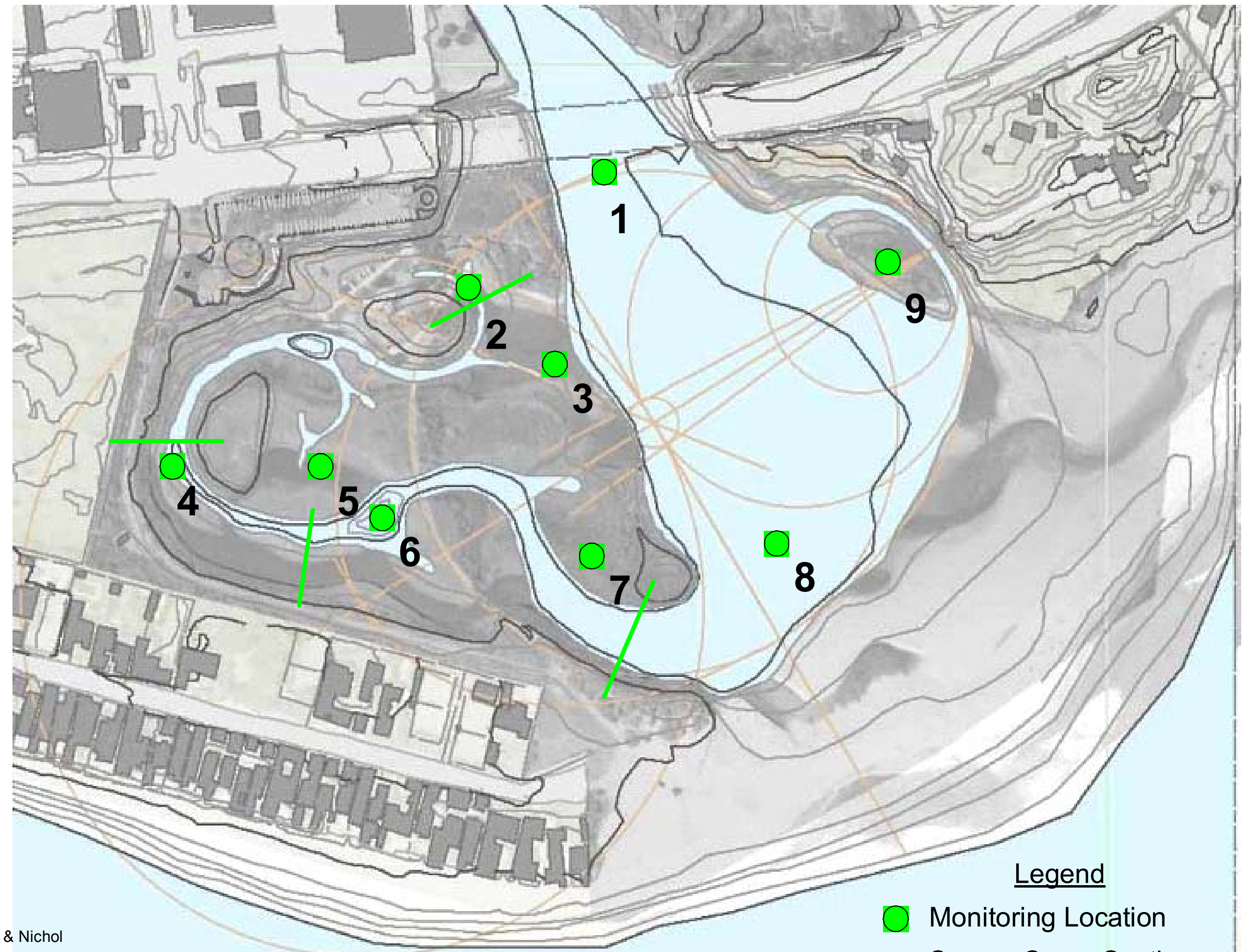
## 5.3 MONITORING PHILOSOPHY

The following monitoring plan includes an array of physical, chemical and biological parameters that all address different functional aspects of a healthy and sustainable lagoon system. The key to restoration of Malibu Lagoon will be observable improvements in the physical and chemical conditions that facilitate biological stability by the reestablishment and persistence of species diversity and native organisms well beyond the first 5 years following construction. In order to confidently measure improvements in the system, the monitoring program needs to:

1. Standardize sampling protocols to account for the inherent temporal and spatial variations as much as possible;
2. Select monitoring parameters that will directly address restoration goals and intended successes;
3. Acquire a reliable baseline dataset; and
4. Maintain parameter and technique continuity throughout the monitoring program.

Understanding baseline conditions prior to ecological restoration is imperative to accurately and quantitatively assess the physical, chemical and biological changes as a result of restoration efforts. While a gamut of previous monitoring information exists on Malibu Lagoon, the spatial and temporal variability of previous sampling, as well as variations in techniques, would make it difficult to apply the previous data sets as baseline conditions from which to evaluate future restored conditions. The most robust assessment of restoration performance will be provided by a standardized monitoring program that provides baseline and post-restoration data using the same parameters, the same techniques, functionally similar spatial sampling locations and constrains the temporal variability of sampling as much as possible. The monitoring sites are provided in Figure 16. Sampling consistency with continual consideration of the inherent dynamic nature of coastal lagoons is the most effective means to obtain reliable evaluation of restoration success.

The monitoring plan presented herein has been designed to be consistent the Comparative Lagoon Ecological Assessment Project (CLEAP) currently being conducted in Santa Cruz County (2ND NATURE, 2004). The monitoring plan may be slightly modified in the future to be consistent with forthcoming restoration monitoring guidelines prepared by the Southern California Wetlands Recovery Project (www.scwrp.org).

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| **Final Malibu Lagoon Restoration and Enhancement Plan** | Monitoring Locations | **Figure 16** |
|---|---|---|

## 5.4 RESTORATION GOALS

Based on the initial goals prepared by the Malibu Lagoon Task Force, a series of detailed restoration goals have been developed to set measurable targets for the restoration program.

### *5.4.1 Physical*

1. Improve water circulation during all hydrologic conditions (i.e., storm flows, tidally dominated open conditions, and closed conditions). Circulation directly relates to the stability of the restored lagoon bathymetry and morphology (quantity of sedimentation dynamics), grain size distribution (quality of sediments), and water quality (temperature, dissolved oxygen, salinity, and ORP.
2. Provide an optimum three-dimensional lagoon geometry to provide for maximum water circulation under all conditions, and a desirable and diverse habitat mix.
3. Improve storm flow and tidal sediment discharge characteristics to reduce the erosion and accretion of sediments within the lagoon and the maintenance requirements to sustain a functional lagoon system.

### *5.4.2 Chemical*

1. Reduce sediment nutrient content. Previous research has identified that increased grain size of lagoon substrate will decrease available summer nutrient loads regenerating from the lagoon sediments, thus reducing the potential for eutrophication and low dissolved oxygen conditions during warm months of the year (Sutula *et al*. 2004).
2. Increased circulation and water exchange during tidally dominated and closed conditions. Increased circulation and water exchange will improve temporal and spatial frequency of oxygenated water contact with surface sediments, thus increasing organic matter decomposition and increasing the transformation of ammonia to nitrate. This, in turn, will facilitate the permanent loss of nitrogen, the limiting nutrient, from the lagoon through denitrification and reduce its supply to the primary producer communities.

### *5.4.3 Biological*

1. Protect existing natural biological communities represented within Malibu Lagoon during and following restoration.
2. Reduce the incidents and geographic limits of depressed dissolved oxygen levels that adversely affect native lagoon communities.
3. Reduce predator encroachment in the lagoon habitats by improving habitat isolation during open and closed lagoon conditions.
4. Expand desirable native habitats and reduce habitat dominance by exotic species.
5. Promote habitat suitability for threatened and endangered species by increasing the available slough channel refugia habitat with sandy bottom for tidewater gobies and providing increased isolation of island habitats for seasonal snowy plovers and least tern use.

*The ability of the restoration efforts to attain improvements in lagoon water quality may be significantly limited by the extreme watershed loading of annual nutrients to Malibu Lagoon. As management efforts continue to focus on reducing nutrient loading, the water quality benefits of restoration efforts maybe more likely.*

## 5.5 PARAMETER SELECTION

Monitoring parameters have been selected specifically to support the restoration needs for the lagoon and to evaluate the progress towards restoration goals. The needs for the project include both pre-action environmental and regulatory reviews as well as pre- and post-restoration monitoring to assess actions and guide management.

### *5.5.1 Pre-Restoration Monitoring To Inventory Existing Conditions To Facilitate Environmental Review And Permitting*

Project review is required under the California Environmental Quality Act (CEQA) and for necessary permitting under the federal and state Endangered Species Acts (ESA, CESA), the Clean Water Act (CWA), the California Fish & Game Code, the California Coastal Act, and the Porter-Cologne Act. To support these review processes, it will be necessary to fully document resources that will be affected by the restoration activities. Much of the habitat and wetland mapping has been completed through the restoration planning process, however, additional biological data collection are necessary in two primary areas as specified below.

**General Biological Resource Inventories**

While Malibu Lagoon has been extensively studied over the past two decades, the most comprehensive inventories of species resources within the identified habitats are now ten years old and information cannot be relied on at this time to support a current evaluation of the potential effects of the restoration on existing communities. To provide a current baseline biological report and impact assessment, it will be necessary to conduct updated surveys of the plants, fish, and wildlife resources of the lagoon system. To a great extent, the work may be limited to verification and updates of data already collected and reported in prior studies. Using the habitat mapping work completed in 2004 as a baseline, resource inventories should identify species dominating the delimited habitats. These data will be important to evaluating the probable effects of project implementation on the biological resources of the lagoon. Surveys to be conducted should include the following:

1. Floristic Inventory – A one time floristic inventory should be conducted during the spring/early summer season (spring/summer seasons) to document the plants present within the lagoon environment and to link plants to previously mapped vegetation communities. The survey should be conducted by a qualified field botanist.
2. Fish Community Inventory – Species present within the lagoon are not anticipated to differ substantially from those detected during the completion of the Ambrose et al. 1995 studies. For this reason, no further broad scale surveys are warranted. However, see section on threatened and endangered species.
3. Avian Community Inventory – Resource inventory surveys of the lagoon that should be conducted to support environmental review and permitting should include a seasonal

survey of avian species that results in an inventory and count of species present as well as an identification of species use of the represented habitats. A comprehensive species list for the lagoon has previously been prepared and extensive surveys have been conducted (Garrett field notes 1980-1996, Manion and Dillingham 1989). Ambrose et al. (2005) began the process of linking avian guilds to habitats. A knowledgeable ornithologist with extensive experience at Malibu Lagoon should be retained to prepare a comprehensive avian species matrix that indicates important habitat usage, frequency of occurrence, and relative abundance. Combined with an updated survey, the habitat utilization matrix is expected to provide adequate information to support environmental assessments of the project effects on birds.

4. Mammalian Community Inventory – Comments have been made by the public regarding the general lack of information available regarding the mammalian fauna of Malibu Lagoon. Based on a concern that the inventories and environmental impact assessments be complete, it is recommended that a spring/summer season mammalian survey be conducted that would focus on identification of small mammal fauna that may exist in and around the lagoon. A multiple night small mammal trapping and bait station trackplate program should be implemented within all vegetated habitats represented in the lagoon. In addition, a survey should be conducted to identify mammal signs including scat and tracks for the purposes of developing an inventory of mammals present by represented habitat types.
5. Herpetofauna Surveys – Prior surveys of the lagoon have not focused on the presence of reptiles and amphibians. Given the perennial nature of Malibu Creek there is some potential for the lower creek and upper lagoon to support sensitive herpetofauna including southwestern arroyo toad, western pond turtle, and two striped garter snake. To determine the status of these species as well as more common reptiles and amphibians, it is recommended that a spring/summer season survey be conducted. This work could be conducted coincident with mammalian surveys and could employ the use of visual surveys, seining of quiescent waters, drift fences and pitfall traps, as well as nocturnal surveys for auditory and visual detection. Surveys should be conducted over multiple nights during warm periods. Depending upon rain events and temperature, it may be necessary to conduct surveys during spring as well as summer to effectively detect all sensitive species.
6. Terrestrial Entomological Surveys – Comprehensive surveys of terrestrial invertebrate fauna present at the lagoon would be costly and not particularly useful in analyzing the restoration effort effects. However, there are a number of sensitive species that are found in the region with potential to occur at the lagoon. These include salt marsh skipper, other lepidoptera, and various Cicindelid beetles. These species are best inventoried during the warm spring or early summer months during visual surveys of the site. Nocturnal surveys may be conducted using attractant techniques such as black lights, however, it is not expected that such methods will be required.

**Threatened & Endangered Species Surveys**

Malibu Lagoon is known to support year-round presence of tidewater gobies, seasonal presence of southern steelhead, and seasonal use by California least tern and western snowy plover. While the seasonal presence and habitat use around the lagoon is well known for listed avian species, the habitat utilization of the lagoon by listed fish is less well known. In order to assess the potential for adverse effects and to minimize impacts to listed fish resulting from construction activities, a focused investigation should be undertaken to assess the distribution of tidewater gobies and steelhead in the lagoon. Updated surveys should be implemented during open and closed lagoon conditions. The surveys should include widespread seining of the lagoon to identify high use areas by gobies and to determine the presence or absence of southern steelhead throughout the year or the time period available prior to completion of the CEQA document. The results of these surveys should be used to plan construction phasing and impact minimization measures. Results should also be incorporated into the assessment of environmental impacts under CEQA and in the development of information necessary to support Endangered Species Act consultation.

#### *5.5.2 Pre- and Post-Restoration Monitoring to Evaluate Restoration Success*

Below are the monitoring parameters that have been selected to quantitatively address the ability of the restoration program progress towards the physical, chemical and biological goals of this project outlined in Section 5.4. Sampling protocols, sampling schedules and specific locations are provided below. These protocols are to be used as a guide for implementation of the monitoring program and may be subject to change. In addition to specific protocols, the frequency of monitoring is likely to change as it is anticipated to be more frequent immediately following restoration to detect short term recovery and then become less frequent to detect long-term changes.

Monitoring site locations are suggested in this document, but their exact locations may need to be modified over time. The goal of selecting final monitoring sites is to identify functionally equivalent sites for pre- and post-restoration monitoring. Planning of sites must demonstrate some functional similarity based on physical/chemical/biological rationale to allow the most reliable comparisons of data in the future.

The most cost effective, robust and reliable monitoring program would be best served under the oversight and with the expertise of professional personnel. Consistency and repeatability are the keys to useful monitoring data collection in the field. Data management and analysis should be performed by trained professionals who can provide insight to the nuances, trends and interpretation of the data.

It is anticipated that training of agency monitoring staff by professionals may be useful. The professionals will assist to establish the data management and database format techniques to be used for each these parameters. Training can also include establishing data recording, data management and procedures to provide for organized and consistent field data. The monitoring will require a strong commitment by the selected agency and personnel to render it effective. Protocols for each monitoring parameter are provided below.

## Physical

Physical components to be monitored include those items described below.

### *Cross-Section Monitoring*

For cross-section monitoring, four (4) permanent and repeatable cross-section locations will be monitored bi-annually during pre and post restoration. Horizontal and vertical locations of cross section end points will be fixed by monuments. Changes in bathymetry at 4 selected locations will be monitored over time. Estimates of sediment volume scour or deposition can be made from data, and cross sections can be used with water budget data to calculate inflowing/outflowing channel velocities through cross-sectional area. Cross-section monitoring should be performed at the end of the rainy season during open conditions (~April) and again prior to the wet season (~September).

*Pre-restoration preparation:* Semi-permanent monuments will be established by qualified staff with fence posts and eyelets at locations indicated in Table 7 and surveyed into an existing topographic map. Cross-sections will be obtained by attaching a taught survey tape to the monuments and recording channel depth and water elevation at equal increments across cross section to collect at least 20 data points. Field personnel must be prepared with hip waders or inflatable boat depending upon water level conditions.

*Pre-restoration monitoring:* Monitoring will continue following the sampling schedule until restoration construction ensues. Data will be recorded in a field notebook and entered into Microsoft Excel in a database format developed by the qualified staff.

*Post-Restoration monitoring:* Following construction, qualified staff will establish permanent monuments at the restored lagoon locations indicated in Table 7 and surveyed for vertical and horizontal locations. The monuments should be tied to the updated topographic survey once conducted. Monitoring techniques remain the same as above.

### *Continuous Water Surface Elevation And Flow Velocity Monitoring*

Continuous water surface elevation monitoring will be accomplished by using meters. Deployable water quality instruments will be installed and maintained at 3 locations within Malibu Lagoon. The recommended instruments are equipped with water pressure transducers to allow continues water depth measurements. The recommended instruments are used to measure additional water quality parameters. An example instrument is shown in Figures 17 and 18.

Water surface elevation monitoring will be used for various purposes, but one use is to estimate tidal flow velocity within channels. This method requires calculations to quantify velocities. Alternatively, a separate instrument can also be deployed to directly measure flow velocities and eliminate the need for the calculation. Both approaches are described below.

The parameters above (cross-sections and continuous water surface elevation monitoring) will allow the assessment of the spatial distribution of circulation and an evaluation of the circulation benefit restoration efforts provided during tidally-dominated conditions. The continuous depth data can be used to create a rating curve that relates the water depth to lagoon volume for both existing and anticipated restored conditions. Time series changes in water volume can be used to create a simple water budget of the lagoon. The water budget data will be applied to:

1. Track the water volume changes over time (depth data) related to the tidal cycle at the mouth (WXTides or some other tidal time series program) and evaluate tidal influence on lagoon circulation during tidally dominated conditions; and
2. Create a time series of estimated flow velocities at channel cross-section locations using water volume changes over time. These data, combined with the water quality time series from the data loggers, will allow for the quantification of the critical tidal elevation that induces flushing of the western restored areas and the frequency of that tidal elevation.

During closed lagoon conditions, the continuous depth data will be used to determine the lagoon volume filling rates, equilibrium lagoon water volumes and detailed data on sandbar dynamics. This information can be evaluated with tidal variations and surface water inflow hydrology to quantify specific parameters of the lagoon water budget during closed conditions.

Alternatively, a continuously-recording velocity meter can be installed near the downstream end of the western arm to record tidal flow currents. The type of meter can vary, but a Doppler-type of technology is recommended for semi-permanent deployment for the annual dry season.

*Pre-restoration preparation:* The qualified staffs will determine the most appropriate instrumentation necessary to collect in-situ velocity measurements. Options include manual pigmy meters or digital velocity meters.

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| Final Malibu Lagoon Restoration and Enhancement Plan | The YSI 600XLM | Figure 17 |
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| | |
|---|---|
| **Medium:** | Fresh, sea or polluted water |
| **Temperature:** | -5 to +45°C |
| **Computer interface:** | RS232, SDI 12 |
| **Logging Memory:** | 384K, logs 150,000 readings |
| **Software:** | EcoWatch for WIndows 3.1 included: PC compatible, 3.4" disk drive, 386 processor or better, running Windows 3.1 or later, 4 MB RAM minimum, English and French |
| **Size:** | 1.7" OD x 21.3" long (4.32 x 54.1cm) |
| **Weight with batteries:** | 1.5 lbs (0.7 kg) |
| **Internal power supply:** | 4 AA-size alkaline cells |
| **External power supply:** | 12 VDC |

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**Final Malibu Lagoon Restoration and Enhancement Plan**

YSI 600XLM Specifications

**Figure 18**

*Pre-restoration monitoring:* Monitoring locations will correspond with the cross-section locations as presented in Table 7. Exact timing of each sampling will be determined by the qualified staff, taking into consideration, tides, stream discharge, weather, sand bar status and other relevant concerns. Velocity measurements are taken only during open sandbar conditions and during a falling tide. Velocity measurements will be collected at 4 equal distances across the cross section. Each location will include 3 measurements to quantify the vertical variations in velocity within the water column. The water depth at each site will be measured, divided by 3 and velocity measurements will be conduced in the middle of each third. Data will be recorded in a field notebook and entered into Microsoft Excel in a database format developed by the qualified staff.

Alternatively, direct flow velocity monitoring can be done continuously using a Doppler technology meter such as the Sontec Argonaut shown in Figures 19 and 20, and described in Appendix C.

*Post-restoration monitoring:* Monitoring locations will correspond with the cross-section locations in the restored lagoon as presented in Table 7. Field techniques will remain the same as used above.

***Aerial Topographic Surveys***

For aerial topographic surveys, surveys should be recorded to address lagoon circulation and sediment aggradation/degradation dynamics over the long-term. Their timing is immediately post-construction, then at 2.5 years post-construction, 5 years post-construction, 10 years post-construction, and every 10 years thereafter into perpetuity.

*Pre-restoration preparation:* No pre-restoration preparation is need as that was already completed for the Feasibility Study in 2004.

*Pre-restoration monitoring:* This may already be covered with the 2004 data. If construction occurs very soon (close to 2005) without significant changes on-site, rely on 2004 data. If changes occur such as parking lot installation ahead of other construction, and/or construction does not occur until 2010, then do the survey immediately pre-construction.

*Post-restoration monitoring:* Perform the survey immediately post-construction, then at 2.5 years post-construction, 5 years post-construction, 10 years post-construction, and every 10 years thereafter into perpetuity. Perform an aerial topographic survey at low tide in the Spring season of the identified year. If photographed in color, the aerial image may be useful for vegetation mapping as well. Hire a surveyor to perform the entire project. They set ground survey markers and fly over the site to create a topographic map from the aerial for dry land areas. Areas covered by water will require standard surveying of points by a crew in a boat or wading. More accurate estimates of sediment volume scour or deposition can be made from data for longer-time periods to identify trends in accretion or erosion. The resolution of the survey should be at 1 foot contour intervals, with points accurate to ¼ of foot.


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| Final Malibu Lagoon Restoration and Enhancement Plan | The Argonaut-SL | Figure 19 |
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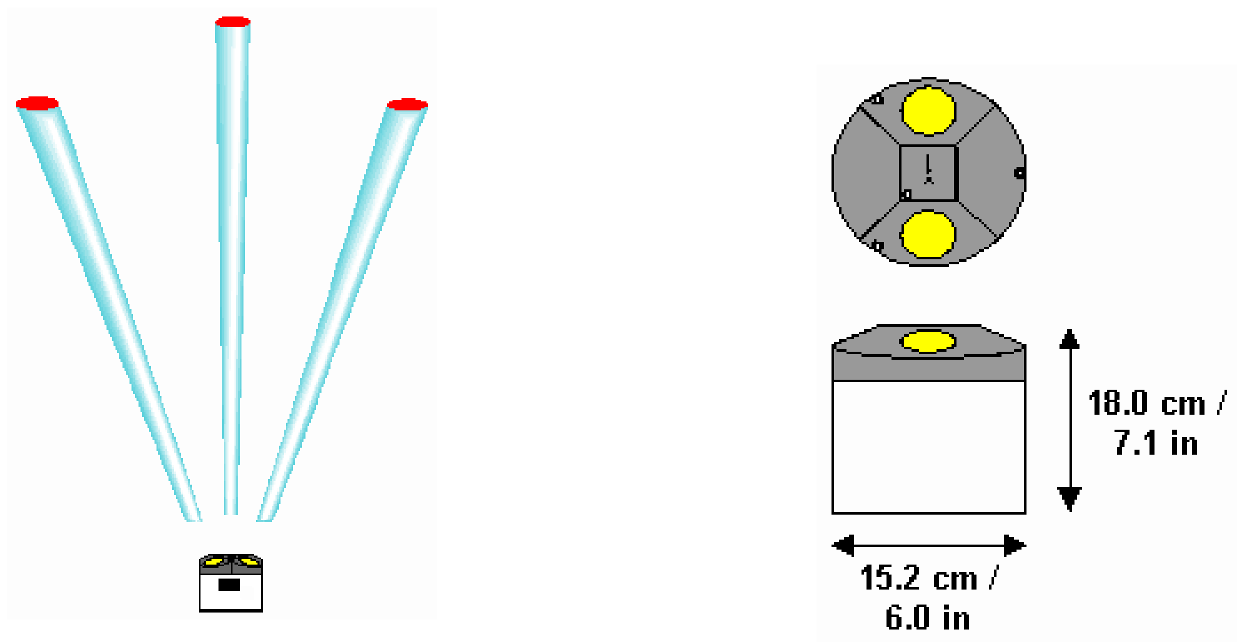


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| Final Malibu Lagoon Restoration and Enhancement Plan | The Argonaut SL in Concept | Figure 20 |
|---|---|---|

It may also be useful to perform a response survey immediately following severe storm flood events greater than the 25-year storm as determined by flow measurements from the Malibu Creek gage.

The survey should be conducted by a professional team to ensure surveys are repeatable over time. The first survey is the most expensive at nearly $20,000, because all survey monuments need to be established. All subsequent surveys are lower, at nearly $10,000. The costs are lower if clear water allows visual assessment of the lagoon bed thus reducing the need for ground shots.

Analysis of the change in sediment volumes throughout the site is to be done and should cost ~$5,000 for a qualified individual to calculate the volume changes along cross-sections and interpret the data.

***Sediment Sampling***

Surface sediment samples (top 0-2 cm) will be collected bi-annually (end of April and end of September) at 4 locations within the lagoon (3 cross-section locations in the West Arm and one within the main channel) to evaluate the spatial circulation dynamics of the existing and restored lagoon. Sediment samples will be submitted to a laboratory for testing of grain size distribution and total organic carbon (TOC), total nitrogen (TN) and total phosphorous (TP) concentrations. The seasonal and temporal sediment sampling results will allow the evaluation of the storm flow capability to scour organic material from the previous summer, the distribution of storm flow deposition of sand and relative supply of nutrients emanating from the sediments. The results from the sediment sampling will be used to evaluate the success of the restoration and help guide adaptive management decisions.

*Pre-restoration preparation:* Qualified staff will coordinate sampling handling procedures and select the analytical facility to perform the grain size and nutrient analyses. Qualified staff will coordinate sample container obtainment based on analytical facility needs. A sampling apparatus will be constructed to allow sampling during times of site inundation. All samples will be analyzed for grain size distribution in order to obtain the following size distribution information for each sample:

- Greater than Sand: >2.0 mm
- Sand: .05 to 2.0 mm in diameter
- Silt: .002 to 0.5 mm in diameter
- Clay: less then .002 mm in diameter
- Average size (d50) (um)

Sediment samples will also be analyzed for total nitrogen, total organic carbon and total phosphorous concentrations.

*Pre-restoration monitoring:* The 4 sediment sampling transects are indicated in Table 7 and correspond with the cross-section sites. In order to eliminate variability, a minimum of 5 sediment samples will be collected at each transect, sampling distinct habitat types (bank, bar, channel thalweg, and mudflat), and should be collected to represent the variation within the cross section. Sample locations should be marked by GPS and resampled at each sampling event regardless of inundation regime. Data from the analytical laboratory should be submitted directly to the qualified staff. Sampling should continue according to the schedule in Table 7 until construction commences.

*Post-restoration monitoring:* Following construction, sediment sampling should ensue at the restored sites and schedule presented in Table 7.

#### *Photographic Point Time Series*

Photographic points will be established at each of the terrestrial monitoring locations depicted in Figure 16. The direction and orientation of the photographs will remain consistent throughout the pre and post monitoring program. Photographs will be taken seasonally (4 times per year) and a photograph log will be maintained to qualitatively evaluate the visual changes within the lagoon over time. Information concerning climate, sandbar conditions, stream flow discharge, tidal heights, etc, will be noted along with date and time of each site photograph.

*Pre-restoration preparation:* The qualified staff and selected monitoring personnel will preview the site and establish the specific direction of each photographic point at the stations indicated in Figure 16 and Table 7. The qualified staff will generate a map to indicate the specific locations and directions of the photographic points. A photo logging, labeling and storage system will be developed by the qualified staff.

*Pre-restoration monitoring*: The photographic points will be monitored by the same personnel who maintain the continuous water quality instruments every 30-45 days.

*Post-restoration monitoring:* The photographic points will be monitored by the same personnel who maintain the continuous water quality instruments every 30-45 days.

### Chemical

The following parameters will be monitored by trained professionals selected by the qualified staff team. The following monitoring requires a significant amount of specialized field equipment that most aquatic and habitat qualified staffs possess or should obtain to properly perform the monitoring requirements of this plan. Table 8 provides a list of the required equipment to perform monitoring components and the estimated associated costs.

#### *Continuous Ancillary Water Quality (Water Temperature, DO, Salinity, Conductivity, pH, ORP)*

The continuous water quality monitoring provides a number of benefits to accurately assess the dynamic nature of Malibu Lagoon. Due to the cost of these instruments and the seasonal water quality dynamics of lagoon environments, it may not be prudent to have them deployed during rainfall/runoff events (November through March) to reduce the probability of instrument loss. The instruments should be deployed and maintained continuously each year from April up until the first significant runoff event of the season. During tidally-dominated conditions, dissolved oxygen, temperature and salinity data collection at strategic locations will identify the extent of penetration of saline, oxygenated, and cooler (oceanic) water exchange in the western arm sites at various tidal elevations and cycles. The ancillary water quality data will also provide information on the biogeochemical cycling as a function of climate and season during open conditions. Deployment during open conditions must be done considering their potential for vandalism and/or theft. They must be secured and optimally be screened from sight, and possibly maintained covertly to minimize the potential for vandalism and/or theft.

During closed conditions, measurements of dissolved oxygen, water temperature, ORP and salinity in the bottom water column will be collected over the duration of closure at 3 locations, one in the main channel and two in the western arm area. To control for inter-annual variability, data in the restored areas will be compared to the main channel conditions as well as baseline (pre-restoration) conditions at the functionally similar sites. Water temperature is an indication of solar exposure and water circulation. Minimum and daily variation of ORP and DO values are direct proxies for biogeochemical cycling and aquatic habitat conditions. DO is significantly influenced by primary production and respiration rates and will provide data regarding the seasonal and spatial magnitude of eutrophic conditions. ORP is the ability of water to oxidize or reduce. The ORP is measured in millivolts (mV), with positive values indicating an oxidizing behavior and negative values indicating a reducing behavior. When DO values get very low, the relative negativity of ORP in an aquatic environment provides insight on the magnitude of anaerobic (reducing) conditions. Frequency and duration of critical conditions such as low dissolved oxygen levels, ORP values, and elevated water temperatures will be evaluated to assess restoration performance. Measurement of surface water temperatures at the automated sites will provide maximum daily surface temperatures and be compared with bottom water temperature time series to map the degree of thermal stratification in 3 locations over time.

*Pre-restoration preparation:* Additional equipment is required to perform and maintain continuous monitoring equipment, including 3 YSI 600XLM data loggers shown in Figures 17 and 18 and described in Appendix B, pH/ORP probes, calibration solutions, HoBo temperature loggers and hardware for proper and secure deployment. Equipment will be purchased with the intent that State Parks will need all necessary cables, software, calibration solutions and other components to maintain the instruments on a regular basis. State Parks will need a field laptop or palm pilot to download data files on site. Qualified staff will design and install the equipment hardware within the lagoon for proper instrumentation deployment. The qualified staff will remove the equipment hardware prior to construction, and store for reinstallation following restoration activities. One or more units may remain during construction if the unit does not impact construction and may provide valuable construction water quality monitoring data. The qualified staff will train the designated staff personnel on instrument maintenance, calibration, data management and storage.

*Pre-restoration monitoring:* The YSI 600XLM data loggers must be removed and serviced every 30-45 days for proper operation. The HoBo temperature loggers may need to be serviced every

6 months to ensure proper operation. Following the initial training by the qualified staff, maintenance of the automated instrumentation will be the responsibility of the staff personnel.

*Post-restoration monitoring:* Following construction, instruments will be reinstalled in the new locations designated in Table 7 by the qualified staff. The maintenance of the instruments post-construction will remain the responsibility of the staff personnel. Data sharing from the staff to the qualified staff will follow strict procedures to ensure all data is provided electronically to the qualified staff over the course of the monitoring.

### *Manual Water Quality Sampling*

#### Vertical Profiles

Bi-annual vertical profiles (0.5 foot intervals) of ancillary water quality parameters (DO, temperature, pH, salinity) at 6 sites will allow the expansion of the spatial representation of the continuous data loggers in addition to providing a QA/QC method to ground truth the continuous datasets. Turbidity will be measured with a turbidity meter. This information complements the vertical profile, nutrient and chlorophyll sampling.

*Pre-restoration preparation*: Qualified staff will obtain the necessary equipment to perform vertical profile measurements of DO, temperature, pH, and salinity as shown in Table 8. Field data sheets and a data management database will be developed by the qualified staff to ensure proper data maintenance and field collection.

*Pre-restoration monitoring* : The location and timing of vertical profile sampling is provided in Table 7. Vertical profiles should be conducted at that same time of day for each monitoring event and efforts should be made to correlate the time of day to an outgoing tide during open sandbar conditions. At each of the 6 stations, ancillary water chemistry parameters (DO, temperature, salinity, and conductivity) are collected with a hand held multi-parameter probe from a floating platform (e.g., kayak, boat, inflatable raft, paddleboard) at 0.5 foot intervals by securing a weight to the YSI probe and measuring tape-marked depths. With every vertical profile, turbidity will be measured using a turbidity meter. Data sheets should used and data should be entered into the digital database upon return to the office.

*Post-restoration monitoring:* The same procedures will be conducted at the restored monitoring sites indicated on Table 7.

#### Surface And Bottom Water Nutrient Sampling

Bi-annual surface water (1 foot below surface) and bottom water samples will be collected at the 6 vertical profile sites. Surface water samples will be analyzed for nitrogen (N) and phosphorous (P) species and chlorophyll a. Bottom water samples will be analyzed for the suite of primary nutrient only (N and P). The surface water sampling will provide a dataset to evaluate the concentrations of total and biological available fractions of nutrients required for primary production. Surface water chlorophyll data will provide an indication of the primary producer metabolic inputs from phytoplankton and algal communities.

The establishment of the temporal and spatial sampling protocols will allow continual monitoring of the water quality benefits of future source control efforts on the nutrient conditions within the Malibu Lagoon. The collection and evaluation of bottom water nutrient levels will allow a quantification of the degree of biogeochemical cycling occurring within the lagoon and additional data regarding the magnitude of surface sediment regeneration of nutrients. The seasonal and long term nutrient data will provide invaluable information on the long-term restoration of water quality within the Malibu Lagoon.

*Pre-restoration preparation*: Qualified staff will obtain the necessary equipment to conduct water quality monitoring Table 8. The vertical profile data base will include nutrient and chlorophyll sampling results at each station during each monitoring effort to ensure proper data management.

*Pre-restoration monitoring*: Surface water nutrient sample collection will be concurrent with vertical profiles at all 6 stations indicated in Table 7. Bottles will either be purchased or obtained from the analytical laboratory. Bottles are triple-rinsed instream, surface sample collected (do not fill completely), labeled with station, date and other relevant information and put on ice immediately until filtered or delivered to the laboratory. Samples must be filtered or delivered to the laboratory within 3 hours of collection. If filtered on site, personnel should use a 0.45 uM filter, Masterflex tubing, battery operated pump, to transfer the filtered sample to a pre-rinsed 30 ml bottles (or whatever volume is recommended by the analytical facility). Filtered samples are stored in a freezer until delivery to lab. Holding times of frozen filtered samples can be up to 28 days from date of collection. Chain of custody documenting sample label, date/time collected, and sample identification will accompany samples to the laboratory. At least one field replicate will be collected during each sampling effort to quantify field sampling precision. At each sampling location bottom water samples should be collected using a Van Dorn sampler and submitted for nutrient analyses. Samples are to be filtered and stored, or placed on ice and delivered to the laboratory in the same manner as surface samples.

All water samples should be submitted to an analytical laboratory for the following analyses:

- Total dissolved organic nitrogen (TKN);
- Dissolved nitrate ($NO3-$);
- Dissolve nitrite ($NO2-$);
- Dissolved ammonia ($NH4+$);
- Total dissolved phosphorous (TP);
- Soluble reactive phosphorous (SRP).

Additional surface water samples should be collected at each site in 250 mL amber bottles and submitted for chlorophyll a concentrations. Samples should be immediately placed on ice following collection. Samples must either be submitted to the laboratory with 3 hours or collection or filtered on-site. If filtered by field personnel, all filtration should occur away from direct sunlight. Watman 0.45 uM 25mm glass microfiber filters are placed on a screen using forceps. A carefully measured amount of sample (using a graduated cylinder) is added to a funnel filtration system designed with a hand pump to create a vacuum and slowly pull the sample through the filter. Following filtration, the volume of sample filtered is documented and the filter is removed with forceps and placed in aluminum foil for labeling (date, time, site, volume filtered) and storage (frozen at < $4^{o}$C until analysis within 28 days).

Post-restoration monitoring: The same procedures will be conducted at the restored monitoring sites indicated on Table 7.

**Biological**

Biological Components

***SAV/Algal Percent Cover Monitoring***

Submerged aquatic vegetation (SAV) and macroalgae are to be monitored at each of the non-marsh sampling stations (anticipated to include Stations 1-6 and 8). Monitoring shall be conducted during the months of April and September of each year preceding as well as for a period of five years post restoration. Each station will be represented by three replicate $1m^2$ square enclosure randomly placed within 10 meters of the station coordinates. The percent algal and SAV covers will be individually estimated at each station. Depth to surface of SAV and location of algal in water column should be noted. Samples should be collected of each species observed, properly labeled and identified.

*Pre-restoration preparation:* Qualified staff will prepare field data sheets and photo identification cards to be completed and used during field monitoring. Qualified staff will prepare the database format to maintain field data in digital form.

*Pre-restoration monitoring:* SAV/algal surveys will be conducted in the locations according to the schedule presented in Table 7.

*Post-restoration monitoring:* The same procedures will be conducted at the restored monitoring sites indicated on Table 7.

***Habitat/Vegetation***

Permanent Transect Monitoring Program

At each Site 1-9, a baseline transect will be established perpendicular to the shoreline such that it crosses the maximum vertical range beginning at or near the identified station location. Points will be established along each baseline within each habitat zone represented on the transect. At each point a 20-meter (m) fiberglass measuring tape shall be extended away from the baseline, parallel to the shoreline. Transects will be marked with PVC stakes at the beginning of the survey program and coordinates will be obtained using a Differential GPS to aid in stake relocation or replacement if necessary during the course of monitoring.

Along each transect, the percent cover of plant species and bare ground/open water shall be recorded. Cover of individual plant species shall be recorded for each meter along the 20-meter transect, and percent cover of plant species and bare ground/open water will be determined using the line-intercept method (PERL 1990). Plants and bare ground/open water are to be recorded only if a part of the plant or bare space falls underneath the visual line of the fiberglass measuring tape. The minimum unit of intercept recorded shall be one decimeter. Often, percent cover along a transect will exceed 100% due to overlapping canopy layers.

If resources are available, soil and/or water salinity shall also be determined along each sampling transect. Soil salinity are to be estimated using a 10-centimeter (cm) soil core. Water is to be filtered from soils using a syringe containing two No. 1 filter papers. Interstitial soil water will be pressed onto a salinity refractometer and salinity will be estimated to the nearest part per thousand (ppt). If a transect occurred in an open water area, water salinity shall be measured instead with the salinity refractometer. A 200 milliliter (ml) sediment sample is to be randomly collected along each transect, transported to the laboratory, and analyzed for grain size distribution and total organic carbon (TOC).

Vegetation Mapping: Utilization of Aerial Photography and Field Truthing

In order to facilitate vegetation mapping, as well as the long-term vegetation trend analyses, color infrared (CIR) aerial photography is to be used. The photography products provide a base-map for ongoing field studies, facilitate vegetation community and habitat association classification, and allow for analysis of change in each vegetation community. The CIR photography is to be acquired during flights conducted at low tides during open lagoon conditions in the later spring months. This allows photography of as much exposed intertidal habitat as possible. The imagery is to be acquired each year or at other regular intervals (such as every five to ten years) during the same approximate seasonal and tidal conditions to allow for a comparison of any changes that occur within the lagoon and provide the basis for long-term vegetation trend analysis. The aerial imagery can be acquired as part of the aerial survey for topography/bathymetry previously discussed. Both efforts should be combined to reduce costs and maximize effectiveness.

Using the aerial photograph and field truthing, the conditions within the lagoon should be mapped in a spatially rectified and consistent coordinate system using GIS to produce year to year maps of the lagoon and to identify any progressive changes in lagoon conditions.

*Benthos*

Benthic surveys are to be conducted at Stations 1 through 9. Station profiles are outlined as follows in Table 6 below.

**Table 6 – Benthic Survey Station Profiles**

| STATION | TARGET ELEVATION (FEET MSL) | DESCRIPTION |
|---|---|---|
| 1 | 0 feet or lower channel bottom | Upper main lagoon |
| 2 | +1 feet or lower channel bottom | Upper slough channel |
| 3 | +2 feet | Mudflat – central bar |
| 4 | 0 feet or lower channel bottom | Middle slough channel |
| 5 | +2 feet | Mudflat – western arm |
| 6 | -2 feet or lower channel bottom | Lower slough channel |
| 7 | +4 feet | Seasonally inundated marsh |
| 8 | 0 feet or lower channel bottom | Lower main lagoon |
| 9 | +4 feet | Seasonally inundated marsh |

Benthic sampling shall be conducted in August of each year in order to characterize communities at the most stressful period of the year. Sampling shall be undertaken annually preceding and following restoration. A differential GPS will be used to accurately locate sampling stations during each of the sampling efforts. Following restoration, it may be necessary to relocate stations slightly in order to maintain desired reference elevations and habitat type equivalency. Once station relocation is conducted, monitoring station locations should be maintained to the greatest extent practical to maintain habitat equivalency in sampling. Field crews must possess a valid California scientific collectors permit issued by the California Department of Fish & Game.

At each station, three replicate cores shall be collected along the station's sampling isobath using a large (15 cm) diameter corer pushed 15 cm into the sediment surface. An additional core shall be collected at each benthic station and shall be used for analysis of TOC, sediment grain size analysis, and TKN.

Each of the three benthic sample replicates shall be rinsed through a 1.0 mm sieve. Organisms from each sample shall be preserved in a buffered 10% formalin:seawater mixture, and transported to the laboratory. Between three and ten days, samples will be rinsed and transferred to 70% ethanol for laboratory taxonomic analysis and for long-term archival of samples. Following sample transfer to alcohol, all individuals in each replicate sample are to be identified to the lowest practical taxonomic level (typically species) and then counted. The occurrence of nematodes, foraminiferans, and pelagic organisms not classified as infauna or which were too small to quantify shall be noted; however, these organisms are not to be quantified. The benthic community characterization shall principally be structured to provide an indication of the relative availability and abundance of infaunal and epifaunal organisms within the various regions of the lagoon and to provide a means to evaluate community profiles using such tools as a benthic response index (BRI).

Organisms shall be grouped by phylum and weighed to determine the wet weight biomass of each phylum in each replicate sample. Wet weight is to be determined by transferring organisms, including alcohol, onto a paper towel and blotted quickly to remove excess liquid from the animals. Organisms are then to be transferred to a tared weighing dish and weighed to the nearest 0.001g using an analytical balance. Samples shall be stored in 70% alcohol for future review.

*Epibenthos*

Epibenthic sampling shall be conducted coincident with fish communities studies described in the following section. The epibenthic invertebrate by-catch collected in the fish-sampling program will be identified and counted to characterize changes in the distribution, composition, and abundance of these organisms within the lagoon. For species that cannot be identified in the field, collections will be made for subsequent laboratory taxonomy. A voucher collection shall be prepared for invertebrate species. Collected and archived individuals shall be preserved in a 10% formalin:seawater mixture for 3 to 10 days prior to transfer to 70% ethanol for archival.

*Pre-restoration preparation:* The qualified staff will prepare field instructions, data sheets and site maps for the completion of field surveys. The qualified staff shall assist the volunteer field teams in the acquisition of appropriate sampling equipment and will train field teams in equipment use. Field survey teams shall be assembled from State Parks staff or local volunteers. Those participating in the taxonomic identification must be qualified to make accurate species identifications of most of the collected organisms to avoid large volumes of laboratory work.

*Pre-restoration monitoring:* The qualified staff will participate in a first survey event with staff and volunteers to establish survey protocols and resolve any unforeseen data collection or recording issues. Following a first field survey, staff and volunteers will conduct further surveys and will coordinate with the qualified staff as necessary to ensure consistent data collection methods are employed. For benthic samples and unidentifiable epibenthos, preserved samples shall be preserved in formalin, transferred to alcohol, and shipped to a qualified benthic laboratory to accomplish sorting, taxonomy and biomassing tasks.

*Post-restoration monitoring:* Following construction, staff and volunteers will continue annual field surveys for a period of five years and shall continue to use qualified benthic laboratory support services.

*Fish Communities*

Four fish sampling stations are to be established within Malibu Lagoon to characterizes fish communities in all aquatic environments represented in the system. A differential GPS will be used to accurately locate sampling stations during each of the sampling efforts. Fish sampling shall be undertaken at each station during daylight hours in late summer of each year. While sampling during other periods of the year would be expected to yield potentially different fish communities, the period of greatest concern relative to potential system stress is middle summer and as such this is the period of greatest interest in evaluating effectiveness of restoration efforts and necessity for implementation of adaptive management efforts. Implementation of the fish sampling efforts requires possession of a valid California scientific collectors permit issued by the California Department of Fish & Game and a California State Parks Department special use permit. In addition, given the reasonable expectation of capturing the federally-listed tidewater goby, a federal Endangered Species Act section 10(a) permit is required to conduct fish sampling in the lagoon.

<u>Methods:</u>

Using at least two 6 foot by 20 foot blocking nets, set up sampling areas in a minimum of 4 locations:

1. near the mouth of the lagoon
2. at the outlet of channel C
3. along the west edge near the bird peninsula
4. upstream of the PCH bridge on the west bank

A 4 foot by 10 foot 1/8$^{th}$ inch mesh minnow net affixed to 2 PVC poles is pulled across the water body, with the weighted bottom of the net kept firmly along the substrate, and the net angled to prevent fish from escaping. At the end of each pull, the net is raised and all fish species are counted, sized, and released. Distances for each seine pull vary depending on the locations. In creek channels, pulls start downstream and move upstream if the channel is small enough.

In addition to documenting numbers, size class, reproductive status of individuals and their characteristics, the location of the seine, direction of pull, distance seined, habitat characteristics are also noted.

At the start of each event, water quality observations are taken, including, depth, temperature, dissolved oxygen, salinity, pH, and in the case of creek channels, flow.

If a haul includes so many fish that keeping them in the net for counting is not possible, then buckets filled with water are used to sort each species before release.

<u>Deliverables</u>:

1. Excel spreadsheet will all field data
2. Report providing summary of all observations and recommendations for protecting the gobies during restoration implementation.
3. Map of seine locations and goby distribution areas.

4. Electronic copies of all materials.

*Pre-restoration preparation:* The qualified staff will prepare survey instructions, data sheets and site maps for the completion of field surveys. The qualified staff shall assist the volunteer or staff field teams in the acquisition of appropriate sampling equipment and will train field teams in equipment use. Field survey teams shall be assembled from State Parks staff or local volunteers.

*Pre-restoration monitoring*: The qualified staff will participate in a first survey event with staff and volunteers to establish survey protocols and resolve any unforeseen data collection or recording issues. Following a first field survey, staff and volunteers will conduct further surveys and will coordinate as necessary to ensure consistent data collection methods are employed.

*Post-restoration monitoring*: Following construction, staff and volunteers will continue field surveys for a period of five years.

*Avian Communities*

A qualified ornithologists shall conduct general avian surveys during the months of January, April, July, and October. If resources are available, more frequent survey should be conducted. In addition, it would be beneficial to set up a program that promotes an ongoing archive database of filed sightings. For example, Cornell Laboratory of Ornithology's "eBird" project may be used as a centralized database of Malibu Lagoon bird sightings (see www.ebird.org). It is also important to include specific breeding bird surveys such as those outlined in the Breeding Bird Atlas, standard territory mapping procedures, and Audubon/Association of Field Ornithologists "Breeding Bird Census" techniques.

For general surveys, the lagoon is to be surveyed on foot using binoculars and spotting scopes. The entire lagoon is to be broken into 4 geographic zones defined as the Western Arm, the Main Lagoon, the East Shore and the berm/beach. The lagoon is to be surveyed twice, on two consecutive days during each of the quarterly survey events to minimize the probability of missing any species that may have not been present or not observed on a particular day. Surveys typically occur in the early morning and can be completed in several hours at this site. The survey team walks the zone that they are assigned to observe. They are to use existing trails for completion of surveys and shall reverse the direction of travel between the two survey dates. Surveys during open lagoon periods shall be conducted at approximately mean sea level tidal elevations. Data collected included species and individual counts, time of day, activities of the birds (e.g., foraging, flying, resting, and courting), and habitats in which the birds occurred (open water [> 1 foot depth], shallow water [<1 foot depth], as well as habitat represented in the existing lagoon conditions or the restored conditions such as mudflat, sand beach, gravel shoals, salt marsh, brackish marsh, cattail/tule marsh, willow riparian, upland disturbed including landscaped park areas and hardscapes, and upland scrub.

The habitats utilized shall also be categorized as open shoreline, peninsulas, islands, and open water. Additional data collected shall include any factor affecting the behavior of birds, such as an injury or the presence of a predator. Weather conditions, including air temperature, wind speed, wind direction, cloud cover, precipitation, and water level, shall also be recorded once each hour through the course of the surveys. A count or approximation of the number of human visitors on the beach on an hourly basis and direct disturbances should also be noted (e.g. unrestrained dogs on the beach or in the lagoon, rock-throwing children, etc.).

After each survey, the data shall be entered into a database for subsequent analyses. All habitat, behavioral, and distributional observations shall be used to analyze avian use of the lagoon environments. The average bird counts by species over the two day survey period as well as raw data shall be included in a report to evaluate avian abundance and density within the lagoon and represented habitats during the survey interval.

*Pre-restoration preparation:* The qualified staff will prepare survey instructions, data sheets and site maps for the completion of field surveys. Field survey teams shall be assembled from State Parks staff or local volunteers.

*Pre-restoration monitoring:* The qualified staff will participate in a first survey event with staff and volunteers to establish survey protocols and resolve any unforeseen data collection or recording issues. Following a first field survey, staff and/or volunteers will conduct further surveys and will coordinate with the qualified staff as necessary to ensure consistent data collection methods are employed.

*Post-restoration monitoring:* Following construction, staff and/or volunteers will continue a minimum of quarterly field surveys for a period of five years.

## 5.6 PARAMETERS EVALUATED TO FACILITATE ADAPTIVE MANAGEMENT

The Malibu Lagoon Restoration Monitoring Plan has been designed to provide a management mechanism by which to evaluate the success of the Restoration implementation with respect to the goals stated in section 5.4 and to improve specified components of Lagoon function. A robust evaluation requires consistent data collection parameters and associated techniques during existing and restored conditions to allow confident conclusions that measured differences are due to Lagoon physical, chemical and ecological improvement and not an artifact of sampling variability.

In theory, constraining all spatial and temporal variability to confidently attribute measured change to restoration efforts should be feasible, but in many instances the complexity and dynamic nature of the seasonal lagoon will leave many questions unanswered. An expansive restoration monitoring program, as the one developed herein, will provide a diverse breadth of site-specific physical, chemical and biological information to both improve our understanding of the ecological function of these complex systems, as well as providing quantitative data from which evaluations of restoration, enhancement and source control actions can be assessed well into the future.

Specific performance criteria to observe in post-restoration monitoring are provided below. Triggers and options for adaptive management are also included where appropriate, however, adaptive management options should not be constrained to those listed below.

Goal: Improved water circulation in restored areas over existing conditions.

Specific Lagoon Performance Criterion: The restoration effort expects that a tidal and hydrologic connection will be maintained between the western arm and main channel of the Lagoon. Development of a sand bar that isolates the western arms from the main channel should be removed as soon as feasible to restore intended water circulation. Continual occurrence of sandbar formation (3 times over a 6 year period) should signal the need for adaptive management alternatives and reevaluate lagoon hydrodynamics as a result of restoration.

Adaptive management may be needed to achieve and maintain desired lagoon circulation over time. Measurements of circulation and water quality parameters will indicate if the project is functioning as desired or if modifications are needed to improve the desired effect. Signals, or triggers, to indicate the need for adaptive management can vary from open to closed conditions.

Potential triggers for adaptive management that may be observable during open conditions are if:

- The west arm main channel closes off from the main lagoon by sedimentation, and/or
- Peak tidal flow velocity drops to less than 0.25 feet per second, and/or tide range drops to 1 foot during spring tides. This value is an estimate based on adequate tidal flushing measured at other sites (Carpinteria Marsh, Talbert Marsh, and Batiquitos Lagoon), and observations made at Malibu Lagoon in the summer of 2004 (M&N, 2005).

Potential adaptive management actions for open conditions include those listed below in order of preference:

- Do nothing and allow the entire lagoon to close and fill during summer, and monitor the natural breach the following fall season to identify if the sediment deposit is scoured; or
- Manually open the closure between the west lagoon and main lagoon with either hand-held equipment or larger earthmoving equipment such as a backhoe; and/or
- Create a connection to the main creek via an alternate path to route water through the West Arms to eventually breach the barrier to the main lagoon.

Potential triggers for adaptive management than may be observable during closed conditions include if:

- Water quality data indicate significant and persistent stratification of lagoon waters (either thermally or density driven, e.g., salinity differences) and indications of depressed bottom water DO and ORP values;
- Significant areas of algal mats form and persist for many days to weeks; and
- Lagoon stagnation is obvious and areas of the surface collect algal mats, debris, and scum.

Potential adaptive management actions for closed conditions include those listed below in order of preference:

- Create a connection to the main creek via an alternate path to route water through the West Arms; and/or
- Consider installing circulation devices to move water artificially as a last resort if watershed sources of nutrient persist and nutrient loading to the lagoon remains a problem.

Specific Lagoon Performance Criterion: Results from the hydrologic monitoring should indicate sustained sediment transport velocities to mobilize and expel fine grained sediments from the west arm sampling locations during sufficiently high flow events. Residence of mainly sand size particles in the channels of the west arm areas should be consistently observed at the sampling sites. Grain size distribution (percent sand in the sample and/or of the median grain size, $D_{50}$) at each sampling location should increase by 20% (based on the judgment of the qualified project ecologist/scientist) from baseline monitoring conditions. Grain size distribution in west arms should be compared to results from main channel sites and should not result in less than 80% sand relative to main channel results for the same sampling period (also as judged by the qualified project ecologist/scientist). As judged by the qualified project ecologist/scientist, adaptive management alternatives should be seriously considered if any one of the following is observed in the grain size data:

1. If any one site fails the grain size criteria above for 6 consecutive samplings (3 consecutive years);
2. If any one site in the west arm has less than 60% of the sand fraction of the main channel for 4 consecutive samplings (2 consecutive years); or
3. If the average of any transect in the west arm contains predominantly (>50%) clay and silt-sized particles ($D_{50}$<50 micrometers, um) for 4 consecutive sampling efforts (2 consecutive years).

Time series velocity estimates from the water budget and the cross-sectional changes over time should be evaluated in concert with the sediment grain size data to provide additional insight to the broader temporal, spatial and physical mechanisms potentially responsible for the system's circulation performance. The grain size distribution data (especially for early spring data) should be evaluated in light of the Malibu Creek hydrology and climatic conditions during the wet months of the year. Annual precipitation totals, timing and magnitude of peak stream flows and estimates of annual peak reoccurrence intervals will allow more informed comparisons of grain size distributions across various water years.

Specific Lagoon Performance Criterion: Results from continuous water quality monitoring at 3 strategic locations should indicate an increase of tidal mixing and exchange during tidally-dominated, open lagoon conditions. The degree of tidal influx on the water quality of the western arm areas should be thoroughly investigated. The time series DO, temperature, ORP and salinity data will be evaluated in concert with tidal elevation data to determine the critical tidal elevation necessary to introduce relatively nutrient poor, cooler, higher DO water to the west arm locations. Although that tidal elevation may change over time, the intent is to identify a threshold tidal elevation condition that could be expected to promote flushing of the western arms that can be a benchmark over time. Significant changes in this threshold elevation (*e.g.*, by 50%) may signal significant changes occurring within the lagoon system.

The magnitude and frequency of observed water quality changes as a result of flushing should be linked to tidal elevations to improve the understanding of the existing and restoration hydrologic dynamics of Malibu Lagoon. At least 12 occurrences of DO, salinity, and water temperature differences during a flushing event (transition from low to high tide) should be recorded during tidally-dominated conditions each year and compared to both main channel results (monitoring station 1) for the same time period and with comparable data (same relative tidal flux) for pre- and post-restoration conditions.

As judged by the qualified project scientist, adaptive management should be considered if data described above indicate any of the following as measured by continuous water quality monitoring during open conditions:

1. 2 consecutive years where DO values do not increase in the bottom waters by an average of 20% at high tide relative to previous low tide values (over an 8-hour period) during maximum tidal elevations over 5 feet;
2. 2 consecutive years where minimum DO concentrations are more than 50% below those observed in the main channel during the same time periods during tidally-influenced conditions;
3. 2 consecutive years where overall DO concentrations do not show at least a 20% improvement during similar flushing events at the same site during restored, relative to existing conditions;
4. 2 consecutive years where average salinity values during tidal flushing events are less than 50% of the salinity observed in the main channel; and/or
5. 2 consecutive years where average bottom water/surface water temperature differences are more than 3 times greater than the gradients observed in the main channel.

The continuous water quality data record will provide numerous other comparisons of lagoon physical and chemical function during open conditions between existing and restored conditions, as well as spatially within the restored lagoon (main channel versus west arm sites). Standardizing the data for tidal variations will improve the validity of the comparisons.

Specific Lagoon Performance Criterion: Results from continuous water quality monitoring at 3 strategic locations should indicate an increase in water exchange (e.g., mixing, movement, aeration, internal turnover) during closed lagoon conditions. Time series of water quality parameters provide insight to biogeochemical conditions and function. Improvements should occur in bottom water DO and ORP levels in the restored lagoon over existing conditions, as well as reductions in surface water temperatures in the western arms due to increased wind mixing and surface water movement. Water quality during closed conditions should be evaluated by comparing the frequency and duration of minimum DO and ORP values.

Site data should be compared to both baseline conditions at the analogous sites, as well as the use of the main channel water quality data as a reference to compare to the west arm restored area. Since closed lagoon conditions are most likely to have the poorest water quality conditions due to the excessive nutrient loading from surrounding land uses, the expectations for water quality improvements during this time should be limited. In the short-term (first 3 years), a 20% improvement in the frequency, duration and magnitude of the minimum DO, minimum ORP and maximum surface water temperatures relative the main channel conditions is feasible. Over the long-term (with progressive source control improvements), more significant improvements in the Lagoon water quality is likely.

Specific Lagoon Performance Criterion: Sediment nutrient (nitrogen, N, and phosphorous, P) concentrations influence biological activity and ultimately the Lagoon water quality and ecological health. Restoration efforts are expected to increase surface sediment grain size distribution throughout the west Lagoon, thus directly reducing the supply of N and P to primary producers from the sediment reservoir. The sediment nutrient data will directly complement the grain size distribution data to assess the performance of the restoration to reduce the supply of N and P. Adaptive management should be considered if:

1. The N and P sediment concentrations at any particular site are not reduced relative to existing conditions in the mean of sediment samples from any transect in the west lagoon following 4 consecutive restored monitoring efforts (2 consecutive years); ideally reductions should approach 30% relative to existing sediment quality.

Specific Lagoon Performance Criterion: Wetland vegetation communities should attain a percent cover of native species of 50% within 3 years and 90% within 5 years of restoration, as measured at vegetated habitats during peak growing conditions (late spring/early summer) prior to summer closure. If these goals are not attained, targeted studies should be performed to determine why goals are not being met and devise adaptive management solutions to achieve goals.

Specific Lagoon Performance Criterion: The abundance and diversity of fish and wetland avian species shall not decrease following restoration. Although a short-term decrease may be expected due to construction related impacts, fish and avian species should be at commensurate pre-restoration levels within 3 years of restoration activities. If these goals are not attained, targeted studies should be performed to determine why goals are not being met and devise adaptive management solutions to achieve goals.

## 5.7 QUALITY ASSURANCE / QUALITY CONTROL

A quality assurance/quality control program shall be undertaken for all aspects of the investigations conducted to ensure accuracy in field data collection, laboratory analysis, and data management. This program shall include pre- and post- calibration of sampling probes, review of datasets and removal of suspect data based on *a priori* data acceptance guidelines, consistent labeling of samples in the field, archival of laboratory samples and development and use of voucher collections and chain of custody forms, adherence to holding time requirements and adopted standard protocols for performance of tests and subsampling.

All field and laboratory results are to be recorded on pre-printed data sheets along with collection location, time, gear type, sample number, replicate, and collectors. Whenever possible, samples are to be worked up in the field or immediately after sampling. Live specimens are then to be released back to the point of capture. Representative individuals that are difficult to identify shall be transported to the laboratory and identified utilizing field guides and a dissecting microscope. In the laboratory, the investigator, date of analysis, and sample parameters are again to be recorded on hard copy data sheets. A voucher collection of fish species shall be created for future reference. A master list of species collected and photograph identification cards shall be utilized in the field to determine which species should be added to the voucher collection. If a new or unknown species is captured, it shall be transported to the laboratory where it is to be preserved, labeled (with species name, date, time, and location of collection), and added to the voucher collection.

For taxonomic laboratories, after the initial laboratory sorting, a second party shall select 10% of the samples and re-sort them for accuracy. A sample sorting efficiency of 95% of total number of individuals shall be considered acceptable for each sample. If more than 5% of the organisms in a sample is missed during the initial sorting (i.e. less than a 95% sorting efficiency), samples shall be resorted. Taxonomic verifications shall be addressed through completion of an independent review by a second taxonomist.

Computer data entry shall be verified by comparing the number of lines of data entered against the field data sheets, filtering the data for unreasonable entries to available data fields, and through conducting a number of rapid plot comparison tests, such as length:weight ratios for fish, to search for spurious outliers in the data and potential entry errors.

**TABLE 7 - Sampling Frequency and Locations**

| COMPONENT | DATA USE | DATA APPLICATION | FIELD PERSONNEL | PRE-RESTORATION FREQUENCY | SITES | POST RESTORATION FREQUENCY | SITES |
|---|---|---|---|---|---|---|---|
| **CEQA MONITORING** | | | | | | | |
| General Biological Resource Inventories (floral, fish, avian, mammalian, herpetological, entomological); Threatened and endangered species | Quantify existing project conditions to establish the project baseline for analysis of impacts from restoration | Assess pre-project conditions for environmental review and permitting | State parks staff and qualified professionals | Spring and summer seasons prior to preparation of the CEQA document and permitting | The entire lagoon south of PCH bridge | Not applicable | All 9 sites |

| COMPONENT | DATA USE | DATA APPLICATION | FIELD PERSONNEL | PRE-RESTORATION FREQUENCY | SITES | POST RESTORATION FREQUENCY | SITES |
|---|---|---|---|---|---|---|---|
| **RESTORATION PERFORMANCE MONITORING** | | | | | | | |
| **PHYSICAL COMPONENTS** | | | | | | | |
| **HYDROLOGIC MONITORING** | | | | | | | |
| Cross-section monitoring | 1. Water budget calculations to evaluate tidal circulation (volume flux and velocity time series) used for water level management<br>2. Time series of channel stability<br>3. Estimates of lagoon aggradation / degradation over time (sediment quantity) | Baseline conditions, Restored conditions Facilitate adaptive management | Biannually by qualified staff, potential to train State Parks personnel to expand sampling resolution | At least twice per year (April/Sept); potentially monthly | 4 sites - Sites 2, 4, 6, 7 | At least twice per year in April/Sept; potentially monthly | 4 sites - Sites 2, 4, 6, 7 |
| Water level monitoring with continuous data loggers YSI 600XLM | 1. Water budget calculations to evaluate tidal circulation (volume flux and velocity time series)<br>2. Time series of lagoon channel stability at key locations | Baseline conditions, Restored conditions Facilitate adaptive management | Trained by qualified staff, maintained by State Parks | April - Oct (30 min intervals) Instruments removed during storm flow conditions. | 3 sites Sites 1, 2, 6 | April - Oct (30 min intervals) | 3 sites Sites 1, 2, 6 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Velocity measurements | Manual instruments or in-situ instrumentation to calibrate velocity time series from water budget calculations | Baseline conditions, Restored conditions, model estimate calibration | Biannually by qualified staff, potential to train State Parks personnel to expand sampling resolution | At least 2x per year (April/Sept) potentially monthly | 4 sites (corres-pond to cross-sections) Sites 2, 4, 6, 7 | At least 2x per year (April/Sept) | 4 sites (correspond to cross-section locations) Sites 2, 4, 6, 7 |
| **SEDIMENT QUALITY AND QUANTITY** | | | | | | | |
| Sediment sampling for grain size, TOC, and TN and TP | 1. Grain size distribution, infer circulation conditions both pre and post restoration<br>2. Evaluate seasonal sediment nutrient flux | Baseline conditions, Restored conditions Facilitate adaptive management | Bi-annually by qualified staff | 2x per year April/Sept | 4 sites (5 samples per transect) Sites 2, 4, 7, 8 | 2x per year April/Sept | 4 sites (5 samples per transect) Sites 2, 4, 7, 8 |
| Aerial Topographic Mapping | 3. Sedimentation patterns and volumes throughout the lagoon | Baseline conditions, Restored conditions Facilitate adaptive management | Once every 5 to 10 years by a professional aerial survey firm | One time during low water conditions (spring) | Entire Lagoon south of Pacific Coast Highway | One time during low water conditions (spring) | Entire Lagoon south of Pacific Coast Highway |

| COMPONENT | DATA USE | DATA APPLICATION | FIELD PERSONNEL | PRE-RESTORATION FREQUENCY | SITES | POST RESTORATION FREQUENCY | SITES |
|---|---|---|---|---|---|---|---|
| **CHEMICAL COMPONENTS** | | | | | | | |
| **WATER QUALITY** | | | | | | | |
| Water level monitoring. Continuous data loggers YSI 600XLM | 1. Daily and seasonal, min, max and variations (frequency, duration) of key water quality parameters (DO, water temp, ORP, pH and salinity).<br>2. Evaluate restoration impact on water quality conditions in very chemically dynamic system.<br>3. Tidal circulation. Daily and seasonal variations in dissolved oxygen, water temperature, salinity, pH, ORP as influenced by tidal cycles.<br>4. Closed lagoon water quality | Baseline conditions, Restored conditions Facilitate adaptive management | Trained by qualified staff, maintained by State Parks | April - Oct (30 min intervals) | 3 sites Sites 1, 2, 6 | April - Oct (30 min intervals) | 3 sites Sites 1, 2, 6 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Vertical Profiles (Ancillary parameters) | 1. Expand the spatial (vertical in water column and horizontally throughout lagoon) representation of continuous water quality data.<br>2. Calibration of continuous monitoring equipment | Baseline conditions, Restored conditions Facilitate adaptive management | Bi-annually by qualified staff | 2x per year April/Sept | 6 sites Sites 1, 2, 4, 6, 7, 8 | 2x per year April/Sept | 6 sites Sites 1, 2, 4, 6, 7, 8 |
| Nutrient sampling Surface and bottom water samples:<br>TKN<br>TP<br>Dissolved species include:<br>Nitrate<br>Nitrite<br>Ammonia<br>Soluble reactive phosphorous | 1. Evaluate the degree and extent of biogeochemical nutrient cycling occurring in Malibu Lagoon, pre and post restoration.<br>2. Begin a standardized long-term primary nutrient monitoring effort of specific constituents (N and P) for future watershed source control efforts. | Baseline conditions, Restored conditions. Establish long-term nutrient monitoring in lagoon (key components of long-term water quality) | Bi-annually by qualified staff | 2x per year April/Sept | 6 sites Sites 1, 2, 4, 6, 7, 8 | 2x per year April/Sept | 6 sites Sites 1, 2, 4, 6, 7, 8 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Chlorophyll sampling | 1. Evaluate primary productivity contribution of phytoplankton<br>2. Begin a standardized long-term chlorophyll monitoring effort to evaluate success of future watershed source control efforts. | Baseline conditions, Restored conditions. Establish long-term nutrient monitoring in lagoon (key components of long-term water quality) | Bi-annually by qualified staff | 2x per year April/Sept | 6 sites Sites 1, 2, 4, 6, 7, 8 | 2x per year April/Sept | 6 sites Sites 1, 2, 4, 6, 7, 8 |
| Surface water temperature monitoring (HoBo data loggers) | Tidal and closed lagoon circulation.<br>1. Daily and seasonal variations in surface water temperature as influence by local climate<br>Time series of spatial lagoon differences in vertical water temperature gradients. | Baseline conditions, Restored conditions Facilitate adaptive management | Trained by qualified staff, maintained by State Parks | April - Oct (30 min intervals) | 3 sites Sites 1, 2, 6 | April - Oct (30 min intervals) | 3 sites Sites 1, 2, 6 |

| COMPONENT | DATA USE | DATA APPLICATION | FIELD PERSONNEL | PRE-RESTORATION FREQUENCY | SITES | POST RESTORATION FREQUENCY | SITES |
|---|---|---|---|---|---|---|---|
| **BIOLOGICAL COMPONENTS** | | | | | | | |
| SAV and Algal surveys | 1. Mapping of seasonal and pre/post restoration distribution and species of fixed primary producer community<br>2. Evaluate quantitative changes in the coverage and biomass of SAV and algae during spring and mid-summer conditions | Baseline conditions, Restored conditions. Evaluate restoration success. | Bi-annually by qualified staff | 2x per year April/Sept each year prior to restoration | 7 sites Sites 1, 2, 3, 4, 5, 6, 8 | 2x per year April/Sept for the first 5 years following restoration | 7 sites Sites 1, 2, 3, 4, 5, 6, 8 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Vegetation/ habitat surveys | 1. General survey of lagoon habitats to map habitat changes and record any unexpected or undesirable changes such as erosion or sedimentation zones. 2. Transect surveys along established transects to track vegetation change within each target habitat type. 3. Mapping using aerial photography with color infrared imagery | Baseline conditions, Restored conditions. Evaluate restoration success. | Annually by qualified staff | 1 time per year during open lagoon conditions | Lagoon-wide habitat mapping with transect surveys performed at 9 sites Sites 1-9 in adjacent vegetated areas | 1 time per year during open lagoon conditions for a period of 5 years following restoration | Lagoon-wide habitat mapping with transect surveys performed at 9 sites Sites 1-9 in adjacent vegetated areas |
| Benthos | Replicated cores taken at monitoring sites throughout the lagoon to track changes in benthic infauna from pre- to post-restoration | Baseline conditions, Restored conditions. Evaluate restoration success. | Annually by staff and/or volunteers with external taxonomic lab. services | 1 time per year during September | Sites 1-9 in adjacent vegetated areas | 1 time per year during September for a period of 5 years following restoration | Sites 1-9 in adjacent vegetated areas |
| Fish and Epibenthos | Replicated beach seine sampling at submerged stations throughout the lagoon to track changes in fish and epibenthos diversity, abundance, and distribution patterns pre- to post-restoration | Baseline conditions, Restored conditions. Evaluate restoration success. | Annually by staff and/or volunteers with external taxonomic lab. support as necessary | 1 time per year during September | 5 sites Sites 1, 2, 4, 6, and 8 | 1 time per year during September for a period of 5 years following restoration | 5 sites Sites 1, 2, 4, 6, and 8 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Avian | Two day quarterly surveys of lagoon avifauna focusing on bird use of represented habitat areas. | Baseline conditions, Restored conditions. Evaluate restoration success. | Quarterly by staff/and or volunteers (or monthly with use of volunteer database) | Surveys conducted in January, April, July, and October | Lagoon-wide | Surveys conducted in January, April, July, and October for a period of 5 years following restoration | Lagoon-wide |

The most cost-effective and reliable monitoring program will rely primarily on seasonal sampling by the qualified staff or hired professionals. Hired professionals may own much of the field and additional monitoring equipment necessary to perform all aspects of the bi-annual monitoring components, which would be a significant cost savings for the project to not have to equip State Parks with extensive monitoring equipment. Hired professionals may also be appropriate to perform more specialized sampling efforts that include biannual vertical profiles, nutrient, chlorophyll, and phytoplankton sampling, sediment sampling and biological components. This monitoring approach would allow State Parks to participate in key elements of data collection, yet ensure detailed monitoring data is consistently collected from well-trained field professionals.

**Table 8 – Necessary Monitoring Equipment Summary and Estimated Costs**

| EQUIPMENT | AMOUNT NEEDED | ESTIMATED PURCHASE COST |
|---|---|---|
| Stadia Rod | 1 | $175 |
| Survey tape | 1 | $75 |
| Velocity meter | 1 | $11,000 (possible rental) |
| Station monument hardware | 1 | $350 |
| YSI 600XLM (includes cables, software pH, ORP probes) | 3 | $13,000 |
| HoBo Temperature Loggers | 3 | $250 |
| Installation Hardware | 3 | $300 |
| Calibration solutions (YSI) | pH, ORP, conductivity standards | $250 |
| AA Batteries | Many (4 per YSI, changed every 30 days) | $175/yr |
| Van Doren bottom water sampler | 1 | $200 |
| Sediment and water sample bottles | 100 | $200 (may be supplied by laboratory) |
| Hand Held YSI 85 | 1 | $1,500 (possible rental) |

| EQUIPMENT | AMOUNT NEEDED | ESTIMATED PURCHASE COST |
|---|---|---|
| Secchi Disk | 1 | $60 |
| Digital Scales (0-10,000 g) | 1 | $180 |
| Square Enclosure | 1 | $120 |
| 100 m tape | 1 | $70 |
| 1m2 quadrat | 1 | $40 |
| Color infrared imagery for vegetation mapping | Short-term: Once pre-restoration, Long-term: Every 5 to 10 years post-restoration | $5,000 per event |
| Analytical Balance | 1 | $4300 |
| Benthic Corer | 1 | $40 |
| 1.0mm sieves | 1 | $200 |
| Large beach seine | 1 | $250 |
| Small beach seine | 1 | $140 |
| Digital Scale (0.01g – 100g) | 1 | $220 |
| Digital Scale (1.0g – 1000g) | 1 | $160 |
| Spotting Scope | 1 | $300 |
| Binoculars | 1 | $300 |
| Boat/kayak, anchor, paddles | 1 | $350 |
| Hip Waders | 2 | $200 |
| Field Laptop or Palm Pilot | 1 | $1500 |
| Digital Camera | 1 | $250 |

| ANALYTICAL NEEDS | | | |
|---|---|---|---|
| **CONSTITUENT** | **PRICE PER SAMPLE** | **PROJECT SAMPLE NEED/YR** | **ANNUAL COST** |
| Nutrient analyses (water) | $100 | 28 | $3240 |
| Chlorophyll a analyses | $30 | 15 | $450 |
| Sediment grain size analyses | $100 | 24 | $1200 |
| Aerial Topography | $20,000;<br><br>$10,000 for survey, and<br>$5,000 for analysis of quantities | Immediate Pre-, Post Restoration;<br>Every 5 to 10 years for the long-term for the data acquisition and analysis | $30,000 for both pre- and post-restoration images;<br><br>$1,000 to $2,000 per year for the long-term |
| Nutrient analyses (sediments) | $60 | 24 | $1400 |
| Phytoplankton taxonomist | $100 | 12 | $1200 |
| Benthic sorting and taxonomy | $420 | 27 | $11,340 |
| Consumable lab chemicals/supplies/disposal | $8.50 | 64 | $544 |

## 6.0 REFERENCES

2nd Nature. 2005. 2004 Technical Report, Comparative Lagoon Ecological Assessment Plan, Santa Cruz County RCD.

Ambrose, R. F., and A. R. Orme. 2000. Lower Malibu Creek and Lagoon resource enhancement and management. University of California, Los Angeles.

Burgil and Stadelmann. 2002. Change of phytoplankton composition and biodiversity in Lake Sempach before and during restoration, Hydrobiologia 469: 33–48.

Garrett, Kimball. 1980-1996. Unpublished field notes.

Lall, Yugall. May 13, 2005. City Engineer. City of Malibu. Personal Communication with Chris Webb.

Manion S. and Dillingham, J. 1989. Malibu Lagoon: A Baseline Ecological Survey. Topanga-Las Virgenes Resource Conservation District.

Moffatt & Nichol. 2005. Malibu Lagoon Restoration Feasibility Study, Final Alternatives Analysis

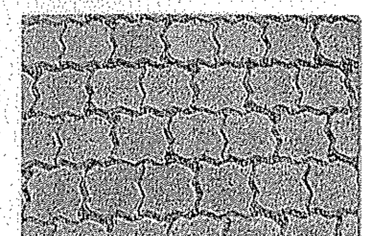
PERL (Pacific Estuarine Research Laboratory). 1990. A manual for assessing restored and natural coastal wetlands with examples from southern California. California Sea Grant Report No. T-CSGCP-021. La Jolla, California.

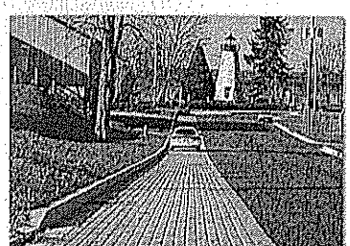
Sutula M., Kamer K., and Cable J., 2004. Sediments as a non-point source of nutrients to Malibu Lagoon, California (USA) DRAFT Final Report to the Los Angeles Regional Water Quality Control Board.

# APPENDIX A

## PERMEABLE INTERLOCKING CONCRETE PAVEMENTS

### Selection – Design – Construction - Maintenance





# Permeable Interlocking Concrete Pavements

**Selection • Design • Construction • Maintenance**

*David R. Smith*

**Second Edition**

ICPI
INTERLOCKING CONCRETE PAVEMENT INSTITUTE ®

# Contents



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# Contents *continued*

## List of Figures



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## List of Figures *continued*

# Acknowledgements

Taking a project from idea to reality often takes longer than anticipated. This manual is an example. It was proposed to the Technical Committee of the Interlocking Concrete Pavement Institute in the early 1990s. The idea was well-received, but other priorities placed the project on the sidelines. Postponements, however, are often a blessing in disguise. More time was provided for research and for literature to be reviewed.

Thanks goes to the Technical Committee and the Board of Directors of the Interlocking Concrete Pavement Institute for providing me the time and funding to create this manual. Deb Stover of Image Media created the drawings and formatted this publication. Thanks is due to Tom Schueler, Executive Director of the Center for Watershed Protection in Ellicott City, Maryland. His practical insights and experience with best management practices for abating water pollution, plus the library at his Center were invaluable to bringing this manual into reality.

My thanks and appreciation are due to several others for their review of the text:

Raymond S. Rollings, Ph.D., P.E. U.S. Army Corps of Engineers
Waterways Experiment Station, Vicksburg, Mississippi

Joeseph Batiatta, Program Manager, Stormwater Management
Virginia Department of Conservation and Recreation,
Richmond, Virginia

The Chesapeake Bay Local Assistance Program, Division of
Environmental Engineering, Richmond, Virginia
C. Scott Crafton, Chief
W. Douglas Beisch, P.E., Senior Civil Engineer
Catherine M. Harold, Environmental Engineer

Gil Wilbanks, P.E., Consulting Engineer, Portland, Oregon

Charles Curtis, P.E. Site Technologies, Atlanta, Georgia

Tom Hunnicutt, P.E., Interlock Paving Systems, Hampton, Virginia

Thanks also goes to Harald von Langsdorff, Richard Bodie, Helga Piro, and Harry Cannon.

Years ago, two persons influenced my career by providing technical and philosophical foundations. They are Gary E. Day, AIA, Associate Professor of Architecture at the State University of New York in Buffalo, and John Randolph, Ph.D., Professor of Environmental Planning at Virginia Tech in Blacksburg. They teach that the opposing forces of urban development and nature's processes can be synthesized through practical operating principles and design tools. They also teach that, given the right tools, the gap between design that respects nature and cost-effective implementation is narrower still. A debt of thanks goes to Gary and John for providing me with those insights and tools, many of which are expressed in this manual.

# Introduction

Compared to North America, Germany consumes about 20 times more per capita of interlocking concrete pavement annually. An increasing portion of this is permeable interlocking concrete pavement. Permeable pavements are popular because the German approach to environmental protection is not simply based on attenuating impacts from development. They consider the benefits of the natural environment to society. Development must maintain and enhance it. This notion is rooted in their word for environment, *umwelt*. Its meaning embraces the health and well-being of people and nature. North American English would translate the German notion of a healthy environment as environmental quality.

Infiltration trenches have been in use for decades as a means to reduce stormwater runoff and pollution, and to recharge groundwater. Recent experience has demonsrated that they work successfully when runoff is filtered prior to entering the pavement. From an engineering perspective, permeable interlocking concrete pavements are infiltration trenches with paving over them to support pedestrians and vehicles. Therefore, much of this manual is borrowed from literature and experience on infiltration trench design, construction, and maintenance. It also borrows engineering from other kinds of permeable pavements.

This manual is written for civil engineers, architects, landscape architects and contractors. Those who use it should be familiar with stormwater management concepts and calculations, notably the Soil Conservation Service (SCS), now National Resources Conservation Service (NRCS), method. They should be also familiar with the design of best management practices. The references cited with numbers in parentheses (e.g., (2)) throughout the text provide a wealth of information. The Glossary of Terms in Appendix A clarifies the meaning of many words and concepts used throughout the manual.

The manual does not portend to be complete, and it does not provide a "one stop" book for design. Rather, it provides criteria for selecting appropriate sites and the basics for sizing storage areas. Detailed inflow and outflow calculations are not covered because they vary considerably from site to site. Calculations must be done by a qualified engineer or landscape architect familiar with hydrology and hydraulics. Construction guidelines are provided as well as a maintenance checklist.

Permeable pavements should be incorporated into broader site designs to improve environmental quality, i.e., the health and well-being of people. Permeable interlocking concrete pavements can do this more elegantly than other pavement, permeable or impervious. For example, they visually annunciate vehicular and pedestrian circulation, reduce micro-climatic temperatures, and soften harsh visual transitions between building walls and the ground. A multitude of colors and patterns define areas and tie them to surrounding buildings and landscape. Sensitivity to these design concerns will improve the health, safety, and well-being of people and nature.

*David R. Smith*
*Washington, D.C.*
*2000*

# Section I. Selection

## Impacts from Impervious Surfaces

Urbanization brings an increasing concentration of pavements, buildings, and other impervious surfaces. They generate additional runoff and pollutants during rainstorms, causing streambank erosion, as well degenerating lakes and polluting sources of drinking water. Increased runoff deprives ground water from being recharged, decreasing the amount of available drinking water in many communities. Figure 1 summarizes the impacts of impervious surfaces.

| Increased Imperviousness leads to: | RESULTING IMPACTS | | | | |
|---|---|---|---|---|---|
| | Flooding | Habitat Loss | Erosion | Streambed alteration | Channel widening |
| Increased volume | * | * | * | * | * |
| Increased peak flow | * | * | * | * | * |
| Increased peak flow duration | * | * | * | * | * |
| Increased stream temperature | | * | | | |
| Decreased base flow | | * | | | |
| Changes in sediment loadings | * | * | * | * | * |

*Figure 1. Impacts from increases in impervious surfaces (1).*

Stormwater generates intermittent discharges of pollutants into water courses. Since the pollutants in stormwater runoff are not generated by a single, identifiable point source such as a factory, but from many different and spatially separated sources, they are called non-point sources of water pollution. During and after rainstorms, non-point sources of runoff pollution flow in huge quantities that render them untreatable by conventional wastewater treatment plants. In many cases, the receiving water cannot process the overwhelming amount of pollutants either. Therefore, the breadth of pollutants are difficult to control, as well as the extent to which they can be treated through nature's process in a lake, stream, or river.

## Best Management Practices (BMPs)

U.S. federal law (2) has mandated that states control non-point source water pollution through the National Pollution Discharge Elimination System (NPDES) program. The law requires, among many things, that states identify and require best management practices, or BMPs, to control non-point source pollution from new development. BMPs are implemented typically through regional and local governments charged with water quality management, planning, and regulation.

BMPs include many technologies and land management practices for reducing the quantity of pollutants in stormwater. They are used in combination at the site, development, and watershed scales to attain the maximum benefits to the stormwater drainage system. BMP's are divided into structural and non-structural practices. Structural BMPs capture runoff and rely on gravitational settling and/or the infiltration through a porous medium for pollutant reduction. They include detention dry ponds, wet (retention) ponds, infiltration trenches, sand filtration systems, and permeable pavements. These are often used to offset increases in pollutants caused by new development (3).

Nonstructural BMPs involve a wider scope of practices. They can range from public awareness programs about preventing non-point water pollution to the use of natural techniques such as bioretention and stormwater wetlands to enhance pollutant removal and promote infiltration of water into the ground.

*Figure 2. Permeable interlocking concrete pavement combines stormwater infiltration, retention and parking into one place, thereby conserving land.*

Many non-structural practices involve more efficient site planning. For example, these can include reducing the overall size of parking lots by reducing parking demand ratios, increasing shared parking, and use of mass transit credits. Many examples of nonstructural and structural practices can be found in *Better Site Design: A Handbook for Changing Development Rules in your Community* (4).

## Permeable Interlocking Concrete Pavement— A Best Management Practice

Permeable interlocking concrete pavements are typically built on an open-graded, crushed stone base. The base offers infiltration and partial treatment of stormwater pollution and therefore, can be categorized as a structural BMP. Infiltration of rainfall helps maintain the balance of water in the soil, groundwater, and streams, thus supporting the water cycle. Besides reducing runoff, a certain degree of treatment occurs to the various pollutants in the water. Figure 2 illustrates a typical permeable interlocking concrete pavement.

If the infiltration capacity of the soil is exceeded, or there are particularly high levels of pollutants, the pavement base can be designed to filter, partially treat, and slowly release water into a storm sewer or water course. When conditions allow, returning rainfall to the soil through infiltration is preferred over retaining the water and slowly releasing it into a sewer or water course.

Economics—Permeable interlocking concrete pavements may be cost-effective in new development where local regulations limit the total amount of impervious cover. However, they will be more expensive than using conventional (impervious) asphalt or concrete pavements and collecting the runoff (temporarily or permanently) in a pond. Nonetheless, the increased cost of using permeable interlocking concrete pavements may be recovered from the increase in rental income from more allowable space in the building. In other words, an increase in site coverage and rentable space may offset the additional cost of permeable pavement. The economic trade-offs of parking surface choices versus building space on the total amount of impervious cover should be reviewed on a project-by-project basis.

Permeable interlocking concrete pavements are especially cost-effective in existing urban development where there is a need to expand parking, but where there is not sufficient space for ponds. Therefore, the pavement can be used to conserve land because parking, stormwater infiltration and retention are combined into one facility.

| | Interlocking shapes with openings | Enlarged joints & spacers | Porous concrete units | Grid pavers with grass |
|---|---|---|---|---|
| Low-speed roads | Contact manufacturer | Contact manufacturer | Not recommended | Not recommended |
| Parking lots*/bays driveways | Excellent | Excellent | Not recommended | Acceptable for low use |
| Overflow parking, Access and emergency lanes | Excellent | Excellent | Not recommended | Good |
| Revetments, boat ramps | Good | Good | Not recommended | Good |
| Bike paths, Sidewalks* Pedestrian areas* | Good | Good (maintain narrow joints) | Excellent | Not recommended |

*Figure 3. Evaluation of applications for concrete permeable pavement.*
**See design considerations for disabled persons on page 10.*

The pavements are also cost-effective in areas where sewers flow at capacity during certain rainstorms. In these situations, replacing existing pipes with larger ones due to an increase in impervious cover from parking or buildings is not often economical. This solution merely transfers the additional runoff downstream and increases erosion and flooding potential.

Urbanized areas with an existing minimum of 50% impervious cover are typically where economics help decide the use of permeable pavement to conserve land or the capacity of the drainage system. Economics suggests that design professionals should study the trade-offs between permeable interlocking concrete pavements and other best management practices for these areas.

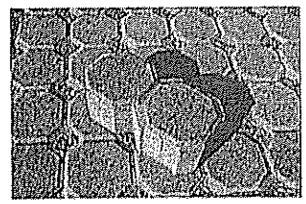


*Figure 4. Interlocking pavers can allow water through openings created by the paver shape.*

### Benefits and Limitations of Permeable Interlocking Concrete Pavements

This BMP essentially functions as an infiltration and retention area that can accommodate pedestrians, vehicular parking, and traffic. This combination of functions offers the following benefits:

- Conservation of space on the site.
- Reduction of runoff by as much as 100% from frequent, low-intensity and short duration storms.
- Reduction of retention requirements in other parts of the drainage system.
- Filtration through the base and soil for improvement of water quality.
- Reduction of runoff temperature.
- Slowing the release of runoff.
- Increased recharge of groundwater.
- Reduction of downstream flows and bank erosion due to decreased peak flows and volumes.
- Reduced overall project development costs due to a reduction in storm sewers and drainage appurtenances.

Limitations are listed below and are addressed throughout the manual:

- Overall cost compared to other BMPs.
- Greater site evaluation and design effort.
- A higher level of construction skill, inspection, and attention to detail.
- Use by handicapped persons.
- Maintenance to minimize clogging to ensure long-term performance.

### Types of Permeable Paving Products Made With Concete

There are many different shapes and sizes of permeable interlocking concrete pavers. These can be grouped into three categories: interlocking shapes, enlarged permeable joints, and porous concrete

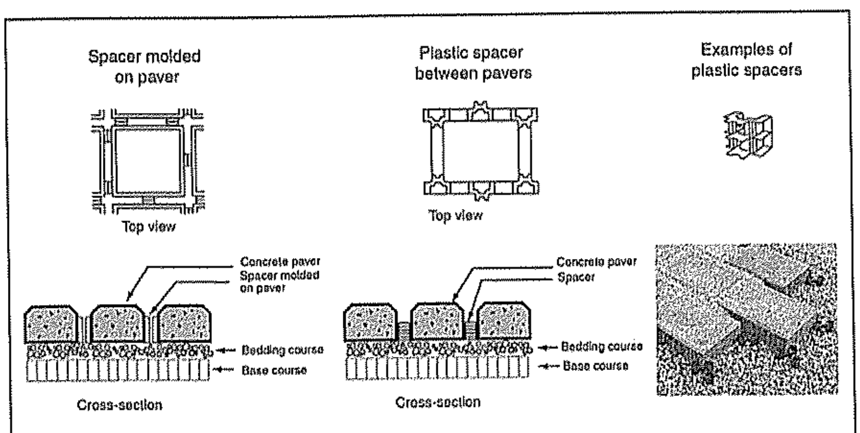



*Figure 5. Methods of spacing units to accommodate aggregate in the joints (5).*

units. Figure 3 lists the various types and rates their suitability in various applications (6). The table also lists concrete grid pavers for comparison purposes.

**Interlocking shapes with openings**—These have patterns that create openings or drainage holes for rainfall to enter, while maintaining high side-to-side contact among the units for stability under vehicular loads. Figure 4 shows one of many designs.

**Enlarged permeable joint**—These are pavers with wide joints for rainfall to enter. Joints can be as wide as 1³/₈ in. (35 mm). The joints are created with large spacers molded into the sides of each paver, or with plastic spacers inserted between each unit. These maintain consistent joints and stable units (Figure 5). Some units have spacers on them for laying either with a narrow joint for drainage filled with open-graded crushed stone, or with a wider joint for accommodating grass and topsoil (see Figure 6). Some joints may include indented sides or chambers in the sides of each unit that can store additional runoff (Figure 7).

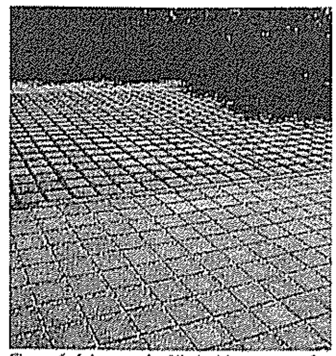
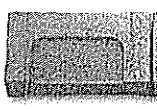


*Figure 6. Joints can be filled with aggregate for infiltration or with topsoil and grass microclimatic cooling.*

**Porous concrete units**—The sponge-like appearance of the unit in Figure 8 allows rainfall to directly enter and pass through it because the concrete has no fines. Like other pavers, the units are tightly fitted together over bedding sand, compacted, joints filled with coarse, washed sand, and compacted again. Care must be taken to not allow joint sand to clog the openings in the surface of the units. Porous units often do not meet the requirements of ASTM C 936, and these types of units are appropriate in non-freeze-thaw areas only. Their use is best for pedestrian areas, bicycle paths, and residential applications.

**Permeable pavers and concrete grid pavers**—A related product, concrete grid pavers, is also a best management practice, and its design and construction are discussed in *ICPI Tech Spec 8—Concrete Grid Pavements* (5). Both concrete grid and solid permeable pavers can be placed on an open-graded base for enhanced runoff control, as well as on a dense-graded base. Grid pavers, however, have a different range of applications. They are intended for light-duty use such as overflow parking areas, occasionally used areas in parking lots, and access and emergency lanes. In contrast, permeable pavers are intended for more heavily trafficked pavements such as regularly used parking lots and low-traffic volume streets. They have been used in industrial yards as well. Figure 9 illustrates solid, grid, and permeable pavers used in concert to satisfy pedestrian needs, bicycle parking, and vehicular support, as well as infiltration requirements.

*Figure 7. Units with indented sides store additional runoff.*



## Infiltration Practices and Municipal Regulatory Approaches

The decision regarding whether to use infiltration practices including permeable pavements is guided by municipal policy and design criteria (plus experience). Site constraints (covered in detail later) are often the most influential factors. Design criteria and regulations vary across the continent due to different rainstorms,

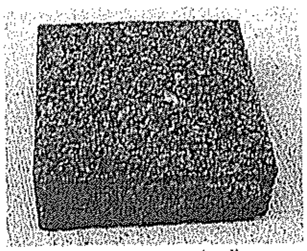


*Figure 8. Porous concrete units allow water directly into open-graded concrete.*

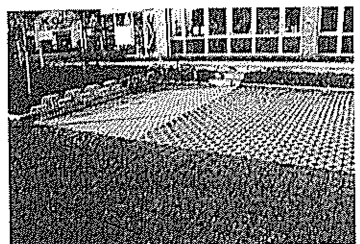


*Figure 9. Solid, grid, and permeable interlocking concrete pavers working in harmony to reduce water runoff and pollution, and to provide a more comfortable microclimate.*

geographic locations and land-use development patterns. In most localities, BMPs are designed to a specific storm recurrance (or return period), duration, and intensity, e.g., a 2-year, 24-hour storm of 1.5 in./hr (33 mm/hr or 106 l/s/ha), or volume from the first ½ to 1 in. (13 to 25 mm).

A well-structured municipal stormwater management strategy will consider the influence of the region's range or spectrum of rainfall frequencies on the selection of BMPs. Each region has its own rainfall frequency distribution patterns. Different management practices can handle various volumes of runoff and pollution within portions of this spectrum. Figure 10 illustrates these overlapping ranges of rain storms, expressed in recurrence intervals. It also shows management objectives that can be achieved within those categories of recurrence and rainfall volume.

## Effective Infiltration Rates for Permeable Interlocking Concrete Pavements

A limited number of studies show that the long-term infiltration rates of permeable interlocking concrete pavements is between 1.0 and 2.5 in./hr (25 and 65 mm/hr or 70 and 176 l/s/ha) (6) (7) (8). This range indicates that they will be able to absorb frequent, short duration storms. In most parts of North America, these comprise 70-80% of all rainstorms. Figure 10 indicates that

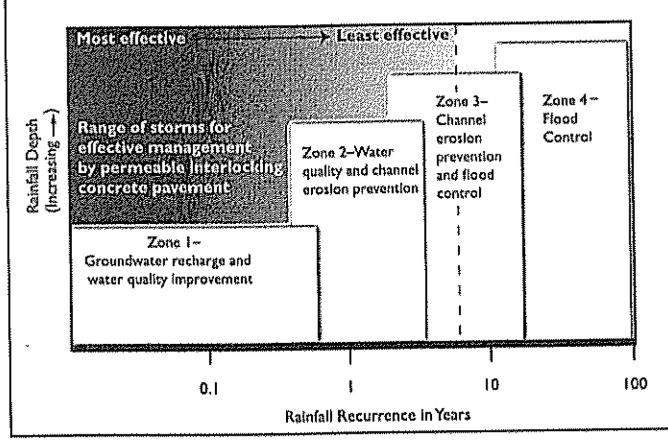



*Figure 10. Rainfall Frequency Spectrum defines the distribution of all rainfall events for a region. It is a tool for applying and sizing permeable interlocking concrete pavements and other BMPs to treat pollutants and to control runoff quantities (after Schueler) (9).*

permeable pavement can be used primarily to capture and treat the "first flush" of pollutants, i.e., the highest concentration of pollutants washed from impervious surfaces at the outset of a rainstorm. Sand filtering systems may offer increased reduction of pollutants and longer life for permeable interlocking concrete pavements (9). The pavements can also offer some ground water recharge. If they are designed to handle bigger storms, runoff volumes can be decreased (with other BMPs) to help reduce erosion of drainage channels. While probably not practical in many situations, larger storage capacity of rainfall volume in the base can provide some local flood control benefits.

Various Municipal Regulatory Approaches—Some localities regulate both water quantity and quality. An example may be a city adjacent to a bay that needs to protect fishing and recreation industries. It may have criteria for reducing runoff and for various types of water pollutants such as nitrogen, phosphorous, metals, and sediment. Water quality regulations are usually written to protect specific uses (e.g., drinking water, fishing, swimming, boating, etc.) of the body of water receiving the runoff. Other localities may only regulate runoff quantities, while recognizing that there will be a corresponding reduction of pollutants when using certain BMPs.

An increasing number of municipalities regulate the amount of impervious cover. This is often based on knowing the maximum capacity of public storm sewers and streams (for a given design storm), that can not be exceeded without flooding and property damage. More sophisticated analyses by some agencies have demonstrated a direct relationship between the amount of impervious cover and the pounds (or kg) of specific pollutants that will wash into receiving waters. In regulating the amount of impervious cover, as well as its configuration and hydrological connections, municipalities can control many pollutants washed by runoff into receiving waters.

Some municipalities have created stormwater utilities similar to water and sewer utilities. The legal rationale for a stormwater utility is rain falls on private property belongs to the property owner. Therefore, removal of runoff from private property through a municipal drainage system should be paid by the property owner to the local municipal utility.

The fee charged by the municipality for this service depends on how much water is discharged from each property. The fee is based on the amount of impervious area, impervious and gross area, or an additional intensity-of-use factor. Since the fees go specifically to managing stormwater, the charge is not considered a tax that pays for a wider range of city services. Typically, fees are used by the municipality for managing stormwater through maintaining and expanding the municipal drainage system. In some instances, fees are also used to restore damaged streams and riparian habitats.

A residential property owner pays a lower fee for stormwater removal while a shopping center owner pays a higher fee due to generating more runoff from a high area of roofs and parking lots. An owner's fee may be reduced if there is reduction of impermeable surfaces such as pavement, or if the water is stored on the owner's site in retention or detention ponds. Permeable interlocking concrete pavement systems are pervious and offer storage. Therefore, a strong rationale exists for *reduction* of storm water utility fees for owners who use this pavement.

# Section 2. Design

## Municipal Stormwater Management Objectives

Selection of base, bedding and fill materials for the openings are guided by local stormwater management objectives. To control runoff, municipal regulations strive to meet one or more of four management objectives (10). The designer should identify the objective(s) behind the design criteria required by the municipality.

• *Capture and infiltrate the entire storm water volume so there is no discharge from the drainage area (sometimes called zero discharge).* The high cost of infiltrating and capturing all runoff can be offset by reducing or eliminating pipes, inlets, and other drainage appurtenances. This may require a large area of permeable interlocking concrete pavement and open-graded base.

• *Infiltrate the increased runoff generated by development and impervious surfaces.* This results in runoff volumes equal to or near those prior to development. The runoff volumes before and after development are estimated. The difference in volume is infiltrated, or stored and slowly released. Places for infiltration can include vegetated swales and permeable interlocking concrete pavements. Storage of runoff can be within the permeable pavement as well as on roof tops, remote areas of impervious parking lots, and detention ponds.

• *Infiltrate a fixed volume of runoff from every storm.* The fixed amount of infiltrated water often represents a large percentage of the storms. The volume is usually expressed as depth in inches (mm) of runoff over the catchment area. Permeable interlocking concrete pavements typically infiltrate the first inch (25 mm) or more of runoff. This helps reduce the "first flush" of concentrated pollutants in this initial volume of runoff. The use of grass swales and sand filters provide enhanced filtering and removal of some water pollutants prior to entering permeable interlocking concrete pavements. Grass swales and sand filters should be considered on every project and implemented wherever possible.

• *Infiltrate sufficient water to control the peak rate of discharge.* Many municipalities establish a maximum rate of peak discharge (in cubic feet/second or liters/second) for specific storm sewers or water courses. The maximum rate should be based on the carrying capacity of the drainage ways. Waterway erosion and sedimentation, as well as flooding, typically occur if the peak discharge is exceeded.

This latter approach favors detention ponds rather than infiltration as a means to control downstream flooding. Permeable interlocking concrete pavements can be used as a means for detention, especially in dense urban areas that do not allow land for detention ponds. High-value property can be used for parking *and* storm water detention instead of merely consuming land for a detention pond.

### Design Options

Figure 11 shows pavement design options for meeting the four stormwater management objectives. Most objectives can be met by selecting full, partial, or no exfiltration of an open-graded base into the soil.

| Design Options | | Management Objectives: Complete infiltration "zero runoff" | Infiltrate post-development runoff | Infiltrate a fixed volume for pollution control | Control peak rate of discharge of runoff |
|---|---|---|---|---|---|
| Paver surface openings | Aggregate | • | • | • | • |
| Base Type | Open-graded | • | • | • | • |
| Exfiltration of Base | Full | • | • | • | • |
| | Partial | | • | • | • |
| | None | | | • | • |

*Figure 11. Application of design options for surface, base, and exfiltration to achieve various stormwater management objectives.*

### Full or Partial Exfiltration

A design for full exfiltration means the water infiltrates directly into the base and exfiltrates to the soil. This is the most common application. Pipes provide drainage in overflow conditions and secondary drainage should the base become clogged and lose some of its capacity over time.

Partial exfiltration does not rely completely on exfiltration of the base into the soil to dispose of all the captured runoff. Some of the water may exfiltrate into the soil while the remainder is drained by perforated pipes. Excess water is drained from the base by pipes to sewers or a stream. Figures 12 and 13 show schematic cross-sections of full and partial exfiltration designs.

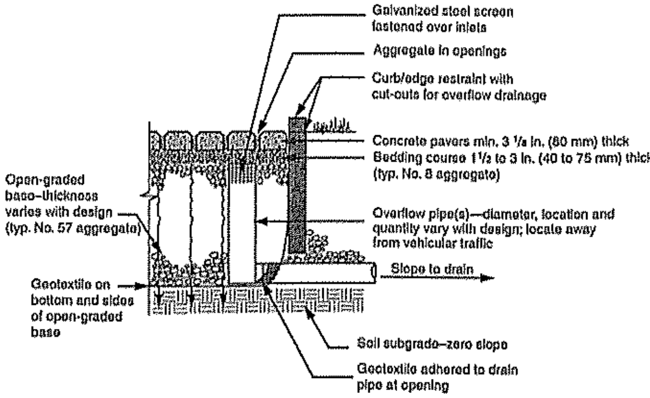



*Figure 12. Full exfiltration through the soil. Perforated pipes (not shown) may be included in the design to handle excess water in heavy, flood-prone rainstorms.*

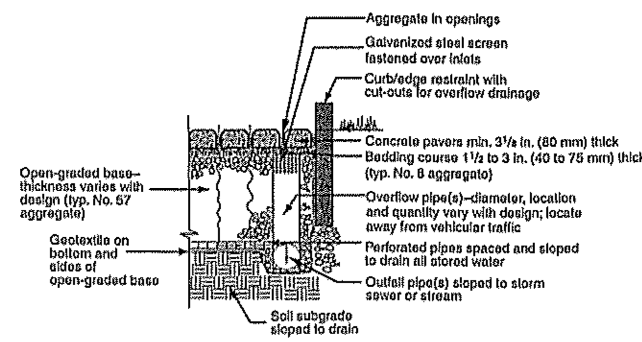



*Figure 13. Partial exfiltration through the soil. Perforated pipes drain excess runoff that can not be absorbed by slow-draining soil.*

### No Exfiltration

No exfiltration is required when the soil has low permeability and low strength, or there are other site limitations. An impermeable liner may be used if the pollutant loads are expected to exceed the capacity of the soil and base to treat them. The liner can be high density polyethylene (HDPE), ethylene propylene diene monomer (EPDM), rubber asphalt, or asphalt-based materials. Manufacturers of these materials should be consulted for application guidance. A liner may also be used if the depth to bedrock or to the water table is only a few feet (0.6 to 0.8 m). By storing water in the base for a time and then slowly releasing it through pipes, the design behaves like an underground detention pond. Figure 14 illustrates a cross-section design for no base exfiltration into the soil. In some cases, the soil may be stabilized to render improved support for vehicular loads. This practice almost reduces infiltration into the soil to practically zero.

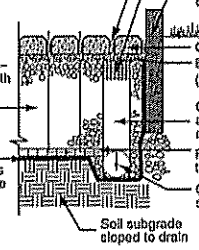



*Figure 14. No exfiltration of water from the base is allowed into the soil due to the use of an impermeable liner at the bottom and sides of the base. Perforated drain pipes are sized to slowly release the water into a sewer or stream.*

There are four situations where permeable interlocking concrete pavements should not exfiltrate. An impermeable liner is used to capture, store and release runoff from the base.

- When the depth from the bottom of the base to the high level of the water table is less than 2 feet (0.6 m), or when there is not sufficient depth of soil to offer adequate filtering and treatment of water pollutants.
- Directly over solid rock, or over solid rock with no loose rock layer or above it.
- Over aquifers where there isn't sufficient depth of soil to filter the pollutants before entering the ground water. These can include karst, fissured or cleft aquifers.
- Over fill soils, natural or fill, whose behavior when exposed to infiltrating water may cause unacceptable behavior. This might include expansive soils such as loess, poorly compacted soils, gypsiferous soils, etc.

While these limitations may not be present, the soil may still have low permeability. In these cases, the soil may hold the water in the base for slow drainage while providing a modest amount of infiltration. In a few cases, soil profiles may offer a more permeable layer further below the pavement. It may be cost-effective to drain the water via a french drain or pipes through the impermeable layer of soil under the base and into the lower soil layer with greater permeability.

## Site Selection Criteria

Permeable interlocking concrete pavements are recommended in areas with the following site characteristics (11):

- Residential walks and driveways.
- Walks, parking lots, main and service drives around commercial, institutional, recreational and cultural buildings.

- Boat ramps and non-commercial boat landings (often owned by local, state or provincial recreation agencies).
- Industrial sites that do not receive hazardous materials, i.e., where there is no risk to groundwater or soils from spills.
- Storage areas for shipping containers with non-hazardous contents.
- The total catchment draining into the permeable pavement is not greater than 5 acres (2 ha).
- The estimated depth from the bottom of the pavement base to the high level of the water table is greater than 2 feet (0.6 m). Greater depths may be required to obtain additional filtering of pollutants through the soil.
- The pavement is downslope from building foundations, and the foundations have piped drainage at the footers.
- The slope of the permeable pavement surface is at least 1%.
- Land surrounding and draining into the pavement does not exceed 20% slope.
- At least 100 ft (30 m) should be maintained between permeable pavements and water supply wells, streams, and wetlands. (Local jurisdictions may provide additional guidance or regulations.)
- Sites where the owner can meet maintenance requirements (see maintenance section).
- Sites where there will not be an increase in impervious cover draining into the pavement (unless the pavement is designed to infiltrate and store runoff from future increases in impervious cover).

Permeable interlocking concrete pavements are not recommended on any site classified as a stormwater hotspot, i.e., if there is any risk that stormwater can infiltrate and contaminate groundwater. These land uses and activities may include the following:

- Vehicle salvage yards, recycling facilities, fueling stations, service and maintenance facilities, equipment and cleaning facilities
- Fleet storage areas (bus, truck, etc.)
- Commercial marina service and maintenance areas
- Outdoor liquid container storage areas
- Outdoor loading/unloading facilities
- Public works materials/equipment storage areas
- Industrial facilities that generate or store hazardous materials
- Storage areas for commercial shipping containers with contents that could damage groundwater and soil
- Land uses that drain pesticides and/or fertilizers into permeable pavements (e.g., agricultural land, golf courses, etc.)
- Other land uses and activities as designated by an appropriate review authority

- Sites where space constraints, high land prices, and/or runoff from additional development make permeable interlocking concrete pavements a cost-effective solution.

### Design Considerations for Pedestrians and Disabled Persons

Before a parking lot or plaza is constructed, existing pedestrian paths across the lot should be studied and defined. Vehicle lanes, parking spaces, pedestrian paths, and spaces for disabled persons can be delineated with solid concrete pavers. Paths with solid units will make walking more comfortable, especially for pedestrians with high-heeled shoes and for the elderly. Likewise, parking spaces accessible to disabled persons and for bicycles should be marked with solid pavers. Permeable interlocking concrete pavers with openings or wide joints should not be used in disabled-accessible parking spaces or on pedestrian ramps at intersections.

### Infiltration Rates of Permeable Interlocking Concrete Pavement Systems

A common error in designing permeable interlocking concrete pavements is assuming that the amount or percent of open surface area is equal to the percent of perviousness. For example, an 18% open surface area is incorrectly assumed to be 18% pervious, or 82% impervious. The perviousness and amount of infiltration are dependent on the infiltration rates of joint filling material, bedding layer, and base materials, not the percentage of surface open area.

Compared to soils, permeable interlocking concrete pavements have a very high degree of infiltration. For example, a clay soil classified as CL using the Unified Soil Classification System might have an infiltration rate in the order of $1.4 \times 10^{-5}$ in./hr ($10^{-9}$ m/sec). A silty sand (SM) could have $1.4 \times 10^{-3}$ in./hr ($10^{-7}$ m/sec) infil-tration rate. Open-graded, crushed aggregate placed in the openings of permeable interlocking concrete pavements will have an initial infiltration over 500 in./hr (over $10^{-3}$ m/sec), i.e, 10,000 times greater than the sandy soil and 100,000 times greater than the clay soil. The open-graded base material has even higher infiltration, typically 500 to 2000 in./hr ($10^{-3}$ to $10^{-2}$ m/sec). Therefore, the small percentnge of open surface area is capable of providing a large amount of infiltration into the pavement.

Regardless of the high infiltration rate of the aggregates used in the openings and base, a key consideration is the lifetime *design* infiltration of the *entire* pavement cross-section, including the soil subgrade. Its infiltration rate is difficult to predict over time. There can be short-term variations from different amounts of antecedent water in it, and long-term reductions of infiltration from partially clogged surface or base, geotextiles or soil subgrade. So a conservative approach should always be taken when establishing the design infiltration rate of the pavement system.

Studies on permeable interlocking concrete pavers have attempted to estimate their long-term infiltration performance. Permeable concrete units (made with no fine aggregates) demonstrate lowest average permeability. Interlocking shapes with openings or those with enlarged permeable joints offer substantially higher infiltration performance over the long term.

Limited research on permeable pavements made with solid, nonporous units provides some guidance on long-term infiltration rates. German studies (6)(7)(8)(12) reviewed parking lots with open-graded materials in the paver openings over an open-graded base. They showed a high initial infiltration when new, and a decrease and leveling off as they aged. The decrease in infilitration is natural and is due to the deposit of fine materials such a dirt, vegetation in the joints, and clogging of the base and geotextiles.

When tested, new pavements demonstrated very high infiltration rates of almost 9 in./hr ($6 \times 10^{-5}$ m/sec) and two four-year old parking lots indicated rates of about 3 in./hr ($2 \times 10^{-5}$ m/sec). Lower rates were exhibited on pavements where openings were filled with sand or aggregate and itinerant vegetation. In another study of two and five-year old parking lots, the infiltration rates were about 6 and 5 in./hr (4 and $3.5 \times 10^{-5}$ m/sec) respectively. Infiltration was measured over approximately one hour for these two studies.

The results of these studies confirm that the long-term infiltration rate depends on the intensity of use and the degree to which the surface and base receive sediment. This is also confirmed in the literature on the performance of infiltration trenches. Since there are infiltration differences between initial and long-term performance, construction, plus inevitable clogging, a conservative **design rate of 1.1 in./hr ($8 \times 10^{-6}$ m/sec or 80 L/sec/hectare) can be used as the basis for the design infiltration rate for a 20-year life.** In other words, the German studies of new and existing pavements, as well those of infiltration trenches, indicate that the lifetime average infiltration rate is roughly 10% of the initial rate. Therefore, a conservative factor of safety of 10 should be applied to the initial infiltration rate to account for clogging over time.

## Site Design Data

### Rainfall and Traffic Data

The following data will be necessary to design the pavement:

1. The total area and percent of impervious surface draining on the permeable pavement.
2. The design storm with the return period and intensity in inches or millimeters per hour (usually supplied by municipality or other regulatory agency). Rainfall intensity-duration-frequency maps can be referenced to establish the design storm (13) (14).

3. The volume of runoff or peak flow to be captured, exfiltrated, or released using the design storm.
4. An estimate of the vehicular traffic loads expressed as 18,000 kip (80 kN) equivalent single axle loads (ESALs) over the design life of the pavement, typically 20 years.

**Soil Subgrade Sampling and Analysis**

The soil sampling and testing program should be designed and supervised by a licensed professional engineer knowledgeable of the local soils. This professional should provide assessment of design strength, permeability, compaction requirements, and other appropriate site assessment information. Some suggested guidelines follow on sampling and testing procedures.

Soil samples extracted with a core auger are recommended every 50 ft (15 m) through the center of the proposed area to be paved with a minimum of two borings per site. All borings should be taken at least 5 ft (1.5 m) deep with soil logs recorded to at least 3 ft (1 m) below the bottom of the base. More frequent sampling may be required by the design engineer in areas where soil types may change, near rock outcroppings, in low lying areas, or where the water table is likely to be within 8 ft (2.5 m) of the surface. Evidence of a high water table, impermeable soil layers, rock, or dissimilar layers may require a base design with no exfiltration.

The following tests are recommended on the soil samples, especially if the soil has clay content. These assist in evaluating the soil's suitability for supporting traffic in a saturated condition while exfiltrating. Other tests may be required by the design engineer. AASHTO tests equivalent to ASTM methods may be used.

1. Unified (USCS) soil classification using the test method in ASTM D 2487 (15).
2. Sampled moisture content in percent.
3. Soaked CBR using the test method ASTM D 1883 (16) or AASHTO T 193 (17).
4. Onsite tests of infiltrate rate of the soil using local, state or provincial recommendations for test methods and frequency. All tests for infiltration should be done at the elevation corresponding to the bottom of the base. If there are no requirements for infiltration test methods, ASTM D 3385 (18), Test Method for Infiltration Rate of Soils in Field Using a Double-Ring Infiltrometer is recommended. ASTM D 5093 (19), Test Method for Field Measurement of Infiltration Rate Using a Double-Ring Infiltrometer with a sealed Inner Ring is for soils with an expected infiltration rate of 1.4 x $10^{-2}$ in./hr ($10^{-7}$ m/sec) to 1.4 x $10^{-5}$ in./hr ($10^{-10}$ m/sec). Percolation test results for the design of septic drain fields are not suitable for the design of stormwater infiltration systems (20).

*Caution:* Results from field tests are approximations because the structure and porosity of soils are easily changed. On-site tests do not account for loss of the soil's conductivity from construction, compaction, and clogging from sediment. Nor do they account for lateral drainage of water from the soil into the sides of the base. Individual test results should not be considered absolute values directly representative of expected drawdown of water in the open-graded base. Instead, the test results should be interpreted with permeability estimates based on soil texture, structure, pore geometry, and consistence (20).

A minimum tested infiltration for full exfiltration subject to vehicular traffic is 0.52 in./hr (3.7 x $10^{-6}$ m/sec). Some sites may require higher rates and there may be cases where lower rates are used. Local requirements for the design of infiltration trenches may also specify minimum rates.

Soils with a tested permeability equal to or greater than 0.52 in./hr (3.7 x $10^{-6}$ m/sec) usually will be gravel, sand, loamy sand, sandy loam, loam, and silt loam. These are usually soils with no more than 10-12% passing the No. 200 (0.075 mm) sieve. These are characterized as A and B group soils using the SCS (NRCS) classification system. Silt and clay soils will likely have lower permeability, and not be suitable for full exfiltration from an open-graded base. For cold climates in the northern U.S. and Canada, the lowest recommended infiltration rate for the soil subgrade is 0.5 in./hr (3.5 x $10^{-6}$ m/sec).

| USCS Soil Classification | Typical ranges for Coefficient of Permeability, k, in./hour (approximate m/s) | Relative Permeability when compacted and saturated | Shearing strength when compacted | Compressibility | Typical CBR Range |
|---|---|---|---|---|---|
| GW-well graded gravels | 1.3 to 137 ($10^{-5}$ to $10^{-3}$) | Pervious | Excellent | Negligible | 30-80 |
| GP-poorly graded gravels | 6.8 to 137 ($5 \times 10^{-5}$ to $10^{-3}$) | Very pervious | Good | Negligible | 20-60 |
| GM-silty gravels | $1.3 \times 10^{-4}$ to 13.5 ($10^{-9}$ to $10^{-4}$) | Semi-pervious to impervious | Good | Negligible | 20-60 |
| GC-clayey gravel | $1.3 \times 10^{-4}$ to $1.3 \times 10^{-2}$ ($10^{-8}$ to $10^{-6}$) | Impervious | Good to fair | Very low | 20-40 |
| SW-well graded sands | 0.7 to 68 ($5 \times 10^{-6}$ to $5 \times 10^{-4}$) | Pervious | Excellent | Negligible | 10-40 |
| SP-poorly graded sands | 0.07 to 0.7 ($5 \times 10^{-7}$ to $5 \times 10^{-6}$) | Pervious to semi-pervious | Good | Very low | 10-40 |
| SM-silty sands | $1.3 \times 10^{-4}$ to 0.7 ($10^{-9}$ to $5 \times 10^{-6}$) | Semi-pervious to impervious | Good | Low | 10-40 |
| SC-clayey sands | $1.3 \times 10^{-5}$ to 0.7 ($10^{-9}$ to $5 \times 10^{-6}$) | Impervious | Good to fair | Low | 5-20 |
| ML-inorganic silts of low plasticity | $1.3 \times 10^{-5}$ to 0.07 ($10^{-9}$ to $5 \times 10^{-7}$) | Impervious | Fair | Medium | 2-15 |
| CL-inorganic clays of low plasticity | $1.3 \times 10^{-5}$ to $1.3 \times 10^{-3}$ ($10^{-9}$ to $10^{-8}$) | Impervious | Fair | Medium | 2-5 |
| OL-organic silts of low plasticity | $1.3 \times 10^{-5}$ to $1.3 \times 10^{-2}$ ($10^{-9}$ to $10^{-6}$) | Impervious | Poor | Medium | 2-5 |
| MH-inorganic silts of high plasticity | $1.3 \times 10^{-6}$ to $1.3 \times 10^{-5}$ ($10^{-10}$ to $10^{-7}$) | Very impervious | Fair to poor | High | 2-10 |
| CH-inorganic clays of high plasticity | $1.3 \times 10^{-7}$ to $1.3 \times 10^{-5}$ ($10^{-11}$ to $10^{-9}$) | Very impervious | Poor | High | 2-5 |
| OH-organic clays of high plasticity | Not appropriate under permeable interlocking concrete pavements | | | | |
| PT-Peat, mulch, soils with high organic content | Not appropriate under permeable interlocking concrete pavements | | | | |

*Figure 15. Suitability of soils (per the Unified Soils Classification System) for infiltration of stormwater and bearing capacity (21)(22)(23). This table provides general guidance. Testing and evaluation of soils are recommended.*

To help maximize infiltration, the subgrade should have less than 5% passing the No. 200 (0.075 mm) sieve, although soils with up to 25% passing may drain adequately depending on site conditions and specific characteristics. Soils with a permeability lower than 0.52 in./hr ($3.7 \times 10^{-6}$ m/sec) can be used to infiltrate water as long as the soil remains stable while saturated, especially when loaded by vehicles. However, drain pipes will be required. Soil stability under traffic should be carefully reviewed for each application by a qualified geotechnical or civil engineer. Pedestrian applications not subject to vehicular traffic can be built over soils with a lower permeability.

Figure 15 characterizes the permeability of soils using the Unified Soil Classification System (USCS). It also shows typical ranges of the California Bearing Ratio (CBR) values for these classifications. These are general guidelines and do not substitute for laboratory and field testing.

This design procedure assumes a soil CBR (minimum 96-hour soaked) strength of at least 5% or an R-value of 24 to qualify for use under vehicular traffic. The compaction required to achieve this will greatly reduce the infiltration rate of the soil. Therefore, the permeability or infiltration rate of soil should be assessed at the density required to achieve 5% CBR. If soils have a lower soaked CBR or are highly expansive, they should be treated to raise the CBR above 5%. Treatment can be with cement, lime or lime/flyash (to control expansive soils) while raising the CBR. Guidelines on the amount and depth of cement required for soil stabilization can be found in reference 24 by the Portland Cement Association.

An alternative approach to raising the CBR of non-expansive soils to over 5% is by placing a capping layer of compacted crushed stone on the subgrade. The layer should have a minimum soaked CBR of 20% and be a minimum of 8 in. (200 mm) thick. Geotextile is recommended between these layers and the soil subgrade.

The CBR treatments described above reduce the infiltration of soil to practically zero. In these cases there is no exfiltration of water into the soil, so all water is stored and slowly released from the open-graded base. Obviously, this rate of drainage is taken into account when sizing pipes draining the base.

There are other factors on sites not specifically covered in this manual that influence design decisions. The guidance of an experienced civil or geotechnical engineer familiar with local site conditions and stormwater management should be sought to confirm the suitability of the soil characteristics and possible treatments for use under all permeable interlocking concrete pavements.

### Filters and Geotextiles

Fines particles suspended in slowly moving water will be deposited in the pores of the adjacent material. In the case of permeable interlocking pavements, particles will be deposited in another soil, the aggregate base, bedding course, the aggregate in the pavement openings or geotextile. The build-up of fines eventually clogs and reduces permeability of these materials. To reduce this action, filter criteria must be met whenever there is a change in materials. Criteria must be met for joint and bedding materials (if different materials are used), the bedding course, the bedding course and the base, base and sub-base (as applicable), and the soil subgrade. While aggregate materials can be used for filters, the use of geotextiles is more common. Figure 16 provides geotextile filter criteria from the U.S. Federal Highway Administration (FHWA) (25) and the American Association of State Highway and Transportation Officials (AASHTO) (26).

### Materials for the Base, Bedding And Openings

The following data is required on materials for the base, bedding course, and aggregate in the pavement openings:

1. Sieve analysis, including washed gradations.

2. Void space in percent for the open-graded base.

**Crushed stone, open-graded base**—This material should be a hard, durable rock with 90% fractured faces and a Los Angeles (LA) Abrasion of < 40. A minimum effective porosity of 0.32 and a design CBR of at least 80% are recommended. A water storage capacity of open-graded base will vary with its depth and the percent of void spaces in it. The void space of open-graded aggregate can be supplied by the quarry or from independently conducted tests.

The in-situ aggregate base should have a porosity of at least 0.32 to allow void space for water storage. The structural strength of the material should be adequate for the loads to which it will be subjected. ASTM No. 57 crushed aggregate is commonly used for open-graded bases and is re-commended for most permeable pavement applications. It often has a porosity (volume of voids ÷ total volume of the base) over 0.32 and storage capacity in its void spaces (volume of voids ÷ volume of aggregate), typically 20% to 40%. A 40% void space means that the volume of the base will need to be 2.5 times the volume of the water to be stored. The infiltration rate of No. 57 stone base is over 1,000 in./hr (over $7 \times 10^{-3}$ m/sec).

The large size of the aggregates in No. 57 crushed stone creates an uneven surface when compacted. To smooth the surface, a bedding course of ASTM No. 8 crushed aggregate is placed and compacted into the top of the No. 57 open-graded base. The No. 8 material is often called choke stone since it stabilizes and partially chokes or closes the surface of the open-graded base. The thickness of the No. 8 layer should not exceed 3 in. (75 mm) prior to compaction. Like No. 57, it should be hard material, having 90% fractured faces and an LA Abrasion < 40. The infiltration rate should be at least 1,000 in./hr ($7 \times 10^{-3}$ m/sec). The No. 8 material stabilizes the surface of the No. 57 and provides some filtering of water. Therefore the No. 8 stone should meet the following criteria:

$$D_{15\ \text{open-graded base}} / D_{50\ \text{choke stone}} < 5 \text{ and } D_{50\ \text{open-graded}} / D_{50\ \text{choke stone}} > 2$$

$D_x$ is the particle size at which x percent of the particles are finer. For example, $D_{15}$ is the particle size of a soil or aggregate gradation for which 15% of the particles are smaller and 85% are coarser.

Besides use as a bedding material, No. 8 crushed stone aggregate is also recommended for fill material in the paver openings. Smaller sized aggregate such as No. 89 may be needed to enter narrow joints between interlocking shapes. The void space in the bedding and joints is not considered in water storage calculations. Nonetheless, they provide an additional factor of safety since they have capacity for storing water.

***U.S. Federal Highway Administration (FHWA)***

For fined grained soils with more than 50% passing the No. 200 (0.075 mm) sieve:

Woven geotextiles: Apparent Opening Size (AOS) $\leq D_{85}$

Nonwoven geotextiles: $AOS_{geotextile} \leq 1.8 D_{85\ soil}$

AOS $\leq$ 0.3 mm or $\geq$ No. 50 sieve

For granular soils with 50% or less passing the No. 200 (0.075 mm) sieve:

All geotextiles $AOS_{geotextile} \leq B \times D_{85\ soil}$

Where:

$B = 1$ for $2 \geq C_U \geq 8$

$B = 0.5$ for $2 < C_U < 4$

$B = 8/C_U$ for $4 < C_U < 8$

$C_U = D_{60}/D_{10}$

Permeability criteria: k (fabric) $\geq$ k (soil)

Clogging criteria

Woven: Percent of open area $\geq$ 4%

Nonwoven: Porosity $\geq$ 30%

***American Association of State Highway and Transportation Officials (AASHTO)***

For soils $\leq$ 50% passing the No. 200 (0.075 mm) sieve:

$O_{95} < 0.59$ mm ($AOS_{fabric} \geq$ No. 30 sieve)

For soils > 50% passing the No. 200 sieve:

$O_{95} < 0.30$ mm ($AOS_{fabric} \geq$ No. 50 sieve)

Notes:

1. $D_x$ is particle size at which x percent of the particles are finer. Determined from gradation curve. Example: $D_{10}$ is the size particle of a soil or aggregate gradation for which 10% of the particles are smaller and 90% are coarser.
2. $O_x$ is geotextile size corresponding to x particle size base on dry glass bead sieving. Hence $O_{95}$ is the geotextile size opening for which 95% of the holes are smaller.
3. AOS is apparent opening size is essentially the same but normally defined as a sieve number rather than as a size (ASTM D 4751). POA is percent open area for (woven fabrics only). Permeability, k of the soil and geotextile (nonwoven only) are designated $k_s$ and $k_g$ respectively.

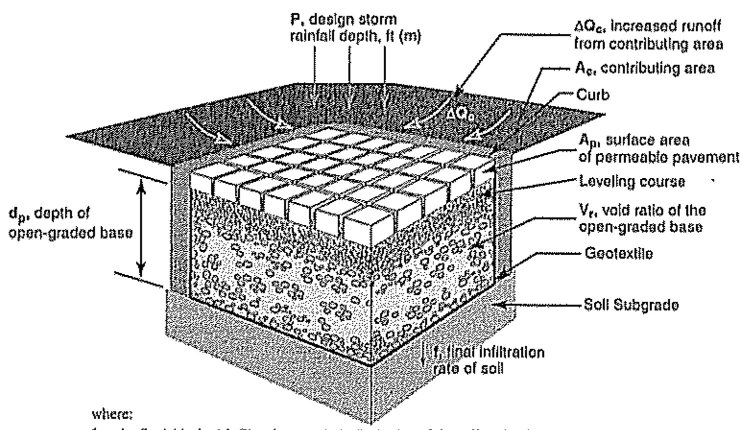
*Figure 16. Geotextile filter criteria*

**Concrete units for permeable pavement**—The following data is needed on the pavers:

1. Minimum thickness = $3^1/_8$ in. (80 mm).
2. Percent of open area of the surface.
3. Test results indicating conformance to ASTM C 936, *Standard Specification for Solid Interlocking Concrete Paving Units* (27), or CSA A231.2, *Precast Concrete Pavers* (28) as appropriate. If the dimensions of the units are larger than those stated in these standards, then CSA A231.1, *Precast Concrete Paving Slabs* (29) is recommended as a product standard.

## Sizing an Open-Graded Base for Stormwater Infiltration and Storage

The following design method is adapted from *Standard Specifications for Infiltration Practices* (30) and the *Maryland Stormwater Manual* published by the State of Maryland, Department of the Environment (31). The procedure is from "Method for Designing Infiltration Structures." This method assumes familiarity with SCS (NCRS) TR 55 method (32) for calculating stormwater runoff. References 11, 33, 34, and 35 provide other methods. Provinces, states, and cities may mandate the use of other methods. The Maryland method is provided because it has been refined over many years and it illustrates important aspects of infiltration design.




where:

f = the final (design) infiltration rate in in./hr (m/hr) of the soil under the pavement (infiltration rates are determined from permeability tests and engineering judgement);

$T_s$ = the maximum allowable storage time of 72 hours; and

$V_r$ = the void ratio (space) of the crushed stone base (typically 0.4).

The maximum allowable depths are given in Figure 19 for selected values of f, $T_s$, and $V_r$.

$A_c$ = contributing area, sf ($m^2$)

$\Delta Q_c$ = increased runoff from contributing area, ft (m) per a given design storm

$A_p$ = surface area of permeable interlocking concrete pavement, sf ($m^2$)

P = design storm rainfall depth, ft (m)

$d_p$ = depth of crushed stone base, ft (m)

T = effective filling time of the base, hours (2 hours is typical)

*Figure 17. Design parameters for calculating the base depth for permeable interlocking concrete pavements.*

Like porous asphalt pavement, permeable interlocking concrete pavement relies on an open-graded aggregate base into which water rapidly infiltrates for storage. The pavement base functions as an underground detention structure. Therefore, pavement base storage can be designed with the same methods as those used for stormwater management ponds. The design method in this section assumes full exfiltration, e.g., removal of water from the base by infiltration into the underlying soil subgrade.

The catchment for permeable interlocking concrete pavement consists of the surface area of the pavement and an area that contributes runoff to it. A schematic cross-section and the design parameters are shown in Figure 17. The base is sized to store the runoff volume from the pavement area and the adjacent contributing areas.

Soil with infiltration rates or permeability less than 0.27 in./hr (2 x $10^{-6}$ m/sec) are generally silt loam, loam, sandy loam, loamy sand, and sand. Soils with lower permeability will limit the flow of water through the soil. They will require a high ratio of bottom surface area to storage volume. Therefore, careful consideration should be given to designing drain pipes to remove excess water in these situations.

The method described below does not provide guidance on drain pipe design within the base. This can be found in reference 35. Reference 36 includes methods for determining the diameter and spacing of pipes in open-graded bases for highway pavement drainage, as well as general guidance on pavement drainage design. This method accounts for monthly variations in the water generated from background flows in the soil and infiltration area, as well as that from the runoff from the design storm. It does not include structural design for base thickness under vehicular traffic.

The Maryland method finds the maximum allowable depth of the pavement ($d_{max}$) for a maximum storage time of 3 days. Shorter storage times are desirable to minimize risk of continually saturated and potentially weakened soil subgrade for areas subject to vehicular traffic. In that light, calculations should be done for 1 and 2 days, as well as 3 days, to compare differences in base thickness. In some instances, the calculated depth of the base for storage may be too shallow to support vehicular traffic. In these cases, the minimum base thickness would then be the depth required to accommodate traffic per Figure 18.

| | Soaked CBR of Subgrade Soil | | | Frost Conditions | | | |
|---|---|---|---|---|---|---|---|
| ESALs* over 20 yrs. | >15 | 10 to 14 | 5 to 9 | Gravelly Soils | Clayey Gravels, Plastic Sandy Clays | Silty Gravel, Sand, Sandy Clays | Silt, Silty Gravel, Sand, Silty Clays |
| 50,000 | 6 (125) | 8 (175) | 10 (225) | 9(175) | 10 (250) | 12 (300) | ** |
| 150,000 | 8 (150) | 10 (200) | 12 (275) | 10 (250) | 12(300) | 14 (350) | ** |
| 600,000 | 10 (175) | 12 (225) | 14 (350) | 12 (300) | 18 (450) | 22 (550) | ** |

*ESALs = 18 kip equivalent single axle loads

Note: All thicknesses are after compaction and apply to all exfiltration conditions. Greater thicknesses may be required in soils subject to frost heaving. Pedestrian applications should use a minimum base thickness of 6 in. (150 mm).

**Strengthen subgrade with crushed-stone aggregate sub-base to full frost depth.

Note: Silt soils or others with more than 3% of particles smaller than 0.02 mm in size are considered to be frost susceptible.

*Figure 18. Recommended minimum open-graded base thicknesses for permeable interlocking concrete pavements in inches (mm) (37) (38).*

The values in Figure 18 are adopted from thickness designs for permeable asphalt pavement (49) (50). Their use rests on the assumption that 3¹/₈ in. (80 mm) thick concrete pavers provide a structural contribution similar to an equivalent thickness of porous asphalt. The base thicknesses assume that the strength of the soil subgrade is at least 5% CBR (elastic modulus of 7,500 psi or 50 MPa).

The SCS (NRCS) method typically uses 24-hour storm events as the basis for design. Therefore, this design method is based on controlling the increased runoff for a specific 24-hour storm. The specific duration and return period (e.g., 6-months, 1-year, 2-year, etc.) are provided by the locality. If the increase in peak discharge associated with the storm event cannot be managed, a first flush event should be the minimum selected for design.

| | | Soil Subgrade Texture/Infiltration Rate Inches/Hour (m/sec) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sand | Loamy Sand | Sandy Loam | Loam | Silt Loam | Sandy Clay Loam | Clay Loam | Silty Clay Loam | Sandy Clay | Silty Clay | Clay |
| Criterion | $T_s$ (hrs) | 8.27 ($6\times10^{-5}$) | 2.41 ($2\times10^{-5}$) | 1.02 ($7\times10^{-6}$) | .52 ($4\times10^{-6}$) | .27 ($2\times10^{-6}$) | .17 ($1\times10^{-6}$) | .09 ($6\times10^{-7}$) | .06 ($4\times10^{-7}$) | .05 ($3\times10^{-7}$) | .04 ($2\times10^{-7}$) | .02 ($10^{-7}$) |
| $f \times T_s/V_r$ | 24 | 496 (12.6) | 145 (3.7) | 61 (1.5) | 31 (0.8) | 16 (0.4) | 10 (0.25) | 5 (0.12) | 4 (0.1) | 3 (0.07) | 2 (0.05) | 1 (0.02) |
| for | 48 | 992 (25.2) | 290 (7.4) | 122 (3.1) | 62 (1.6) | 32 (0.8) | 20 (0.5) | 11 (0.3) | 7 (0.17) | 6 (0.15) | 2 (0.15) | 2 (0.05) |
| ($V_r$=0.4) | 72 | 1489 (37.8) | 434 (11) | 183 (4.6) | 93 (2.4) | 149 (1.2) | 31 (0.8) | 16 (0.9) | 11 (0.13) | 9 (0.2) | 7 (0.17) | 4 (0.1) |

$T_s$ = Maximum allowable storage time  $V_r$ = Voids ratio  [shaded] = Lowest values unless base exfiltration is supplemented with drain pipes.

*Figure 19. Maximum allowable depths, inches (m) of storage for selected maximum storage times ($T_s$ in hours), minimum infiltration rates, inches/hours (m/sec)(31).*

For runoff storage, the maximum allowable base depth in inches (m) should meet the following criteria:

$$d_{max} = f \times T_s / V_r$$

As shown in Figure 17, the design volume of water to be stored in the pavement base ($V_w$) is:

| the runoff volume from the adjacent contributing area; | plus | the rainfall volume falling on the permeable pavement | minus | the exfiltration volume into the underlying soil |
|---|---|---|---|---|
| = $\Delta Q_c A_c$ | + | $PA_p$ | — | $fTA_p$ |

Values of f for infiltration rate should be obtained from Figure 19 for preliminary designs and checked against field tests for the infiltration rate of the soils.

For designs based on the Soil Conservation Service or SCS Type II storm, the permeable pavement base filling time (T) is generally less than a 2-hour duration where the flow into the pavement exceeds the flow out of the pavement. Thus, a duration of 2 hours is used for T. The volume of water that must be stored ($V_w$) may be defined as:

$$V_w = \Delta Q_c A_c + PA_p - fTA_p$$

The volume of the stone base can also be defined in terms of its geometry:

$$V_p = V_w/V_r = d_p A_p$$

Where:

$d_p$ = the depth of the stone base,
$A_p$ = the permeable pavement surface area, and
$V_r$ = the stone base void ratio (typically 0.4).

Setting the previous two equations equal will result in the following relationship:

$$d_p A_p V_r = \Delta Q_c A_c + PA_p - fTA_p \quad \text{(Equation 1)}$$

The surface area of the permeable pavement ($A_p$) and the depth of the base ($d_p$) can be defined in the following forms from the above equation:

$$A_p = \frac{\Delta Q_c A_c}{V_r d_p - P + fT} \quad \text{(Equation 2)}$$

and

$$d_p = \frac{\Delta Q_c R + P - fT}{V_r} \quad \text{(Equation 3)}$$

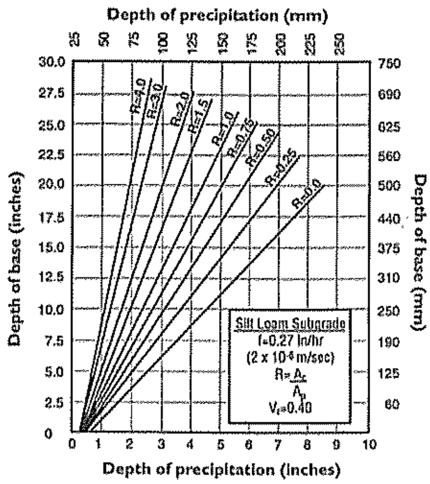



*Figure 20. Open-graded base depth for silt loam subgrade.*

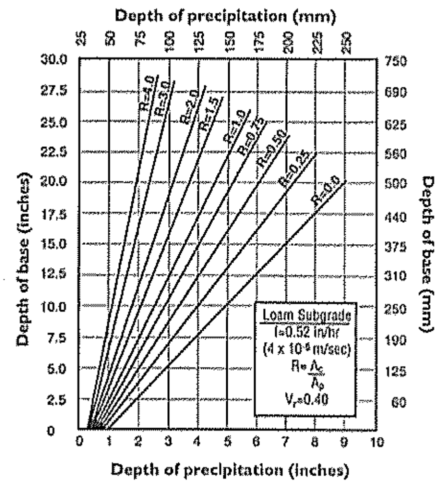



*Figure 21. Open-graded base depth for loam subgrade.*

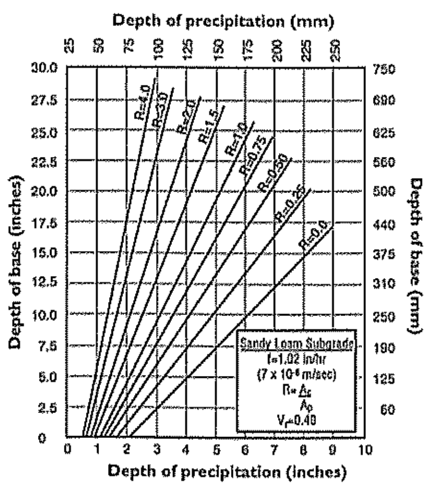



*Figure 22. Open-graded base depth in sandy loam subgrade.*

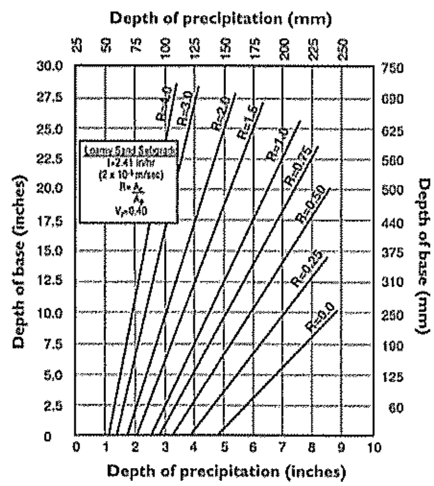



*Figure 23. Open-graded base depth for loamy sand subgrade.*

Where:

R = equal to the ratio of the contributing area and the permeable pavement area ($A_c/A_p$).

Equation 3 will be used most often since the surface area of the pavement is normally known and the depth of the stone base is to be determined. All units in the above two equations are in terms of feet. Metric equivalents can be substituted.

The solution to Equation 3 is shown graphically in Figures 20 through 23. The graphs are based on storing the entire contributing area runoff volume ($Q_cA_c$) based on the SCS curve number for an impervious area, CN = 98. The SCS method offers a chart to assist in finding the depth of runoff from a given 24 hr. design storm for less than completely impervious areas, i.e., curve numbers lower than 98. This chart is shown in Figure 24. Since many localities use 24-hour storms for storm water management.

**Design Procedure**—There are two methods to design the base storage area. The first method computes the minimum depth of the base, given the area of the permeable pavement. This is called the *minimum depth method*. The other is compute the minimum surface area of the permeable pavement given the required design depth of the base. This is the *minimum area method*. The minimum depth method generally will be more frequently used.

### Minimum Depth Method

1. From the selected design rainfall (P) and the SCS runoff curve number, compute the increased runoff volume from the contributing area ($\Delta Q_c$).

2. Compute the depth of the aggregate base ($d_p$) from Equation 3:

   Figures 20 through 23 may be used to determine the approximate stone base depth if the total runoff depth ($Q_c$) is to be stored.

3. Compute the maximum allowable depth ($d_{max}$) of the aggregate base by the feasibility formula:

$$d_{max} = f \times T_s/V_r$$

   where $d_p$ must be less than or equal to $d_{max}$ and at least 2 feet (0.6 m) above the seasonal high ground water table. If $d_p$ does not satisfy this criteria, the surface area of the permeable pavement must be increased or a smaller design storm must be selected.

### Minimum Area Method

1. From the selected design rainfall (P) and the SCS runoff curve number for the contributing area to be drained, compute the increased runoff depth from the contributing area ($DQ_c$).

2. Compute the maximum allowable depth ($d_{max}$) of the aggregate base from the feasibility formula:

$$d_{max} = f \times T_s/V_r$$

   Select a design depth of the aggregate base ($d_p$) less than or equal to $d_{max}$ or the depth at least 2 feet (0.6 m) above the seasonal high ground water table, whichever is smaller.

3. Compute the minimum required surface area of the permeable interlocking concrete pavement ($A_p$) from Equation 3:

$$A_p = \frac{\Delta Q_c A_c}{V_r d_p - P \times fT}$$

### Design Example

Step 1—Assess site conditions. A parking lot is being designed in an urbanized area where storm sewers have limited capacity to convey runoff from an increase in existing impervious surfaces. Runoff from a 1 acre (4,047 m²) asphalt parking lot (100% impervious: SCS curve number or CN = 98) is to be captured by a 2 acre (8,094 m²) permeable interlocking concrete pavement parking area over an open-graded base. The project is not close to building foundations nor are there any wells in the area. Soil borings revealed that the seasonal high water is 10 ft (3 m). The soil borings and testing indicated a USCS classification of SP (poorly-graded sandy soil) with 4%

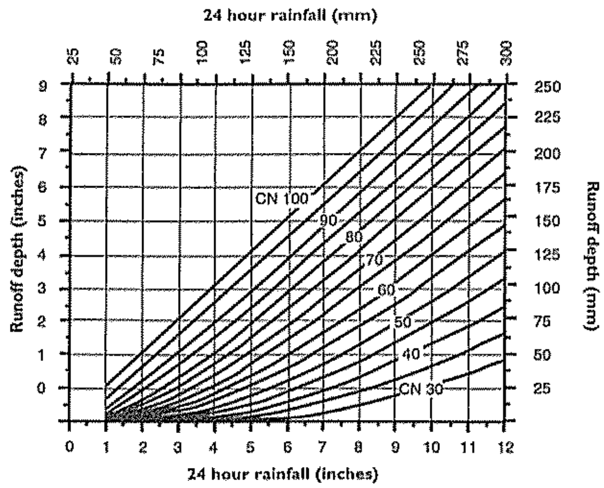



*Figure 24. SCS (NRCS) chart for finding runoff depth for various curve numbers.*

passing the No. 200 (0.075 mm) sieve. Permeability was tested at 1.02 in./hr ($5 \times 10^{-6}$ m/sec). While this was the tested permeability rate, the designer is taking a conservative position on design permeability by assuming it at half or 0.51 in./hr ($3.6 \times 10^{-6}$ m/sec).This approach recognizes that there will be a loss of permeability from construction, soil compaction and clogging over time. The 96-hour soaked CBR of the soil is 12%. An estimated 300,000 ESALs will traffic this parking lot over 20 years. The pavers have an 8% or 0.08 open surface area. The site is in an area that receives frost.

Local regulations require this site to capture all runoff from a 2-year 24 hour storm. This is 5 in. (0.125 m) based on weather maps and local historical storm data. (Other localities often may require capturing the difference in runoff from before and after development for a given design storm or storms. A fairly rigorous requirement is given here of capturing all the runoff due to the limited capacity of the storm sewers. This is also done to simplify the design example.)

The void space in the No. 57 open-graded, crushed stone base provided by the local quarry is 40% or 0.40. A 1-day drainage of the base (or 24-hour drawdown) is the design criteria.

**Step 2—Check the required permeability of the surface openings:** 1 in./hr ÷ 0.08 = 12.5 in./hr ($9 \times 10^{-5}$ m/sec). This will require the use of No. 8 aggregate in the openings since the permeability of this material well exceeds 12.5 in./hr.

Since the area of the permeable interlocking concrete pavement parking lot is established, the depth of the base needs to be determined with the Minimum Depth Method

**Step 3—Compute the increased runoff depth from the contributing area ($\Delta Q_c$) from the selected design rainfall (P) and the SCS runoff curve number.**

Since the contributing area is impervious asphalt with a curve number = 98, all of the rainfall from design storm, or 5 in.(0.125 m), will flow from it into the permeable pavement.

**Step 4—Compute the depth of the aggregate base ($d_p$) from Equation 3:**

$$d_p = \frac{\Delta Q_c R + P - fT}{V_r} = \frac{0.42 \text{ ft } (1 \text{ ac.}/2 \text{ ac.}) + 0.42 \text{ ft} - 0.0425 \text{ ft/hr } (2 \text{ hr})}{0.4} = 1.36 \text{ ft } (0.4 \text{ m})$$

As a short cut, Figure 21 may be used to determine the approximate stone base depth if the total runoff depth ($Q_{cc}$) is to be stored. Use this figure to find 16.3 in. or 1.36 ft (0.4 m).

Step 5—Compute the maximum allowable depth ($d_{max}$) of the base by the feasibility formula:

$$d_{max} = f \times T_s / V_r$$

where $d_p$ must be less than or equal to $d_{max}$ and at least 2 feet (0.6 m) above the seasonal high ground water table. If $d_p$ does not satisfy this criteria, the surface area of the permeable pavement must be increased or a smaller design storm must be selected. The drainage time is 24 hours.

$$d_{max} = 0.0425 \text{ ft/hr} \times 24 \text{ hr}/0.40 = 2.5 \text{ ft } (0.75 \text{ m})$$

Step 6—Check the structural base thickness to be sure it has sufficient thickness to meet the storage requirements plus function as a base for 300,000 ESALs. The Frost Condition side of Figure 18 with interpolation yields a thickness close to 17 in. (0.425 m). This is slightly thicker than what is required, 16.3 in. (0.4 m), to infiltrate and store the water in the base.

In no case should the structural thickness be reduced for the sake of economy. In some cases, the designer may wish to provide a thicker base due to expected heavy loads, or from spring thawing conditions that leave the soil completely saturated and weak. A frost protection layer of sand with drains can be placed under the base (separated by geotextiles) to reduce heave from highly susceptible soils in freeze-thaw conditions. This layer of sand offers additional filtering and reduction of pollutants, and construction details are discussed elsewhere.

It is very unlikely that the base and leveling courses will heave from ice. There is typically sufficient void space in them to allow frozen water to expand (9%) without heaving because it is rare that the base will be entirely and thoroughly saturated when freezing.

Step 7—Check to be sure the bottom of the base is at least 2 ft (0.6 m) from the seasonal high water table. The total thickness of the pavement will be:

3 1/8 in. (80 mm) thick concrete pavers
3 in. (75 mm) No. 8 stone leveling course
17 in. (425 mm) No. 57 stone base
Total thickness = 23 in. (580 mm)

Almost 2 ft. (0.6 m) minus 10 ft (3 m) leaves about 8 ft (2.4 m) to the top of the seasonal high water table. This is greater than the 2 ft (0.6 m) minimum distance required.

A somewhat hidden consideration is the storage capacity of the layer of No. 8 crushed stone. As a factor of safety, the void space in the No. 8 layer is not part of the storage calculations. This additional volume in the leveling course can serve as a safety buffer for storage in heavy rainfall.

Step 8—Check geotextile filter criteria. Sieve analysis of the soil subgrade showed that 4% passed the No. 200 (0.075 mm) sieve, and the gradation also showed the following:

| | $D_{10}$ | $D_{15}$ | $D_{50}$ | $D_{60}$ | $D_{85}$ |
|---|---|---|---|---|---|
| Soil subgrade | 0.10 | 0.12 | 0.25 | 0.32 | 0.63 |

FHWA geotextile filter criteria—For granular soils with ≤50% passing the No. 200 (0.075 mm) sieve, the following selection criteria is used for geotextiles taken from Figure 18.

**All geotextiles:** $AOS_{geotextile} \leq B \times D_{85(soil)}$

$C_u = D_{60}/D_{10} = 0.32/0.10 = 3.2$

Where:

$B = 1$ for $2 \geq C_u \geq 8$, 3.2 is okay.
$B = 0.5$ for $2 < C_u < 4$, 3.2 is okay.
$B = 8/C_u$ for $4 < C_u < 8$

8/3.2 = 2.5 which does not satisfy 4 < 2.5 < 8. (Do not use for **B**.)

Therefore, select a geotextile with an **AOS** (or **EOS**) between 0.5 x 0.63 = 0.32 mm and 1.0 x 0.63 = 0.63 mm.

Permeability criteria: k (fabric) $\geq$ k (0.52 in./hr)
Clogging criteria:
Woven: Percent of open area $\geq$ 4%
Nonwoven: Porosity $\geq$ 30%

AASHTO geotextile filter criteria (36)—For soils $\leq$ 50% passing the No. 200 (0.075 mm) sieve:

$$O_{95} < 0.59 \text{ mm } (AOS_{geotextile} \geq \text{No. 30 sieve})$$

The FHWA and AASHTO criteria provide similar guidance in selecting the **AOS** of a geotextile. In both cases, the **AOS** should be less than the No. 30 (0.600 mm) sieve, but greater than 0.32 mm.

## Other Design Methods

Like most structural BMPs, the hydrological and pollution abatement characteristics of permeable interlocking concrete pavements should be incorporated into managing runoff within the large catchment, sub-watershed or watershed. The SCS method is well-established, easy to use and easy to adapt to various BMPs. For example, reference 35 applies the SCS method to infiltration trench design. For the permeable pavements themselves, the curve number can be estimated at 65 for all SCS soil groups assuming an average, life-time design infiltration rate of 1.1 in./hr (28 mm/hr) with an initial abstraction of 0.2. Users of other quantitative models (HEC-1, EPA SWMM, etc.) are encouraged to modify their programs to include permeable interlocking concrete pavements.

Some caution should be exercised in applying the SCS method to calculating runoff in catchments as small as 5 acres (2 ha). This method is intended to calculate runoff from larger storms (2, 10, and 100 year return periods) with 24-hour durations. Therefore, the SCS procedure tends to underestimate runoff from smaller storms in small drainage areas. Permeable interlocking concrete pavements control runoff from smaller storms. Typically, they generate the most amount of non-point water pollution. Claytor and Schueler suggest methods to calculate runoff from small areas from smaller storms especially when water quality needs to be controlled (9).

### Rational Method Calculations

The SCS method is commonly used for calculating runoff volumes and peak discharges. The Rational Method is only useful for estimating peak runoff discharges in watersheds up to 200 acres (80 ha). Peak flow is derived from the formula

$Q = CIA$

Where:

Q = peak discharge in cubic feet per second
I = design rainfall intensity in inches per hour
A = Drainage area in acres
C = Coefficient of runoff

Since the formula does not account for volume, *it cannot be used in water quality calculations.* For peak runoff calculations, the coefficient of runoff, C for the design life of interlocking concrete pavements can be estimated with the following formula: $C = \frac{I - 1.1}{I}$

### Protection Against Flooding From Extremely Heavy Rainstorms

There may be cases of extreme rainfall completely saturating the entire pavement structure. Drainage pipes should be built into the open-graded base to handle overflow conditions. As an added measure of protection, there should be provision for an overflow area, by-pass, or drainage swale adjacent to the parking lot should it be completely saturated and flooded. An example of a drainage swale designed to handle overflows from an adjacent pervious parking lot is illustrated in Figure 25.

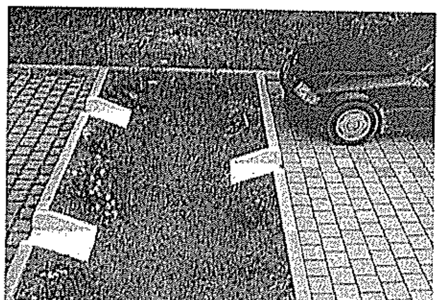


*Figure 25. Curbing and drainage swale handle flows that exceed the design rainstorm.*

Placing filter areas upslope from the pavement to reduce pollutants are recommended when space allows.

### Cold Climate Design

The following design considerations apply to freezing climates with extended winters having large, rapid volumes of snow melt in the late winter and early spring. These areas are mostly in the northern U.S. and Canada (39).

1. Permeable interlocking concrete pavements should not be used in permafrost regions.
2. Chlorides and road abrasives (sand) can be concentrated in snowmelt. It's impossible for any best management practice, including permeable interlocking concrete pavements, to remove chlorides found in deicing materials. In addition, road sand can clog and reduce the infiltration capacity of these pavements. It is best to stockpile snow with chlorides and/or sand away from permeable interlocking concrete pavements. Possible locations include parking lot islands or bioretention areas.
3. If salts are used for deicing, then the groundwater should be monitored for chlorides. This can be done through sampling water in observation wells located in the pavement base and soil. Chloride levels in the samples should be compared to local or national criteria for the particular use of the water in the receiving lake, stream, or river (e.g., drinking water, recreation, fishing, etc.).
4. When the frost depth exceeds 3 ft. (1 m), all permeable parking lots should be set back from the subgrade of adjacent roads by at least 20 ft (6 m). This will reduce the potential for frost lenses and heaving of soil under the roadway.
5. Plowed snow piles and snow melt should not be directed to permeable interlocking concrete pavements if groundwater contamination from chlorides is a concern. However, this may not be avoidable in some situations. If high chloride concentrations in the runoff and groundwater are anticipated, then consideration should be given to using one or two design options below:

   (a) Runoff from snow melt can be diverted from the pavement during the winter. The diversion of runoff away from the pavement is typically through channels or pipes. Pipe valves must be operated each winter and spring. Snowmelt, however, is not treated but diverted elsewhere.

   (b) Oversized drainage pipes can be used to remove the runoff during snowmelt, and then be closed for the remainder of the year.

   The owner of the pavement must take responsibility for operating pipe valves that divert snowmelt. This may not be realistic with some designs.
6. Maintenance should include annual inspection in the spring and vacuum removal of surface sediment, as well as monitoring of groundwater for chlorides. This is paramount to continued infiltration performance.

### Design for Control of Water Quality

Since urbanization significantly alters the land's capacity to absorb and process water pollutants, an increasing number of localities are regulating the amount of pollutants in stormwater. This is particulary the case when drinking-water supplies and fishing industries need to be protected. Urban stormwater pollutants and their sources are shown in Figure 26.

Permeable interlocking concrete pavements designed as an infiltration area over an open-graded base can reduce nonpoint source pollutants in storm water. Figure 27 illustrates the projected average annual pollutant removal capability of infiltration practices. While field data is limited, Figure 27 demonstrates their effectiveness in reducing typical pollutants.

Keep in mind that the type of soil subgrade affects the pollution reduction capabilities of infiltration areas. Clay soils with a high cation exchange capacity will capture more pollutants than sandy soils. Debo and Reese (11) recommend that for control runoff quality, the storm water

| Pollutant Category Source | Solids | Nutrients | Bacteria | Dissolved oxygen demands | Metals | Oils (PAHs)* SOCs* |
|---|---|---|---|---|---|---|
| Soil erosion | * | * | | * | * | |
| Cleared vegetation | * | * | | * | | |
| Fertilizers | | * | | | | |
| Human waste | * | * | * | * | | |
| Animal waste | * | * | * | * | | |
| Vehicle fuels and fluids | * | | | * | * | * |
| Fuel combustion | | * | | | * | |
| Vehicle wear | * | | | * | * | |
| Industrial/household chemicals | * | * | * | * | * | * |
| Industrial processes | * | * | * | * | * | * |
| Paints and preservatives | | | | * | * | * |
| Pesticides | | | | * | * | |

PAHs = polynuclear aromatic hydrocarbons
SOCs = synthetic organic compounds

*Figure 26. Common sources of pollution in urban stormwater runoff (3)*

| Pollutant | Infiltration Trench Design Type* | | | Infiltration Trenches & Porous Pavement |
|---|---|---|---|---|
| | 0.5 in. (13 mm) of Runoff per Impervious acre | 1.0 in. (25 mm) of Runoff per Impervious acre | 2-year Design Storm Treatment | Median Pollutant Removal** |
| Total Suspended Solids | 60-80 | 80-100 | 80-100 | 95 |
| Total Phosphorous | 40-60 | 40-60 | 60-80 | 70 |
| Total Nitrogen | 40-60 | 40-60 | 60-80 | 51 |
| Biological Oxygen Demand | 60-80 | 60-80 | 80-100 | — |
| Bacteria | 60-80 | 60-80 | 80-100 | — |
| Metals | 60-80 | 60-80 | 80-100 | 99 (Zn) |

*Note: These rates are not based on actual data since monitoring what enters and leaves any infiltration facility is difficult to measure. These data are based on land application of pollutants and their treatment through soils.

**Actual monitored removal rates.

*Figure 27. Projected average annual pollutant removal capability of infiltration areas in percent (from Debo and Reese (11) after Schueler) and actual, monitored removal rates documented by Winer (42)*

should infiltrate through at least 18 in. (0.45 m) of soil which has a minimum cation exchange capacity of 5 milliequivalents per 100 grams of dry soil. However, some clay soils that are effective pollutant filters do not have a sufficiently high infiltration rate or sufficient bearing capacity when saturated to be used under infiltration areas subject to vehicular loads.

Other approaches to reducing pollutants include filtering runoff from impervious areas through sand filters to help reduce sediment and oils. The typical application involves a small area that pretreats runoff prior to entering a detention or retention pond. The sand absorbs and helps treat the concentrated pollutants found in the first flush of a rainstorm. Design of sand filtering systems is found in reference 9.

As desirable as they may be for reducing pollutants, sand filters adjacent to permeable interlocking concrete pavements are likely to be impractical in some cases since directing all runoff through the filter and into the pavement can be difficult. An alternative approach is to place a layer of sand *under* the open-graded base to filter and treat pollutants prior to their release into a stream or storm sewer. Figure 28 illustrates a sand filtering system under the pavement base. The advantage of this design is that the sand layer can be thick (12 in. (300 mm) minimum) and provide a substantial amount of filtering. The disadvantage is that the pavers and stone base will need to be removed should the sand require replacement from becoming clogged and contaminated.

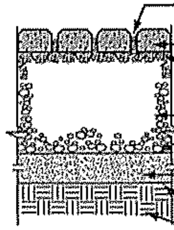



*Figure 28. A thick sand filter at the bottom of permeable interlocking concrete pavement reduces pollutants.*

# Section 3. Construction

### Reducing Clogging

Preventing and diverting sediment from entering the base and pavement surface during construction *must be the highest priority*. Extra care must be applied to keeping sediment completely away from the area. Simple practices such as keeping muddy construction equipment away from the area, installing silt fences, staged excavation, and temporary drainage swales that divert runoff away from the area will make the difference between a pavement that infiltrates well or poorly. Moreover, the pavement should not receive runoff until the entire contributing drainage area is stabilized. This should be included in the construction drawings and specifications.

Preventing and diverting sediment from entering the base and pavement surface during construction must be the highest priority.

### Soil Compaction

If the initial undisturbed soil infiltration can be maintained during excavation and construction, there is a high probability that the base will drain as designed. If the soil is inadvertently compacted by equipment during construction, there will be a substantial loss of infiltration. A loss is acceptable if the infiltration rate of the soil *when compacted* was initially considered during design and in drainage calculations.

Compaction may be necessary to attain sufficient structural support and to minimize rutting from vehicular traffic. The soil subgrade should be compacted to at least 95% of standard Proctor density for pedestrian areas and to a minimum of 95% modified Proctor density for vehicular applications. Drains in the open-graded base will likely be required to remove water since compaction will greatly reduce the soil's permeability.

### Geotextiles

Geotextiles are used in almost all permeable pavement applications. Specifications and minimum physical requirements for geotextiles for separation and drainage can be found in reference 26 by AASHTO Task Force 25. For vehicular applications, high-quality fabric should be specified that resists the puncturing by coarse, angular aggregate from compaction during construction and from repeated wheel loads during its service life. Bases should have their sides and bottoms wrapped in geotextile. Overlap recommendations are provided in AASHTO specifications (min. 2 ft or 0.6 m).

### Handling Excess Water

Designs using full exfiltration should have pipes to handle emergency overflow conditions. Partial or no exfiltration designs require pipes to handle storage and outflow from design storms and those from overflow conditions. The size and placement of drain pipes should be determined by a civil engineer experienced in hydrological design and stormwater management. Pipes in bases subject to traffic should withstand repeated vehicular loads.

Perforations in pipes should be 3/8 in. (10 mm) in diameter and terminate 1 ft (0.3 m) short of the sides of the opening for the base. When corrugated metal drain pipes are used, they should be aluminized, and aluminized pipe in contact with concrete should be coated to prevent corrosion. Perforated metal drain pipes should have caps fastened to the ends. The ends of the pipes should be capped.

A 6 in. (150 mm) diameter perforated pipe that serves as an observation well is recommended in all pavements. The pipe should be kept vertical during filling of the excavated area with open-graded aggregate and during compaction. The bottom of the pipe can be attached to a plate for stability when resting on the geotextile and held in place during base filling and compaction by first placing some open graded aggregate on the plate. The bottom of the pipe should be capped. It should be located in the most downslope position and a minimum of 3 ft. (1 m) from the sides of the base.

### Open-graded Aggregate Bases

After installation of geotextile over the soil subgrade, No. 57 base material should be spread in 4 to 6 in. (100 to 150 mm) lifts and compacted with a static roller. At least 4 passes should be made with a minimum 10 ton (9 T) steel drum roller.

*Figure 29. Mechanized equipment placing permeable pavers at a rate as high as three times greater than manual methods. This project is a parking lot.*

The initial passes with the roller can be with vibration to consolidate the base material. The final passes should be without vibration. A test section of the base should be constructed and closely monitored during compaction. The section will indicate settlement of the pavement section, and whether crushing of the aggregate is excessive. The area should be used to train construction personnel on these and related aspects.

When all lifts are compacted the surface should then be topped with a 3 in. (75 mm) thick layer of moist No. 8 crushed stone. This layer of finer crushed stone is leveled and pressed (choked) into the top of the No. 57 base with at least 4 passes of a 10 ton (9 T) static roller. The No. 8 should be moist to facilitate movement into the No. 57. The surface tolerance of the compacted No. 8 material should be $\pm^1/_2$ in. or 10 ft. ($\pm$13 mm over 3 m).

The minimum surface tolerance of the compacted, open-graded aggregate used for the bedding should be $\pm^3/_8$ in. ($\pm$10 mm) over a 10 ft (3 m) straightedge. The base surface is typically between level and 2% slope.

The concrete pavers should be placed immediately after the No. 57 and No. 8 base courses are placed and compacted. This will reduce the chance of construction equipment passing over the base and contaminating it with sediment. Equipment drivers should avoid rapid acceleration, hard braking, or sharp turning on the compacted base layers. If the base surfaces are disturbed, they should be releveled and recompacted.

### Stabilized Bases

Open-graded bases may be stabilized with asphalt prior to placement. Stablilize the No. 57 layer and not the No. 8 layer used for bedding. The use of asphalt will likely reduce the storage capacity of the base, but stabilization may be necessary to increase its structural capacity. To maintain high void space, only enough asphalt to coat the aggregate is required. For further information on the design and construction of asphalt bases, see reference 40.

Likewise, cement should be applied only to coat the aggregate for the base, and care should be taken not to fill the voids with excess paste. The amount of portland cement required is typically 190 lb/yd$^3$ (170 kg/m$^3$). The water-cement ratio should be controlled to make a paste to coat the aggregate.

### Edge Restraints

Recommended edge restraints for permeable interlocking concrete pavements on open-graded bases are cast-in-place and precast concrete curbs. They should be a minimum of 6 in. (150 mm) wide and 12 in. (300 mm) deep. Consideration should be given to providing a stable footer or concrete haunch under the curbs. Plastic edge restraints that utilize spikes are not recommended.

*Figure 30. Interlocking shapes installed by machine.*

### Paver Installation

In designs with bedding sand, the pavers are placed on this screeded layer and compacted with a plate compactor. For units $3^1/_8$ to 4 in. (80 to 100 mm) thick, the plate compactor should exert a minimum 5,000 lbf (22 kN) at 75 to 90 Hz. For units thicker than 4 in. (100 mm), the compactor should exert at least

6,800 lbf (30 kN). After initial compaction, the joints or openings are filled with No. 8 material and the paving units are compacted again. Excess stone is removed by sweeping. For vehicular areas, proof rolling is recommended with at least two passes of a 10 T rubber-tired roller.

Paver installation can be by hand or with mechanical equipment. Mechanized installation may be a cost-efficient means to install the units and will reduce the installation time. Figure 29 shows mechanized equipment placing permeable pavers for a parking lot adjacent to a baseball field. Figure 30 shows placement of another interlocking shape, while Figure 31 illustrates mechanized placement of pavers with widened joints. For further information on mechanical installation, consult ICPI *Tech Spec 11—Mechanized Installation of Interlocking Concrete Pavements* (41).

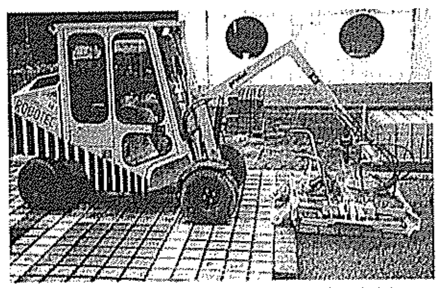


*Figure 31. Mechanized placement of pavers with wide joints.*

Units should be cut to fill any spaces along the edges prior to compaction. Cut units should be no smaller than 1/3 of a whole unit if subject to vehicular traffic. All installed units should be compacted into the No. 8 aggregate and joints filled with the appropriate material at the end of each day.

# Section 4. Guide Specifications and Construction Checklist

## SECTION 02795—PERMEABLE INTERLOCKING CONCRETE PAVEMENTS

Note: This guide specification is for the construction of permeable interlocking concrete pavers on No. 57 crushed stone open-graded base with No. 8 crushed stone (or similar), with or without sand as a bedding layer for the concrete pavers. The openings of the pavers may be filled with No. 8 stone or topsoil and grass. Localities may use aggregate materials similar in gradation to Nos. 57 and 8 materials. This guide specification should be edited by an engineer/architect/landscape architect to conform to project conditions. Pavements should be designed in consultation with a qualified civil engineer and with ICPI Tech Spec technical bulletins.

## PART 1 GENERAL

### 1.01 SECTION INCLUDES

A. Concrete units.
B. Bedding materials.
C. Geotextiles.

### 1.02 RELATED SECTIONS

A. Section [____-____]: Curbs.
B. Section [____-____]: Open-graded base materials.
C. Section [____-____]: Stabilized aggregate base.
D. Section [____-____]: Impermeable liner.
E. Section [____-____]: Edge restraints.
F. Section [____-____]: Drainage pipes and appurtenances.
G. Section [____-____]: Earthworks/excavation/soil compaction.

### 1.03 REFERENCES

Note: Refer to the latest edition of standards.

A. American Society of Testing Materials (ASTM)
   1. C 936, Standard Specification for Solid Interlocking Concrete Pavements.
   2. C 33, Specification for Concrete Aggregates.
   3. D 2490, Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports.
B. Canadian Standards Association (CSA)
   1. A231.2, Precast Concrete Pavers.

### 1.04 QUALITY ASSURANCE

A. The contractor shall have experience with placement of permeable interlocking concrete pavements. The contractor shall have completed [ ] projects comprising of not less than [ ] sy ($m^2$) of permeable interlocking concrete pavements within the last [24] months. The contractor shall submit a list of projects, the area of permeable paving for each, locations, and details on the type of permeable interlocking concrete pavement(s) built.
B. As applicable by state/provincial and local laws, contractor shall hold a current contractor's and business license in the state/province and locality where work is to be performed.

### 1.05 SUBMITTALS

A. Shop or product drawings and data.
B. Samples of paving units to indicate shape selections and color(s).
C. Sieve analysis of aggregates for base and bedding materials.
D. Test results for compliance of paving units to ASTM C 936 or CSA A231.2 as applicable.
E. Soils report indicating density test reports, classification, and infiltration rate measured on-site under compacted conditions, and suitability for the intended project.
F. Erosion and sediment control plan.
G. Stormwater management (quality and quantity) calculations.

### 1.06 MOCK UPS

A. Install a 6 ft. x 6 ft. (2 m x 2 m) paver area as described in Article 3.02. This area will be used to determine surcharge of the sand layer, joint sizes, lines, laying pattern(s), and texture of the job. This area shall be the standard from which the work will be judged.
B. Mock up approved by [engineer][architect][landscape architect] shall be part of the work.

### 1.07 DELIVERY, STORAGE AND HANDLING

A. Deliver concrete pavers to the site in steel banded, plastic banded, or plastic wrapped cubes capable of transfer by fork lift or clamp lift. Unload pavers at job site in such a manner that no damage occurs to the product.
B. [Protect sand and top soil with waterproof covering to prevent exposure to rainfall, removal by wind, or contamination from any source. Secure the covering in place.]

### 1.08 ENVIRONMENTAL CONDITIONS

A. Do not install pavers during rain or snowfall.
B. Do not install frozen base materials.

## PART 2 PRODUCTS

### 2.01 PAVING UNITS

Note: Pavers should be a minimum of 3 1/8 in. (80 mm) thick.

A. Manufactured/supplied by a member(s) of the Interlocking Concrete Pavement Institute (ICPI). The ICPI manufacturer/supplier shall be:
   [name: ]
   [address: ]
   [phone: ]
   [fax: ]
B. Product name/shape, __________, overall dimensions, and thickness of the paver(s):
   ______ mm/in. x ______ mm/in and ______ mm/in thick.
   ______ mm/in. x ______ mm/in and ______ mm/in thick.
C. Meet the requirements of ASTM C 936 or CSA A231.2 as applicable.
   1. When testing 3 1/8 in. (80 mm) thick units for conformance to ASTM C 936, compressive strength tests shall be corrected by multiplying the results by 1.18.
   2. When testing 4 in. (100 mm) thick units for conformance to ASTM C 936, compressive strength tests shall be corrected by multiplying the results by 1.24.
D. Certified by the ICPI.

## 2.02 MATERIALS FOR BEDDING AND OPENINGS

Note: Crushed stone conforming to ASTM C 33 No. 57. Gradation should conform to Table 1 below:

Table 1

| Grading Requirements for ASTM No. 57 | |
|---|---|
| Sieve Size | Percent Passing |
| 1 1/2 in. (37.5 mm) | 100 |
| 1 in. (25 mm) | 95 to 100 |
| 1/2 in. (12.5 mm) | 25 to 60 |
| No. 4 (4.75 mm) | 0 to 10 |
| No. 8 (2.36 mm) | 0 to 5 |

A. ASTM C 33 No. 8 crushed stone per the gradation shown in Table 2.

Table 2

| Grading Requirements for ASTM No. 8 | |
|---|---|
| Sieve Size | Percent Passing |
| 1/2 in. (12.5 mm) | 100 |
| 3/8 in. (9.5 mm) | 85 to 100 |
| No. 4 (4.75 mm) | 10 to 30 |
| No. 8 (2.36 mm) | 0 to 10 |
| No. 16 (1.16 mm) | 0 to 5 |

Note: ASTM No. 89 crushed stone or finer material may be required to fill narrow joints between interlocking concrete paver shapes.

## 2.03 GEOTEXTILES

A. Per [manufacturer, product name/number] as supplied by [source].

# PART 3 EXECUTION

## 3.01 EXAMINATION

Note: Compaction of the soil subgrade should be to a minimum of 95% standard Proctor density for pedestrian areas and residential driveways, and a minimum of 95% modified Proctor for vehicular areas. Density and moisture should be checked in the field with a nuclear density gauge or other test methods for compliance to specifications. Stabilization of the soil and/or base material may be necessary with weak or saturated soils, or when subject to high wheel loads. Compaction will reduce the permeability of soils. These conditions may require the use of drains in open-graded bases.

A. Verify that base is free from standing water, uniform, even, free of any organic material or debris, ready to accept bedding materials, pavers and imposed loads.
B. Verify correct gradients and elevations of open-graded base.
C. Verify placement of geotextile [impermeable liner].
D. Verify compaction of soil to specified density and moisture content.
E. Verify location, type, installation and elevations of edge restraints around the perimeter area to be paved.
F. Beginning of installation means acceptance of base, edge restraints, drain pipes, and overflow devices.

## 3.02 INSTALLATION

Note: Geotextile is typically placed on the compacted soil subgrade under the No. 57 open-graded base. The geotextile is applied to the bottom and sides of the excavation with overlapped joints of 24 in. (0.6 m). Overlaps should follow downslope with drainage. All drain pipes, observation wells, overflow pipes, and impermeable liner (if applicable) should be in place per the drawings either prior to or during placement of the base, depending on their location. The No. 57 base is typically compacted in 4 to 6 in. (100 to 150 mm) thick lifts with a minimum 10 ton (9T) static roller. Care must be taken not to damage drain pipes during compaction and paving. There should be at least 4 passes with no visible movement in the base material when compaction is complete.

A. Keep area where pavement is to be constructed free from sediment during entire job. Geotextiles, base and bedding materials contaminated with sediment shall be removed and replaced with clean materials.
B. Place and compact the No. 8 bedding material. Compact with a minimum [10] ton static roller. Make at least [4] passes. No visible movement should occur in the base material when compaction is complete.
C. The elevation of the compacted surface should not deviate more than ±1/2 in. (±13 mm) over a 10 ft. (3 m) straightedge.
D. Loosen and evenly smooth 3/4 to 1 in. (20 to 25 mm) of the compacted surface of the No. 8 bedding material. Maintain smooth, even surface during paver installation.
E. Lay the pavers [and spacers] in the pattern(s) and joint widths shown on the drawings. Maintain straight pattern lines.
F. Fill gaps at the edges of the paved area with cut pavers [edge units].
G. Cut pavers to be placed along the edges with a double-bladed splitter or masonry saw.
H. Compact and seat the pavers into the bedding material using a low amplitude, 75-90 Hz plate compactor capable of at least 5,000 lbs. (22 kN) centrifugal compaction force. For units thicker than 4 in. (100 mm) use a compactor capable of at least 6,800 lbf (30 kN).
I. Vibrate and compact the pavers again, sweeping No. 8 aggregate into the openings until it is within 1/2 inch (13 mm) from the top surface. This will require at least two or three passes with the compactor.
J. Do not compact within 3 ft (1 m) of the unrestrained edges of the paving units.
K. Remove excess aggregate by sweeping pavers clean.
L. All pavers within 3 ft (1 m) of the laying face must be left fully compacted at the completion of each day.
M. The final surface elevations shall not deviate more than ±3/8 in. (±10 mm) under a 10 ft (3 m) long straight-edge.
N. The surface elevation of pavers shall be 1/8 to 1/4 inch (3 to 7 mm) above adjacent drainage inlets, concrete collars or channels.

## 3.03 FIELD QUALITY CONTROL

A. After removal of excess aggregate, check final elevations for conformance to the drawings.

END OF SECTION

## Construction Inspection Checklist

### Pre-excavation

- ☐ Roped off area to divert construction vehicles
- ☐ Runoff diverted: no runoff enters pavement from disturbed areas
- ☐ No runoff enters pavement until soils stabilized in area draining to permeable pavement
- ☐ Utilities located and marked
- ☐ Marked area to be excavated
- ☐ Walk through with builder/contractor/subcontractor to review Erosion and Sediment Control Plan

### Excavation

- ☐ Size and location conforms to plan
- ☐ At least 10 ft (3 m) from foundation walls
- ☐ At least 100 ft (30 m) from water supply wells
- ☐ Soil permeability: no sealed surfaces, rocks and roots removed, voids refilled with permeable soil
- ☐ Soil compacted to specifications and field tested with density measurements
- ☐ Groundwater/bedrock: no groundwater seepage, standing water, or presence of bedrock

### Geotextile

- ☐ Meets specifications
- ☐ Placement and downslope overlap (typically 2 ft or 0.6 m) conform to specifications and drawings
- ☐ Sides of excavation covered with geotextile
- ☐ No tears or holes
- ☐ Minimal wrinkles, pulled taught and staked
- ☐ Sand filter applied (if applicable) over geotextile: verify thickness and compaction

### Drain pipes/observations wells

- ☐ Size, perforations, locations, slope, and outfalls meet specifications and drawings
- ☐ Elevation of overflow pipes correct

### Aggregate base course

- ☐ Sieve analysis conforms to specifications
- ☐ Laid or spread (not dumped) with a front-end loader to avoid aggregate segregation
- ☐ Thickness, placement, and compaction meets specifications and drawings

### Aggregate choke course or bedding sand

- ☐ Sieve analysis conforms to specifications
- ☐ Laid or spread (not dumped) from a front-end loader to avoid aggregate segregation
- ☐ Thickness, placement, and compaction meet specifications and drawings
- ☐ Geotextile applied under bedding sand (if used)

### Edge restraints

- ☐ Elevation, placement, and materials meet specifications and drawings

### Permeable interlocking concrete pavers

- ☐ Meets ASTM or CSA standards as applicable
- ☐ Elevations, slope, laying pattern, joint spacers, and placement/compaction meet drawings and specifications
- ☐ Joint materials conform to specifications (aggregate or sand/topsoil/grass)
- ☐ Drainage swales for emergency overflow
- ☐ Pre-treatment drainage area for filtering runoff

### Final inspection

- ☐ Elevations and slope conform to drawings
- ☐ Transitions to impervious paved areas separated with edge restraints
- ☐ Stabilization of soil in area draining into permeable pavement (min. 20 ft (6 m) vegetative strip recommended)
- ☐ Sand filter(s) operational.

# Section 5. Maintenance

Permeable interlocking concrete pavements can become clogged with sediment over time, thereby slowing their infiltration rate and decreasing storage capacity. Figure 32 shows an installation subject to nearby construction that has brought sediment into pavement openings. Clogged openings are a major cause of failure. The rate of sedimentation depends on the amount of traffic and other sources that wash sediment into the joints, base and soil. Since the pavement is detaining runoff that contains sediment, there may be a need to eventually remove and replace the base material when the infiltration is reduced to such a degree that the pavement is no longer performing its job in storing and exfiltrating water.

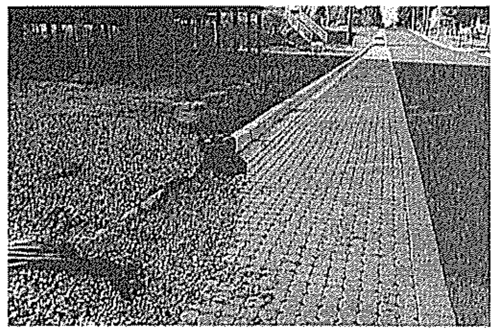


*Figure 32. Unwanted sediment tracked onto permeable pavers via this gravel access ramp to a construction site will clog their openings.*

All permeable interlocking concrete pavements with an open-graded base should have an observation well. The well is typically a 6 in. (150 mm) diameter perforated pipe. It has a screw cap below the surface of the pavers at least 1 in. (25 mm) that can be removed to observe the rate of exfiltration. The cap should lock and be vandal-resistant. The depth to invert should be marked on the lid. As previously noted, the observation well is located in the furthest downslope position within 3 ft (1 m) from the sides of the pavement.

Snow can be plowed from pavers as with any other pavement. Salt will infiltrate into the base and soil. Therefore, deicing salts are not recommended. If a unit cracks from soil or base settlement, it can be removed and replaced. Likewise, the same units can be reinstated after repairs to the base, drain pipes, liners, or to underground utilities. Sealers should never be used.

### In-service Inspection Checklist

- ☐ Vacuum surface openings in dry weather to remove dry, encrusted sediment. These appear as small, curled "potato chips." Vacuum and sweeper settings may require adjustment to prevent uptake of aggregate in the pavement openings and joints.
- ☐ Inspect after at least one major storm per year.
- ☐ Maintained vegetation around pavement to filter runoff.
- ☐ No standing water on the surface after storms.
- ☐ Repair ruts or deformations in pavement exceeding $^1/_2$ in. or 13 mm.
- ☐ Repair pavers more than $^1/_4$ in. or 6 mm above/below adjacent units.
- ☐ Replace broken units that impair the structural integrity of the surface.
- ☐ Replenish aggregate joint materials as needed.
- ☐ Check drain outfalls for free flow of water.
- ☐ Check outflow from observation well annually.

*Figure 33. Owners play a key role in keeping permeable interlocking concrete pavements free from sediment, weeds, and spills. This installation filters runoff prior to entering the Chesapeake Bay in Maryland.*

## Long Term Performance and Maintenance Agreements

When carefully constructed and regularly maintained, permeable interlocking concrete pavements should provide 20 to 25 years of service. Their service life is measured by the extent to which they continue storing runoff. At some point later in the life of the pavement, it may no longer store the required amount of water to control runoff. In such cases, the pavers will need to be removed, the base materials and geotextile removed and replaced. Clogged or broken drain pipes will require replacement. Once new materials are in place, the same pavers can be reinstated.

Removal and replacement of the base and pavers is an expensive operation. Other lower-cost alternatives may be possible such as cleaning or replacing selected clogged pipes (rather than the entire base and pipe system) or diverting drainage to another BMP. Ongoing maintenance and inspection are important to tracking drainage performance, sources of problems, and deciding on possible solutions.

The owner of permeable interlocking concrete pavement plays a key role in maintenance and successful long-term performance of permeable interlocking concrete pavements. The owner should have long-term ownership and oversight of the property and be aware of maintenance requirements. A growing trend to ensure oversight is a maintenance agreement. It is typically between the property owner and the local city or county, and the agreement is recorded and attached to the deed for the property.

The model agreement presented below is applicable to many BMPs. It can be edited to suit local situations and customized for the maintenance of permeable interlocking concrete pavement. A list of maintenance items should be an attachment to this agreement, as well as an inspection schedule. This list of items to be inspected can be developed from the in-service inspection checklist in this section as well as from requirements established by the local government. A growing number of local governments are creating databases in which to place BMP inspection data. This provides continual documentation of care and performance.

## Model Maintenance Agreement

This Maintenance Agreement made this ____ day of ______, [year], by and between [property owner/s], hereinafter referred to as "Grantor," and the [city/county of state/province] hereinafter referred to as the "[city/county]."

WITNESSETH

WHEREAS, the [city/county] is authorized ad required to regulate and control disposition of storm and surface waters within the [city/county/watershed] as set forth by [city/county] [state/provincial] ordinances; and

WHEREAS, the Grantor is the owner of a certain tract or parcel of land more particularly described as [legal description].

ALL THOSE certain lots, pieces or parcels of land, together with buildings and improvements thereon, and the appurtenances thereunto belonging, lying, situated and being in the [city/county] of [state/province] as shown on [tax maps/ subdivisions plats numbers and names], duly recorded in the Clerk's Office of the [court] of [city/county] in Deed Book or Plat Book [number] at page [number] reference to which the plat is hereby made for a more particular description thereof.

It being the said property conveyed unto the Grantor herein by deed dated ________ from ________ and recorded in the Clerk's office aforesaid in Deed Book________ at Page________ such property being hereinafter referred to as "the property."

WHEREAS, the Grantor desires to construct certain improvements on the property which will alter existing storm and surface water conditions on the property and adjacent lands; and

WHEREAS, in order to accommodate and regulate these anticipated changes in existing storm and surface water flow conditions, the Grantor, its heirs and assigns, desire to build and maintain at their expense a storm and surface water management facility and system [more particularly described as a permeable interlocking concrete pavement]. This is shown on plat titled ________________ and dated ________________; and

WHEREAS, the [city/county] has reviewed and approved these plans subject to the execution of this agreement.

NOW THEREFORE, in consideration of the benefit received by the Grantor, its heirs and assigns, and as a result of the [city/county] approval of its plans, the Grantor, it heirs and assigns, with full authority to execute deeds, deeds of trust, other covenants and all rights, title and interest in the property described above hereby covenant with the [city/county] as follows:

1. Grantor, its heirs and assigns shall construct and perpetually maintain, at its sole expense, the above referenced permeable interlocking concrete pavement [storm and surface management facility and system] in strict accordance with the plan approval granted by the [city/county].

2. Grantor, its heirs and assigns shall, at its sole expense, make such changes or modifications to the permeable interlocking concrete pavement [storm drainage facility and system]. Changes or modifications may, in the [city's/ county's] discretion, be determined necessary to insure that the facility and system are properly maintained and continues to operate as designed and approved.

3. The [city/county], it agents, employees and contractors shall have the perpetual right of ingress and egress over the property of the Grantor, its heirs assigns, and the right to inspect [at reasonable times and in a reasonable manner,] the permeable interlocking concrete pavement [storm drainage facility and system]. Inspection is in order to insure that the system is being properly maintained and is continuing to perform in an adequate manner. [Attachment A to this agreement provides a list of items to be inspected by the [city/county]].

4. The Grantor, its heirs and assigns agree that should it fail to correct any defects in the above described facility and system within [ten (10)] days from issuance of written notice, or shall fail to maintain the facility in accordance with the approved design standards and in accordance with the law and applicable regulations, or in the event of an emergency as determined by the [city/county] in its sole discretion, the [city/county] is authorized to enter the property to make all repairs, and to perform all maintenance, construction and reconstruction the [city/county] deems necessary. The [city/county] shall assess the Grantor, its heirs or assigns for the cost of the work, both direct and indirect, and applicable penalties. Said assessment shall be a lien against all properties described within this Maintenance Agreement and may be placed on the property tax bills of said properties and collected as ordinary taxes by the [city/county].

5. Grantor, its heirs and assigns shall indemnify, hold harmless and defend the [city/county] from and against any and all claims, demands, suit liabilities, losses, damages and payments, including attorney fees claimed or made against the [city/county] that are alleged or proven to result or arise from the Grantor, its heirs and covenant.
6. The Covenants contained herein shall run with the land and the Grantor, its heirs assigns further agree whenever the property shall be held, sold and conveyed, it shall be subject to the covenants stipulations, agreements and provisions of this Agreement, which shall apply to, bind all present and subsequent owners of the property described herein.
7. Grantor agrees to not transfer or assign responsibility.
8. The provisions of this Maintenance Agreement shall be severable and if any phase, clause, sentence or provision is declared unconstitutional, or the applicability of the Grantor, its heirs and assigns is held invalid, the remainder of this Covenant shall not be affected thereby.
9. The Maintenance Agreement shall be recorded at the Clerk's Office of the [court] of [city/county], [state/province] at the Grantor's, its heirs and assign's expense.
10. In the event that the [city/county] shall determine its sole discretion at any future time that the facility is no longer required, then the [city/county] shall at the request of the Grantor, its heirs and assigns execute a release of this Maintenance Agreement, which the Grantor, its heirs and assigns shall record, in the Clerk's Office at its expense.

IN WITNESS THEREOF, the Grantor has executed this Maintenance Agreement
On the ______ day of ______, [year].

By Officer/Authorized Agency

[State/Province] of:
[City/County] of :

To with: The foregoing instrument was acknowledged before me this______day of__________, [year], by
______________________________________

Notary Public

My Commission Expires:______________________________________

# References


1. U.S. Environmental Protection Agency, *Urbanization and Streams: Studies of Hydrological Impacts*, Office of Water (4503F), publication no. 841-R-97-009, Washington, DC, December 1997.

2. US Code: Title 33, Section 1329, Nonpoint source management programs.

3. Northern Virginia Planning District Commission, *Nonstructural Urban BMP Handbook*, Annandale, Virginia, December, 1999, p. 1-4

4. *Better Site Design: A Handbook for Changing Development Rules in Your Community*, Center for Watershed Protection, Ellicott City, Maryland, August 1998.

5. Tech Spec 8, *Concrete Grid Pavements*, Interlocking Concrete Pavement Institute, Washington, DC, 1999.

6. Borgwardt, S., "Performance and Fields of Application for Permeable Paving Systems," *Betonwerk + Fertigteil-Technik* (Concrete Precasting Plant and Technology), February, 1997, pp. 100 - 105.

7. Rollings, R. S. and Rollings, M. P., *SF-Rima: A Permeable Paving Stone System, SF Concrete Technologies*, Mississauga, Ontario, 1999.

8. Borgwardt, S., *Tests Performed on the Uni Eco-stone Pavements of Various Ages - Expert Opinion*, Institute for Planning Green Spaces and for Landscape Architecture, University of Hannover, Germany, July, 1994.

9. Claytor, R.A., and Schueler T. R., *Design of Stormwater Filtering Systems*, Center for Watershed Protection, Silver Spring, Maryland, December 1996.

10. Center for Watershed Protection, *Developing an Effective Best Management Practice for the Site*, Excerpts from the Center's Short Course on Practical Stormwater Management Design, Ellicott City, Maryland.

11. Debo, T. N. and Reese, A. J, *Municipal Storm Water Management*, Lewis Publishers, CBC Press, Boca Raton, Florida, 1995.

12. Borgwardt, S., "Suitable Beddings for Paving Blocks Permeable to Water," in *Betonwerk + Fertigteil-Technik* (Concrete Precasting Plant and Technology), March, 1995.

13. U.S. Weather Bureau, Rainfall intensity-duration-frequency curves for selected stations in the United States, Alaska, Hawaii and Puerto Rico. Technical Report No. 55, 1955.

14. *Canadian Climate Normals*, Atmospheric Environment Service, Environment Canada, Toronto, Ontario, Canada.

15. ASTM D 2487, Standard Classification of Soils for Engineering Purposes (Unified Soil Classification System), *Annual Book of ASTM Standards*, Vol. 04.08, American Society for Testing and Materials, Conshohocken, Pennsylvania, 1998.

16. ASTM D 1883, Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils, *Annual Book of ASTM Standards*, Vol. 04.08, American Society for Testing and Materials, Conshohocken, Pennsylvania, 1998.

17. AASHTO Designation T-193, in Standard Specifications for Transportation Material and Methods of Sampling and Testing, Sixteenth Edition, Part II, Tests, American Association for State Highway and Transportation Officials, Washington, D.C., 1993.

18. ASTM D 3385, Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer, *Annual Book of ASTM Standards*, Vol. 04.08, American Society for Testing and Materials, Conshohocken, Pennsylvania, 1998.

19. ASTM D 5093, Standard Test Method for Field Measurement of Infiltration Rate Using a Double Ring Infiltrometer with a Sealed Inner Ring, *Annual Book of ASTM Standards*, Vol. 04.08, American Society for Testing and Materials., Conshohocken, Pennsylvania, 1998.

20. *Infiltration Design Considerations and Practices to Control Stormwater Runoff*, Handout from a Short Course, Fairfax County Department of Extension and Continuing Education, Fairfax County, Virginia, 1991.

21. Asphalt Institute, *Soils Manual for the Design of Asphalt Pavement Structures*, MS-10, Fifth Edition, Lexington, Kentucky, 1993.

22. Cao, S., L., Poduska, D. and Zollinger, D. G., *Drainage Design and Rutting Performance Guidelines for Permeable Pavement*, Texas A&M University, College Station, Texas, January 1998.

23. Rollings, R. S. and Rollings, M. P., *Design Considerations for the Uni Eco-stone Concrete Paver*, Uni-Group USA, Palm Beach Gardens, Florida, March 1993.

24. *Properties and Uses of Cement-Modified Soil*, Portland Cement Association, Skokie, Illinois, 1992.

25. Holtz, R. D. et al, *Geosynthetic Design & Construction Guidelines—Participant Notebook*, Federal Highway Administration Contract No. FHWADTFH61-93-C-00120, McLean, Virginia, 1995

26. AASHTO-AGC-ARTBA Joint Committee, *Guide Specifications and Test Procedures for Geotextiles*, Task Force 25 Report, American Association of State Highway and Transportation Officials, Washington, D.C., 1990.

27. ASTM C 936, Standard Specification for Solid Concrete Interlocking Paving Units, *Annual Book of ASTM*

*Standards*, Vol. 04.05, American Society for Testing and Materials, Conshohocken, Pennsylvania, 1997.

28. Canadian Standards Association, A231.2-95, *Precast Concrete Pavers*, Rexdale, Ontario, 1995.

29. Canadian Standards Association, A231.1-99, *Precast Concrete Paving Slabs*, Rexdale, Ontario, 1999.

30. *Standard Specifications for Infiltration Practices*, State of Maryland, Department of the Environment, Baltimore, Maryland, 1985.

31. *Maryland Stormwater Manual*, State of Maryland, Department of the Environment, Baltimore, Maryland, 1999.

32. United States Soil Conservation Service, *Urban Hydrology for Small Watersheds*, Technical Release 55, Second Edition, Washington, D.C., 1986.

33. Ferguson, B. K., *Stormwater Infiltration*, Lewis Publishers, CBC Press, Boca Raton, Florida, 1994.

34. Ferguson, B. and Debo, T., *On-site Stormwater Management*, Second Edition, Van Nostrand Reinhold, New York, 1990.

35. Goforth, G. F., Danaus, E. V. and Rawhide, J. B., *Stormwater Hydrological Characteristics of Porous and Conventional Paving Systems*, Municipal Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1983.

36. Cedergren, H. R., *Drainage of Highway and Airfield Pavements*, Krieger Publishing Company, Malabar, Florida, 1987.

37. Diniz, Elvidio V., *Porous Pavement Phase I – Design and Operational Criteria*, EPA-600/2-80-135, Municipal Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio, August, 1980.

38. Thelen E. and Howe L. F., *Porous Pavement*, The Franklin Institute Press, Philadelphia, Pennsylvania, 1978.

39. Caraco, D. and Claytor, R., *Stormwater BMP Design Supplement for Cold Climates*, Center for Watershed Protection, Ellicott City, Maryland, 1997.

40. *The Asphalt Handbook*, The Asphalt Institute, MS-4, Lexington, Kentucky, 1989.

41. ICPI Tech Spec 11, *Mechanized Installation of Interlocking Concrete Pavements*, Interlocking Concrete Pavement Institute, Washington, DC, 1998.

42 Winer, R., *National Pollutant Removal Performance Database for Stormwater Treatment Practices, 2nd Edition*, Center for Watershed Protection, Ellicott City, Maryland, 2000.

# Appendix A—Glossary of Terms

AASHTO—American Association of State Highway and Transportation Officials

Aquifer—A porous water bearing geologic formation that yields water for consumption.

ASTM—American Society for Testing and Materials

Best Management Practice (BMP)—A structural or non-structural device designed to infiltrate, temporarily store, or treat stormwater runoff in order to reduce pollution and flooding.

Cation—A positively charged atom or group of atoms in soil particles that, through exchange with ions of metals in stormwater runoff, enable those metals to attach themselves to soil particles.

Choke course—A layer of aggregate placed or compacted into the surface of another layer to provide stability and a smoother surface. The particle sizes of the choke course are generally smaller than those of the surface into which it is being pressed.

Clay soils—1. (Agronomy) Soils with particles less than 0.002 mm in size. 2. A soil textural class. 3. (Engineering) A fine-grained soil with more than 50% pass the No. 200 sieve with a high plasticity index in relation to its liquid limit, according the Unified Soil Classification System.

Crushed stone—Mechanically crushed rock that produces angular particles.

CSA—Canadian Standards Association

Curve Number (CN)—A numerical representation of a given area's hydrological soil group, plant cover, impervious cover, interception and surface storage. The U.S. Soil Conservation Service (SCS) originally developed the concept. A curve number is used to convert rainfall depth into runoff volume.

Dense-graded base—Generally a crushed aggregate base with fines that, when compacted, creates a foundation for pavements and does not allow significant amounts of water into it. Particle sizes can range from 1.5 in. (40 mm) to smaller than the No. 200 (0.075 mm) sieve.

Detention pond or structure—The temporary storage of stormwater runoff in an area with objective of decreasing peak discharge rates and providing a settling basin for pollutants.

Erosion—The process of wearing away of soil by water, wind, ice, and gravity. 2. Detachment and movement of soil particles by same.

Exfiltration—The downward movement of water through an open-graded, crushed stone base into the soil beneath.

Fines—Silt and clay particles in a soil, generally those smaller than the No. 200 or 0.075 mm sieve.

Grade—1. (Noun) The slope or finished surface of an excavated area, base, or pavement usually expressed in percent. 2. (Verb) To finish the surface of same by hand or with mechanized equipment.

Gravel—1. Aggregate ranging in size from $^1/_4$ in. (6 mm) to 3 in. (75 mm) which naturally occurs in streambeds or riverbanks that has been smoothed by the action of water. 2. A type of soil as defined by the Unified Soil Classification System having particle sizes ranging from the No. 4 sieve (4.75 mm) and larger.

Hotspot—A land use that generates highly contaminated runoff with concentrations higher than those typical to stormwater.

Hydrological Soil Group—The soils classification system developed by the U.S. Soil Conservation Service (now the Natural Resource Conservation Service) that categorizes soils into four groups, A through D, based on runoff potential. A soils have high permeability and low runoff whereas D soils have low permeability and high runoff.

Impervious cover—Surfaces that do not allow rainfall to infiltrate into the soil. Examples include pavements, roofs, sidewalks, driveways, etc.

Infiltration rate—The rate at which stormwater moves through soil measured in inches per hour or meters per second.

Karst geology—Regions of the earth underlain by carbonate rock typically with sinkholes and/or limestone caverns.

Observation well—A perforated pipe inserted vertically into an open-graded base used to monitor its infiltration rate.

One year storm—A rainfall event that occurs once a year or has a 100% chance of occurring in a given year.

One hundred year storm—A very unusual rainfall event that occurs once every 100 years or has a 1% chance of occurring in a given year.

Open-graded base—Generally a crushed stone aggregate material used as a pavement base that has no fine particles in it. The void spaces between aggregate can store water and allow it to freely drain from the base.

Outlet—The point at which water is discharged from an open-graded base through pipes into a stream, lake, river, or storm sewer.

Peak discharge rate—The maximum instantaneous flow from a detention or retention pond, open-graded base, pavement surface, storm sewer, stream or river usually related to a specific storm event.

Permeability—The rate of water movement through a soil column under saturated conditions, usually expressed as k in calculations per specific ASTM or AASHTO tests, and typically expressed in inches per hour or meters per second.

Pervious or permeable surfaces/cover— Surfaces that allow the infiltration of rainfall such as vegetated areas.

Porosity—Volume of voids in a base divided by the total volume of a base.

Pretreatment—BMPs that provide storage and filtering pollutants before they enter another BMP for additional filtering, settling, and/or processing of stormwater pollutants.

Retention pond—A body of water that collects runoff and stays full permanently. Runoff flowing into the pond that exceeds its capacity is released into a storm sewer, stream, lake, or river.

Sand—1. (Agronomy) A soil particle between 0.05 and 2.0 mm in size. 2. A soil textural class. 3. (Engineering) A soil larger than the No. 200 (0.075 mm) sieve and passing the No.4 (4.75 mm) sieve, according to the Unified Soil Classification System (USCS).

SCS—U.S. Soil Conservation Service, the authors of a popular method of calculating stormwater runoff called TR (Technical Release)-55, Urban Hydrology for Small Watersheds. SCS is now called the NRCS or the National Resource Conservation Service.

Sediment—Soils transported and deposited by water, wind, ice, or gravity.

Silt—1. (Agronomy) A soil consisting of particles sizes between 0.05 and 0.002 mm. 2. A soil textural class. 3. (Engineering) A soil with no more than 50% passing the No. 200 (0.075 sieve) that has a low plasticity index in relation to the liquid limit, according to the Unified Soil Classification System.

Time of concentration—The time required for water to flow from the most remote point of a watershed or catchment to an outlet.

Void Ratio—Volume of voids around the aggregrate divided by the volume of solids.

**David R. Smith** is the Technical Director for the Interlocking Concrete Pavement Institute or ICPI (www.icpi.org). He and 66 companies started the ICPI in 1993, and have seen this North American industry association grow to over 220 members representing producers, contractors, and suppliers. Since 1985, he has worked closely with engineers in design and construction of every kind of concrete paver project ranging from patios to streets, plus ports and airports. In addition to publishing dozens of articles, guide specifications, and ICPI technical bulletins on concrete pavers, Mr. Smith has written two instructional manuals for contractors. In addition, he co-authored the ICPI manuals, *Port and Industrial Pavement Design with Concrete Pavers* and *Airfield Pavement Design with Concrete Pavers.*

As a leading authority in North America on concrete segmental paving, Mr. Smith regularly speaks at national and international conferences. He is secretary-treasurer of the Small Element Paving Technologists (www.sept.org), a group of international specialists on segmental paving. He is a past chairman of the Canadian Standard Association's Technical Committee on Precast Concrete Paving. He is an active member of ASTM Committee C 27.20 on Architectural Precast Products, having written and revised several paving product standards for that organization. He participates as a member in the American Public Works Association, the American Subcontractors Association, Construction Specifications Institute, Construction Specifications Canada, and the American Society of Landscape Architects (ASLA). Mr. Smith has contributed continuing education programs to the ASLA and to the American Institute of Architects. He is a member of the Container Terminal Pavement Task Committee of the American Society of Civil Engineers Port and Harbor Committee.

His education includes a Bachelor of Architecture and a Masters of Urban and Regional Planning (environmental concentration) from Virginia Tech in Blacksburg. Between earning these degrees, he taught stormwater management for landscape architecture students at Virginia Tech. He also was involved in research there on concrete grid pavements and has written extensively about their design and construction. *Permeable Interlocking Concrete Pavements* represents a synthesis of experience and insights from professional engineers, stormwater regulators, and ICPI member concrete paver manufacturers and contractors.

# Permeable Interlocking Concrete Pavements

**Selection • Design • Construction • Maintenance**

*David R. Smith*

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1444 I Street NW–Suite 700
Washington, DC 20005-6542
Tel: 202-712-9036
Fax: 202-408-0285
E-mail: ICPI@bostromdc.com
Web: www.icpi.org

**In Canada**
P.O. Box 23053
55 Ontario Street Milton, ON L9T 2M0

Every effort has been made to present accurate information. However, the recommendations herein are guidelines only and will vary according to local conditions. Professional assistance should be obtained in the design, specifications, and construction with regard to a particular project.



Second Edition 2001

# APPENDIX B

# ARGONAUT SL – EXPANDED DESCRIPTION

# Argonaut-SL Expanded Description

http://www.sontek.com/product/asl/aslxdsc.htm

*Contents:*



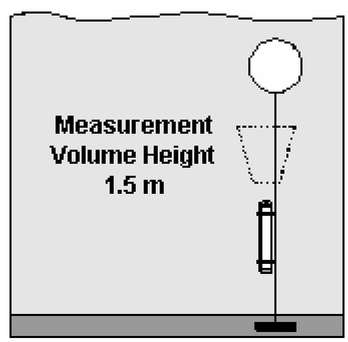
**SonTek/YSI Argonaut-SL current meter**

## *1. Introduction*

Designed with state-of-the-art surface mount electronics and proven Doppler technology, SonTek's Argonaut series of acoustic current meters offers unsurpassed accuracy in velocity measurements. Argonauts are available in several configurations for a wide range of applications. A few of the most common are described below.

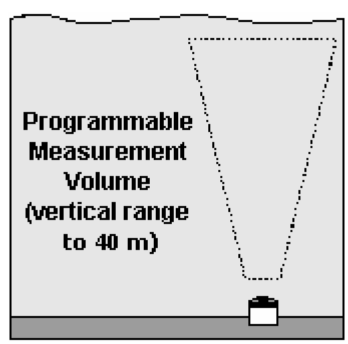
### *1.1. Open-Ocean Moorings - The Argonaut-MD*

The Argonaut-MD (Mooring Deployments) is designed for current monitoring in the open ocean. The Argonaut-MD uses a fixed measurement volume centered 1.5 m from the instrument and is housed in a single canister with internal memory and batteries. The Argonaut-MD can be clamped to the mooring line or mounted within a mooring cage. Low power consumption and flexible sampling strategies allow multiple year deployments using alkaline batteries.

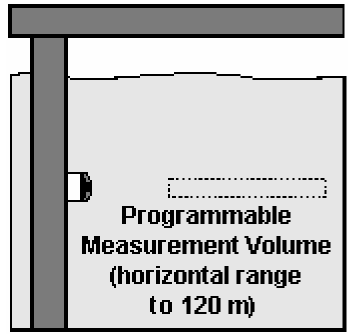



### *1.2. Shallow-Water Deployments - The Argonaut-XR*

The Argonaut-XR (Extended Range) is ideal for shallow water current monitoring in areas such as rivers, irrigation channels, estuaries, and ports. Designed for bottom-mounting, the Argonaut-XR has a measurement volume programmable over a vertical range up to 40 m. With the integrated pressure sensor, the Argonaut-XR can adjust the measurement volume height to report depth-averaged velocity over the entire water column or over a user-programmable range (even with tide or stage variation). The Argonaut-XR can be used for real-time monitoring (cable lengths up to 1500 m) or autonomous deployments with the external battery pack.



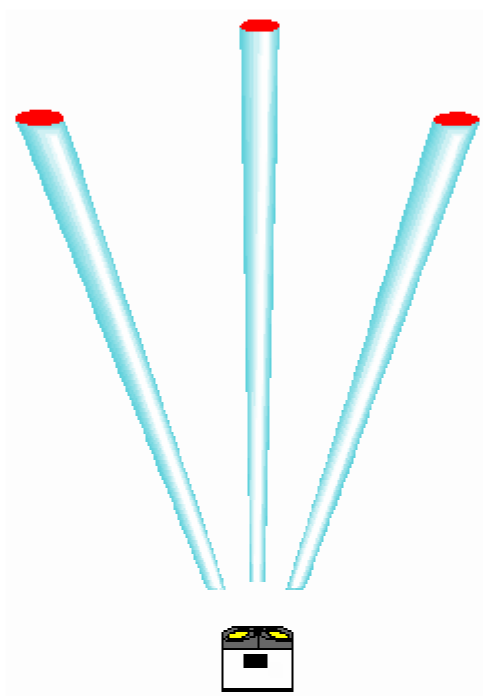
### *1.3. Underwater Structures - The Argonaut-SL*




The Argonaut-SL (Side-Looking) is designed for horizontal operation, making a remote velocity measurement from an underwater structure (pier, bridge, channel, etc.) while allowing a simple and secure instrument mounting. The Argonaut-SL measures 2D currents in an adjustable measurement volume located at a range up to 120 m. Like the Argonaut-XR, the Argonaut-SL can be used for real-time or autonomous applications.

## *2. How Argonauts Work*

3D beam patternThe Argonauts belong to a class of instruments known as monostatic Doppler current meters. Monostatic refers to the fact that the same transducer is used as transmitter and receiver. A monostatic Doppler uses a set of acoustic transducers with precisely known relative orientations. Each transducer produces a narrow beam of sound perpendicular to the transducer face. The operation of a 3D Argonaut (with three transducers) is shown here.



During operation, each transducer produces a short pulse of sound at a known frequency that propagates along the axis of the acoustic beam. Sound from the outgoing pulse is reflected ("scattered") in all directions by particulate matter in the water. Some portion of the scattered energy travels back along the beam axis to the transducer. This return signal has a frequency shift proportional to the velocity of the scattering material. This frequency change (Doppler shift), as measured by the Argonaut, is proportional to the projection of the water velocity onto the axis of the acoustic beam. By combining data from three beams, and knowing the relative orientation of those beams, the Argonaut measures the 3D velocity. In the same manner, the Argonaut-SL measures 2D velocity in the plane defined by its two acoustic beams.

## *3. Argonaut Advantages*

Doppler technology has several inherent advantages that make it the preferred method for current measurement. Combining this with SonTek's proven ability to develop instruments that are both powerful and easy to use, the Argonaut is the ideal choice for a wide range of applications. Argonaut advantages include:

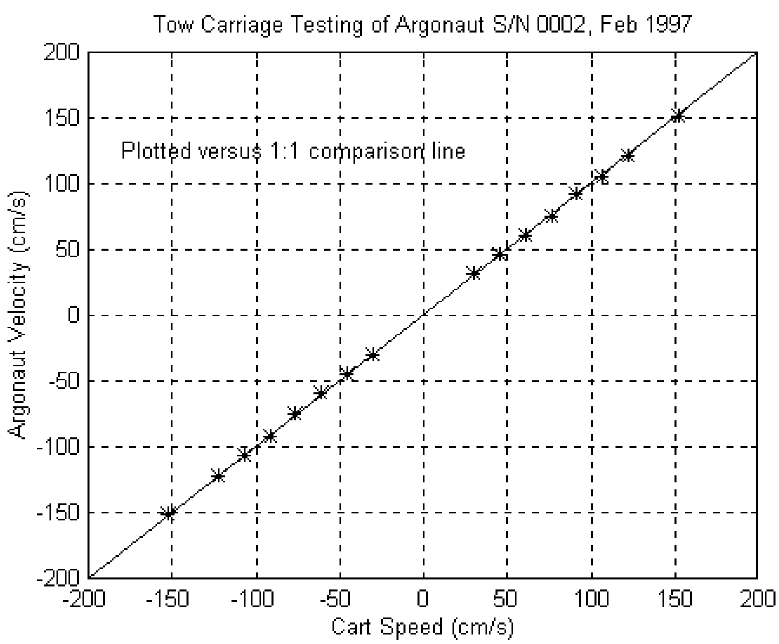
- Measurements are made in a remote sampling volume free from flow distortion.
- Velocity data are free from drift; the Argonaut never requires calibration.
- Doppler technology has no inherent minimum detectable velocity, giving excellent performance at low flows.
- The Argonaut has no moving parts, is immune to biofouling contamination, and the user can directly apply anti-fouling paint to prevent growth.
- The same robust computational algorithms are used for velocities from 1 cm/s to 10 m/s.

SonTek's user interface allows easy operation with minimal training and experience. First time users can collect test data within minutes of receiving the Argonaut. Deployments require only a few minutes to configure the Argonaut and start collecting data. The basic operating parameters include the following: averaging time, time between samples, and start time. The Argonaut provides the highest quality Doppler velocity data without requiring the user to become an expert on Doppler technology.

## *4. Argonaut Performance Verification*

Argonaut velocity data has a specified accuracy of ±1% of measured velocity and ±0.5 cm/s. These specifications have been verified using laboratory simulations, tow-carriage testing, and field comparisons with other meters. Results from one tow-carriage test are presented here.

Argonaut dataAn Argonaut was mounted from the bottom of a moving carriage at the Offshore Model Basin (OMB) tow facility in Escondido, California. The meter was towed over a working tank length of 45 m at eight speeds in both directions. Two different mounting orientations were used with no effect on velocity performance. Tow carriage speed at OMB has been independently verified to ±0.5%. Results from all

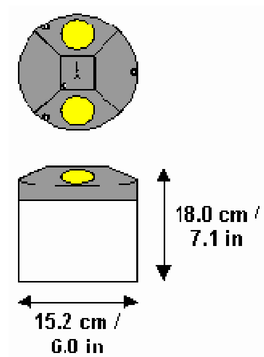


runs are shown in the plot below. A least squares linear fit of the velocity data to the carriage speed gives a slope of 0.996 with an offset of 0.1 cm/s.

## *5. Argonaut-SL Design and Features*

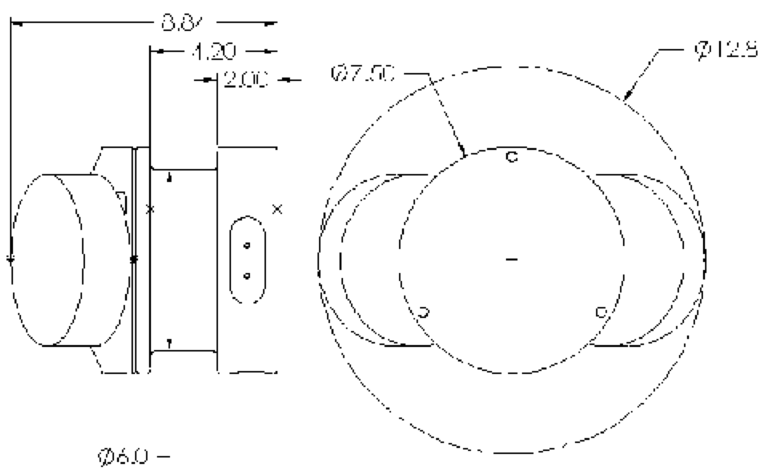
The Argonaut-SL is designed for current monitoring from underwater structures such as piers, bridges, and channel walls. The two-beam configuration measures the 2D water velocity in a plane defined by its acoustic beams. This is typically the two horizontal components of velocity. Mounted on an underwater structure, the Argonaut-SL measures velocity in a user-programmable sampling volume located up to 120 m from the sensor. Thus it measures the true flow away from any interference generated by the structure, while allowing for easy installation and protecting of the sensor from damage. The Argonaut-SL comes standard with programmable sampling volume size, internal memory, and a temperature sensor. Optional features include an external battery pack, pressure sensor, and integrated CTD.

### *5.1. Physical Parameters*




1.5-MHz and 3.0-MHz Systems
- Dimensions: 15.2 cm (6 in) diameter by 18 cm (7.1 in) length
- Weight in air: 2.5 kg (5.5 lb)
- Weight in water: -0.3 kg (-0.7 lb)
- Pressure rating (Delrin housing): 100 m

1.5&3.0-MHz Argonaut-SL Dimensions




500-kHz Systems
- Dimensions: 32.5 cm (12.8 in) diameter by 22.5 cm (8.8 in) length
- Weight in air: 11.5 kg (25 lb)
- Weight in water: 6 kg (13 lb)
- Pressure rating (Delrin housing): 500 m

### *5.2. Standard Features*

User-programmable sampling volume size measured horizontally from the sensor:
- 3.0-MHz systems - Up to 8 m
- 1.5-MHz systems - Up to 22 m
- 500-kHz systems - Up to 120 m

Supports multiple serial communication protocols:

- RS232 – Single system operation for short cables (to 100 m)
- RS422 – Single system operation for long cables (to 1500 m)
- RS485 – Multiple system operation from a single power and communication cable with total cable lengths to 1500 m
- SDI-12 communication protocol

Flexible sampling strategies for reduced duty cycle operation and extended deployments
4-MB internal memory (over 200,000 samples)
Beam angle 25° for near-boundary measurements
Temperature sensor for automatic sound speed compensation
Mounting plate for easy installation

### *5.3. Optional Features*

- Internal flow calculations
- Multi-cell current profiling
- External battery pack for autonomous operation (alkaline batteries have capacity for 60 days continuous operation)
- Integrated pressure sensor for surface level measurement
- Integrated CTD
- Calculation of wave parameters such as significant wave height and peak period band

**Argonaut-SL Applications**

- Current Monitoring
  Shinnecock Inlet - Describes how SonTek side-looking ADP, ADVOcean, Argonaut-MD, and Argonaut-SL systems are being used to monitor currents for the Shinnecock Inlet Field Monitoring Project.
- Discharge Monitoring
  Kankakee River - Describes how an Argonaut-SL was used to develop a standard cross-section to monitor discharge in the Kankakee River.
  River Gauging - Describes a practical approach to carrying out river gauging using an Argonaut-SL. This method provides considerable improvement in velocity accuracy over travel-time systems, while reducing operational costs.
  Spijkenisse Bridge - Describes the results of a comparison test between an Argonaut-SL and a travel time system installed on a bridge in The Netherlands.
- Environmental Monitoring
  Monitoring Water Quality - Combining the Argonaut-SL with a YSI 6820 Multiprobe offers a solution to monitoring water quality.
- Open Channel Flow
  Irrigation Canal - Describes how an Argonaut-SL is being used to compute the open channel flow through an irrigation canal.

Toshka Project Flow Regulation - Side-looking Argonauts are used to collect and log real-time data for day-to-day canal operation.

- Ship Berthing

  Mooring Dolphin - Describes a way to mount an Argonaut-SL on a mooring dolphin to assist in ship berthing operations.

- Velocity Indexing

  Index Velocities - Describes use of four SLs in California Delta to obtain index velocities.

- Vessel Traffic

  Bosphorus Straits VTMIS - SonTek ADPs and Argonaut-SLs are integrated with Endeco systems on real-time data collection platforms (buoys) as part of a Vessel Traffic Management Information System.

# Argonaut-SL

## Specifications

**Water Velocity**
- Range ±6 m/s (20 ft/s)
- Resolution 0.1 cm/s (0.003 ft/s)
- Accuracy ±1% of measured velocity, ±0.5 cm/s (0.015ft/s)

**Standard Features**
- Two-beam transducer for measuring 2D water velocity
- Vertical acoustic beam for water level
- User-programmable sampling volume measuring horizontally away from sensor
- Integrated strain gage pressure sensor (0.25% accuracy)
- Compass/2-axis tilt sensor
- Internal flow calculation, Total flow and output
- RS232/SDI-12 communication protocol
- 4 MB internal nonvolatile memory
- Temperature sensor
  - Resolution ±0.01°C
  - Accuracy ±0.1°C
- 10 m power/communications cable (longer cables are also available)
- ViewArgonaut Software (Windows 95/98/NT/2000/XP) for instrument setup, data collection, flow calculation and post-processing
- PDA Software (SonUtils and deployment module)

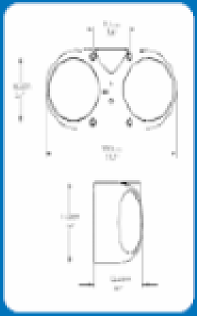
**Physical Parameters**
- Operating temperature -5° to 40°C
- Storage temperature -10° to 50°C

# Argonaut-SL

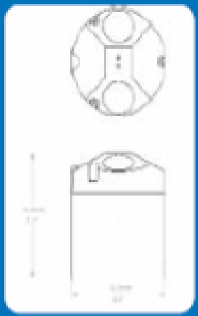
## Specifications Cont.

**Optional Features**
- Multi-Cell current profiling (up to 10 additional cells)
- Flow Display box (See photo on other side)
- External battery pack for autonomous operation (alkaline batteries have capacity for 20 days of continuous operation)
- Wave Spectra output
- 4-20 mA analog output module
- 0-5 V DC analog output module
- RS422 output for cable lengths to 1500 m

### 500 kHz Argonaut-SL



### 1.5 MHz or 3.0 MHz Argonaut-SL



| | 500 kHz | 1.5 MHz | 3.0 MHz |
|---|---|---|---|
| Sampling Volume | 1.5 m to 120 m (5 ft to 400 ft) | 0.5 m to 20 m (1.6 ft to 66 ft) | 0.2 m to 5 m (0.7 ft to 16 ft) |
| Beam Width | Less than 1.5 degrees | Less than 1.5 degrees | Less than 1.5 degrees |
| **Vertical Beam** | | | |
| Range | 0.4 m to 18.0 m (1.3 ft to 59 ft) | 0.25 to 10.0 m (0.8 ft to 33 ft) | 0.10 to 5.0 m (0.3 ft to 17 ft) |
| Accuracy | (depth < 6 m): ±0.6 cm (0.02ft)<br>(depth > = 6 meters): ±0.1% | (depth < 3 m): ±0.3 cm (0.01ft)<br>(depth > = 3 meters): ± 0.1% | (depth < 3 m): ±0.3 cm (0.01ft)<br>(depth > = 3 meters): ± 0.1% |
| **Physical Parameters** | | | |
| Weight in Air | 6.3 kg (14 lb) | 2.5 kg (5.5 lb) | 2.5 kg (5.5 lb) |
| Weight in Water | 1.8 kg (4 lb) | -0.3 kg (-0.7 lb) | -0.3 kg (-0.7 lb) |
| Pressure Rating/ Max. Depth | 30 m (98 ft) | 200 m (656 ft) | 200 m (656 ft) |
| Mounting Plate Dimensions | 35.5 cm x 22.9 cm x 1.5 cm<br>(14.0" x 9.0" x 0.6") | 19.8 cm x 19.8 cm x 1.5 cm<br>(7.8" x 7.8" x .625") | 19.8 cm x 19.8 cm x 1.5 cm<br>(7.8" x 7.8" x .625") |
| **Power Requirements** | | | |
| Input Power | 7 – 15 VDC | 7 – 15 VDC | 7 – 15 VDC |
| Power Consumption* | 0.7 – 1.0 W (cont. operation) | 0.3 – 0.5 W (cont. operation) | 0.3 – 0.5 W (cont. operation) |

*Power consumption will be higher with PowerPing enabled

SonTek
A YSI Environmental Company

## SL Installations

Distributed By:

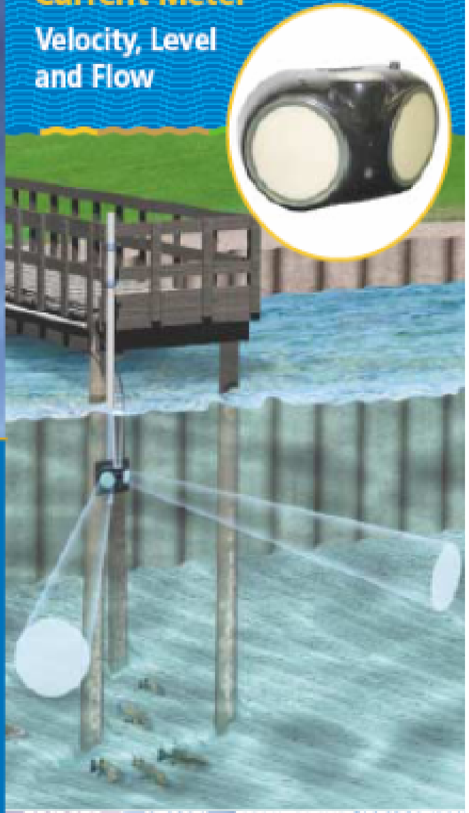


SONTEK/YSI INC.
6837 Nancy Ridge Drive, Suite A
San Diego, CA 92121
Tel: (858) 546-8327
Fax: (858) 546-8150
e-mail: sales@sontek.com
website: www.sontek.com

# Argonaut-SL

## Side-Looking Doppler Current Meter

### Velocity, Level and Flow




SonTek
A YSI Environmental Company

THE WORLD LEADER FOR WATER VELOCITY MEASUREMENT
www.sontek.com

# Velocity, Level and Flow Measurement

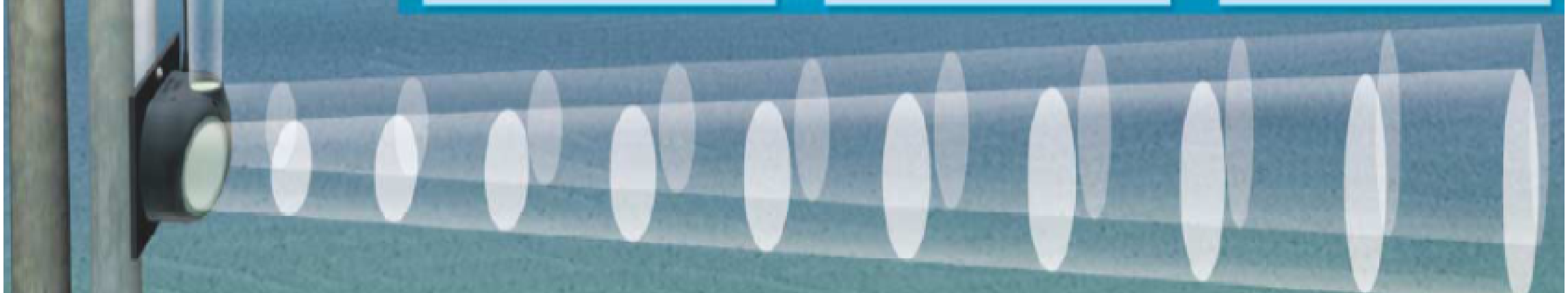
The Argonaut-SL is a side-looking acoustic Doppler current and flow meter that precisely measures water level and 2-D water velocity in a horizontal layer. Because it is easily installed on a riverbank, bridge abutment or other vertical structure, it is the perfect choice for long-term current monitoring. Profiling, analog output and waves extend the capability of the Argonaut-SL to a wide range of applications.

## Features

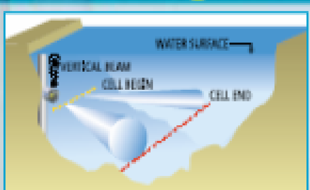
- Water Level Measurement
- Real-time Velocity, Flow, Volume
- Multi-Cell Profiling
- Waves
- Power Ping (Hi-Precision sampling)

## Applications

- River Discharge/Velocity Indexing
- Ship Berthing
- Water Supply
- Irrigation
- Ports and Harbors

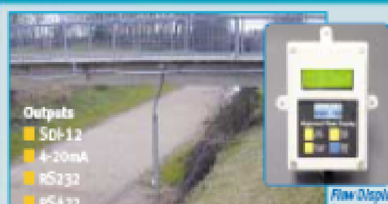


## Multi-Cell Profiling + User-Cell




Featuring a user-programmable cell extending up to 12.0 m horizontally, flow disturbances caused by the mounting structure can be eliminated by beginning the measurement cell past the turbulence zone. The optional profiling feature enables concurrent measurement of up to 10 additional equally spaced cells for quality assurance.

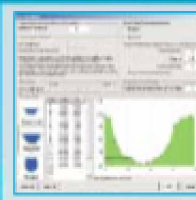
## Real-time Flow + Total Volume




*Flow Display box.*

The Argonaut-SL outputs real-time velocity, level, flow, total volume and diagnostic data in a variety of communication formats. An optional Flow Display box provides an easy-to-use interface for monitoring both the output data and the system status.

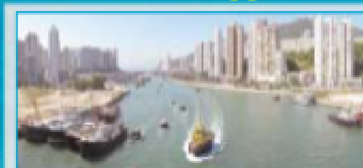
## Windows + PDA Software



*PDA software for quick programming and automatic downloads.*

When you need real-time flow output, the ViewArgonaut software for Windows offers the easy answer for both setup and analysis. Just select from one of our pre-programmed cross-sections or enter your custom geometry using our FlowWizard for a true flow solution.

## Waves + Port Applications



An Argonaut-SL can also provide water velocity information next to a wharf, critical for ship berthing operations. Similarly, an SL mounted on an offshore platform can measure the water velocities across a shipping channel to supplement a traffic management system. The added benefit of the optional wave feature is real-time wave spectra information.

# APPENDIX C

# YSI ENVIRONMENTAL – SONDE DESCRIPTIONS

Y S I Environmental

# YSI 600XL and 600XLM Sondes

The YSI 600XL and 600XLM.

## Measure multiple parameters simultaneously

The YSI 600XL and YSI 600XLM compact sondes measure eleven parameters simultaneously:

| | |
|---|---|
| DO (% and mg/L) | ORP |
| Temperature | Depth or Level |
| Conductivity | Total Dissolved Solids* |
| Specific Conductance* | Resistivity* |
| Salinity* | pH |

## Connect with Data Collection Platform

Either sonde can easily connect to the YSI 6200 DAS (Data Acquisition System), or your own data collection platform, via SDI-12 for remote and real-time data acquisition applications.

## In addition

The YSI 600XLM is an economical logging system for long-term, *in situ* monitoring and profiling. It will log all parameters at programmable intervals and store 150,000 readings. At one-hour intervals, the instrument will log data for about 75 days utilizing its own power source. The 600XL can also be utilized in the same manner with user-supplied external power.

Pure Data for a Healthy Planet.™

***Compatible with EcoWatch® for Windows® software for data analysis and more!***

- **Either sonde fits down 2-inch wells**
- **Horizontal measurements in very shallow waters**
- **Stirring-independent Rapid Pulse™ dissolved oxygen sensor**
- **Field-replaceable sensors**
- **Easily connects to data collection platforms such as the YSI 6200 DAS**
- **Available with detachable cables to measure depth up to 200'**
- **Compatible with YSI 650 Multiparameter Display System**
- **Use with the YSI 5083 flow cell for groundwater applications**

* Calculated parameters.

www.YSI.com

Pure Data for a Healthy Planet.™

***To order or for more information, contact YSI Environmental.***

***800 897-4151***

***www.YSI.com***


YSI Environmental
937 767 7241
Fax 937 767 9353
environmental@YSI.com

Endeco/YSI
508 748 0366
Fax 508 748 2543
environmental@YSI.com

YSI Environmental
European Support Centre
44 1730 710 615
Fax 44 1730 710 614
europe@YSI.com

YSI (Hong Kong) Limited
852 2891 8154
Fax 852 2834 0034
hongkong@YSI.com

YSI/Nanotech (Japan)
81 44 222 0009
Fax 81 44 222 1102
nanotech@YSI.com

YSI (Qingdao) Limited
86 532 389 6648
Fax 86 532 389 6647
china@YSI.com


ISO 9001
ISO 14001



YSI incorporated
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## 600XL & 600XLM Sensor Specifications

| | | |
|---|---|---|
| **Dissolved oxygen % saturation** | Range<br>Resolution<br>Accuracy | 0 to 500%<br>0.1%<br>0 to 200%: ±2% air sat; 200 to 500%: ±6% air sat |
| **Dissolved oxygen mg/L** | Range<br>Resolution<br>Accuracy | 0 to 50 mg/L<br>0.01 mg/L<br>0 to 20 mg/L: ±0.2 mg/L; 20 to 50 mg/L: ±0.6 mg/L |
| **Conductivity †** | Range<br>Resolution<br>Accuracy | 0 to 100 mS/cm<br>0.001 to 0.1 mS/cm (range-dependent)<br>±0.5% of reading + 0.001 mS/cm |
| **Temperature** | Range<br>Resolution<br>Accuracy | -5 to +45°C<br>0.01°C<br>±0.15°C |
| **pH**, includes most low-ionic-strength measurements | Range<br>Resolution<br>Accuracy | 0 to 14 units<br>0.01 unit<br>±0.2 unit |
| **Non-vented depth, shallow** | Range<br>Resolution<br>Accuracy | 0 to 30 feet (0 to 9 m)<br>0.001 foot (0.001 m)<br>±0.06 foot (±0.02 m) |
| **Non-vented depth, medium** | Range<br>Resolution<br>Accuracy | 0 to 200 feet (0 to 61 m)<br>0.001 foot (0.001 m)<br>±0.4 foot (±0.12 m) |
| **Vented level** | Range<br>Resolution<br>Accuracy | 0 to 30 feet (0 to 9 m)<br>0.001 feet (0.0003 m)<br>0 to 10 feet (0 to 3 m): ±0.01 feet (0.003 m)<br>10 to 30 feet (3 to 9 m): ±0.06 feet (0.01 m) |
| **ORP** | Range<br>Resolution<br>Accuracy | -999 to +999 mV<br>0.1 mV<br>±20 mV |
| **Salinity** | Range<br>Resolution<br>Accuracy | 0 to 70 ppt<br>0.01 ppt<br>±1% of reading or 0.1 ppt, whichever is greater |


YSI Model 5083 flow cell and 600XL. This is an ideal combination for groundwater applications.

### YSI 600XLM sonde

**Sampling Medium**: Fresh, sea or polluted water
**Temperature**: -5 to +45°C
**Computer interface**: RS-232, SDI-12
**Logging memory**: 384K flash ROM logs ~150,000 readings
**Software**: PC-compatible, Windows® 95 or higher; 256K RAM minimum. Graphics card recommended.
**Size**: 1.65" dia., 21.3" long (4.32 x 54.1 cm)
**Weight with batteries**: 1.5 lbs (0.7 kg)
**External power supply**: 12 VDC
**Internal power supply**: 4 AA-alkaline cells capable of logging for 75 days at one-hour intervals at 25°C

### YSI 600XL sonde

**Sampling Medium**: Fresh, sea or polluted water
**Temperature**: -5 to +45°C
**Computer interface**: RS-232, SDI-12
**Software**: PC-compatible, Windows® 95 or higher; 256K RAM minimum. Graphics card recommended.
**Size**: 1.65″ dia., 16″ long, 1.3 lbs. (4.19 x 35.6 cm, 0.49 kg)
**External power supply**: 12 VDC

† Report outputs of specific conductance (conductivity corrected to 25° C), resistivity, and total dissolved solids are also provided. These values are automatically calculated from conductivity according to algorithms found in *Standard Methods for the Examination of Water and Wastewater* (ed 1989).