Analysis of Bioswale Efficiency for Treating Surface Runoff

A Group Project submitted in partial satisfaction of the requirements of the degree

Master of Environmental Science and Management

Donald Bren School of Environmental Science and Management

University of California, Santa Barbara

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Description of the Group Project

The group project is a major component of the degree requirements for Master's students in the Donald Bren School of Environmental Science and Management at the University of California, Santa Barbara. The project allows a group of students to tackle an issue involving both scientific investigation and management considerations. This process is meant to serve as a realistic introduction to working as an environmental professional. It provides the opportunity to work and communicate successfully in a team and to complete a professional project. The group structure allows for broader research and analysis of environmental problems than an individual could achieve. The process prepares individuals to successfully apply both technical and managerial skills to solving the myriad of complex issues that face the environmental community. The time frame for project completion is one year.

Abstract

Analysis of Bioswale Efficiency for Treatment of Surface Runoff

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A bioswale is a low-gradient, open channel possessing a cover of vegetation through which all surface runoff is directed. Our analysis focused on the use of a bioswale to improve water quality exiting the site of a new project development in Goleta, CA. Field samples and modeling predictions were used to evaluate the overall performance of the bioswale and its contribution to decreasing pollutant loading to the sensitive estuary, Devereux Slough. The U.S. EPA Storm Water Management Model (SWMM) aided our understanding of future bioswale functioning when vegetation is fully established, and this model was used to analyze potential design modifications. We determined that the bioswale is a cost-efficient method for addressing the project developer's main concerns: flood containment capacity, wetland mitigation, and reduction of pollutant loading off site.

Executive Summary

The Camino Real project is a commercial development located in Goleta, California that includes a shopping center, entertainment facilities, associated parking lots, and playing fields. Stormwater runoff from the project site eventually reaches Devereux Slough, a nearby estuary. A bioswale was installed to minimize the potential impacts of stormwater runoff to Devereux Slough. This bioswale is expected to reduce the peak rate and total volume of stormwater runoff and to reduce total suspended solids and pollutants in stormwater runoff exiting the site.

The bioswale is a low-gradient, open channel possessing a dense cover of vegetation through which all surface runoff is directed. The bioswale decreases the speed of flows, acts as a stormwater detention facility, and allows suspended solids to settle out. Aboveground plant parts filter particulates and their associated pollutants as runoff passes slowly and evenly through the channel. The pollutants are then incorporated into the soil where they may be immobilized and/or decomposed by plants and microbes. The bioswale is considered a creative means of controlling runoff, and has the potential to improve water quality, mitigate wetland loss, provide flood containment, and improve the aesthetics of the project site. As such, the bioswale has hydrologic, chemical, and biological functions. Economic considerations are also an important aspect for assessment of the bioswale and are addressed in the report.

The three main questions the Bioswale Group Project sought to answer were:

1) To what extent does the bioswale improve water quality?
2) What is the total impact of the bioswale in the Devereux Creek Watershed?
3) Given other available options, is the bioswale a cost-effective water treatment method?

To answer these questions, the bioswale group modeled the hydrology and water quality of the bioswale, sampled and analyzed stormwater at the site, and evaluated economic aspects of the use of a bioswale. The bioswale group project used the Storm Water Management Model (SWMM) to simulate the hydrologic and water quality processes of stormwater runoff for the Camino Real Project site. Modeling output included total flow volumes, total pollutant loads, hydrographs, and pollutographs for a wide range of storm events. These output values allowed for the assessment of potential changes in stormwater runoff quantity and quality resulting from the presence of the bioswale. We determined that the bioswale is cost-effective, taking into account its threefold purpose: flood containment capacity, wetland mitigation, and reduction of pollutant loading off site. Conclusions and recommendations were based on interpretations of field data and site observations, as well as on information from relevant documented studies.

Table of Contents

List of Figures

List of Tables

List of Acronyms

ACOE	Army Corps Of Engineers
BMP	Best Management Practice
CSO	Combined Sewer Overflow
CWA	Clean Water Act
EIR	Environmental Impact Report
EMC	Event Mean Concentration
EOA	Eisenberg, Olivieri & Associates, Inc.
EPA	Environmental Protection Agency
NPDES	National Pollutant Discharge Elimination System
NURP	Nationwide Urban Runoff Program
PAH	Polycyclic Aromatic Hydrocarbon
SLAMM	Source Loading and Management Model
SWMM	Storm Water Management Model
TPH	Total Petroleum Hydrocarbons
TSS	Total Suspended Solids

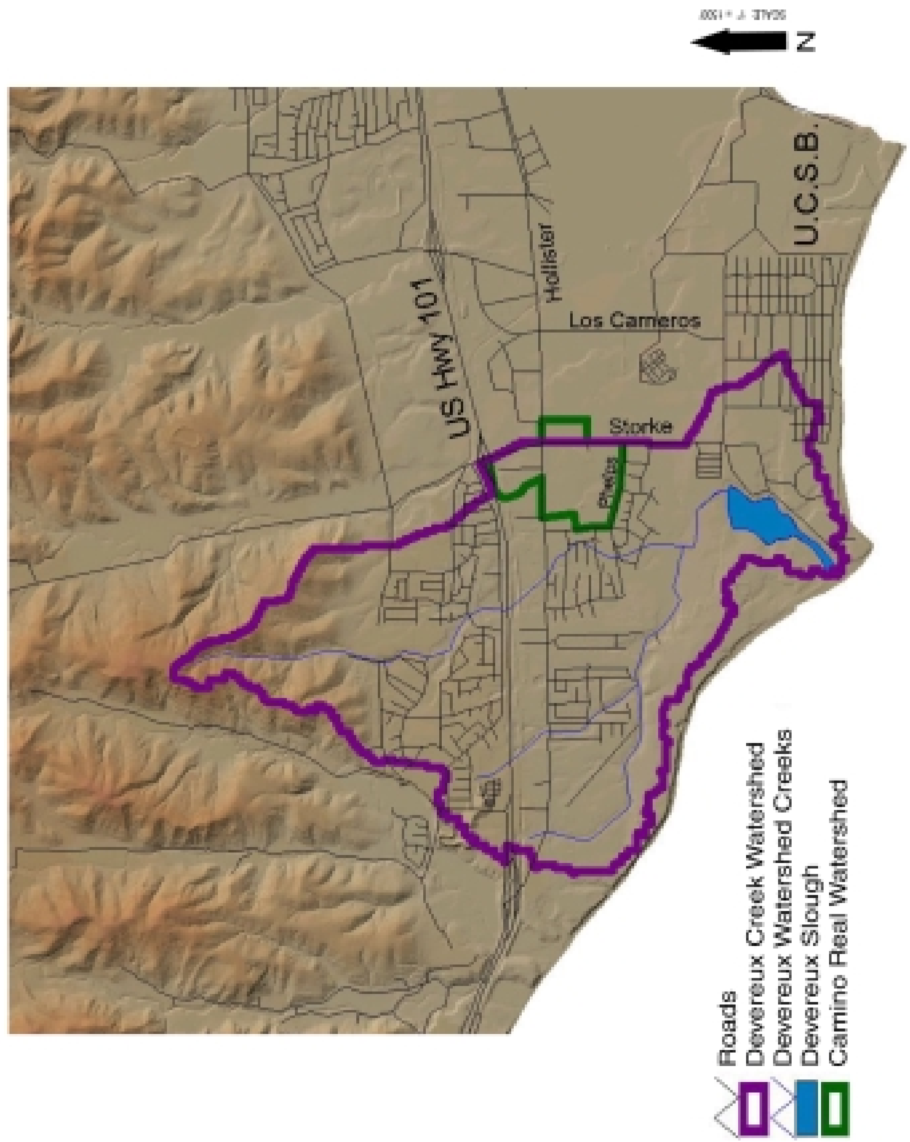
1.0 Introduction

The Camino Real project is a commercial development located in Goleta, California that includes a shopping center, entertainment facilities, associated parking lots, and playing fields. Stormwater runoff from the project site eventually reaches Devereux Slough, a nearby estuary. (Figure 1.1). To minimize the potential impacts of stormwater runoff on Devereux Slough, the project's developer, Wynmark Company, decided to install a bioswale. This bioswale, designed by Fuscoe Engineering, is expected to reduce the peak rate and total volume of stormwater runoff and to reduce total suspended solids and pollutants in stormwater runoff exiting the site.

The bioswale is a low-gradient, open channel possessing a dense cover of vegetation through which runoff is directed during storm events. The bioswale decreases the speed of flows, acts as a stormwater detention facility, and allows suspended solids to settle out. Aboveground plant parts filter particulates and their associated pollutants as runoff passes slowly and evenly through the channel. The pollutants are then incorporated into the soil where they may be immobilized and/or decomposed by plants and microbes. The bioswale is considered a creative means of controlling runoff, and has the potential to improve water quality, mitigate wetland loss, provide flood containment, and improve the aesthetics of the project site. As such, the bioswale has hydrologic, chemical, and biological functions. Economic considerations are also an important aspect for assessment of the bioswale and are addressed later in this report.

The Bioswale Group Project is divided into four main components to reflect these functions: hydrology, chemistry, biology and economic considerations. Each component had a separate scope of work with 2 or 3 people specifically in charge of that aspect of the group project. This ensured that each area of study received sufficient coverage, with everyone equally involved. Overlap between the separate components allowed all group members to participate and to have an understanding of each aspect.

Figure 1.1
Camino Real Property Vicinity



1.1 Purpose and Need of Investigation

The three main questions the Bioswale Group Project sought to answer were:

1) To what extent does the bioswale improve water quality?
2) What is the total impact of the bioswale in the Devereux Creek Watershed?
3) Given other available options, is the bioswale a cost-effective water treatment method?

The main focus of the group project was to analyze the functioning and effectiveness of the bioswale. We wanted to know what impact the bioswale has not only on the development site itself, but also in relation to the whole watershed and its implications for Devereux Slough. It is important to note that the completion of the group project did not coincide with the completion of all building construction and paving at the Camino Real Development, therefore several project findings are preliminary.

The Camino Real development is one of many changes in land use within the Devereux Creek Watershed that have impacted the sensitive wetland and estuarine habitat of the Devereux Slough (Davis, *et al.,* 1990). Water flows from the 2732 acre watershed to the 42 acres Devereux Slough Estuary. Stormwater runoff from the watershed carries sediment and contaminants from the watershed to the Slough. Historical land use changes have increased sediment supply to the Slough, resulting in a reduction in the total size of the Slough and the quality of its wetland habitats (Davis, *et al.,* 1990). From 1965 to 1985, the University Exchange Property immediately north of the Slough was the most significant source of increased sedimentation. Erosion from this property has created a fan-delta with a volume of 486,000 ft^3 which occupies 13.3% of the surface area of the Slough and has displaced 6.5% of its total volume (Davis, *et* *al.,* 1990). This study also found that dissolved oxygen demand from the watershed was negatively impacting the water quality in Devereux Slough.

Continuing urbanization of the Devereux Creek Watershed threatens to exacerbate water quality problems for the Devereux Slough. Although 61% of the watershed has already been urbanized by residential, commercial, and industrial development (de la Garza and Ryan, 1998), development of the watershed, including the Camino Real shopping center, continues to change the quality and quantity of stormwater runoff to the Slough.

Goleta will continue to develop and grow along with the entire Santa Barbara area. In coastal regions it is important that each new change in land use be evaluated for potential impacts to the ecosystem. It is well documented that developments greatly decrease pervious ground cover and increase runoff rates. This runoff is initially characterized by an increased suspension of particles and pollutant loads, which are detrimental to downstream areas. However, once construction is completed, sediment loads are expected to decrease and the system tends to stabilize. A bioswale is one solution to this problem, and this report provides useful information for planners and developers to decide if a bioswale is feasible given their own specific site limitations.

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2.0 Background

2.1 General Description of Camino Real Project Site and Associated Areas

The following discussion is based on information provided in the 1997 Camino Real Project Environmental Impact Report (EIR).

The Camino Real project is an 83-acre development with a variety of land uses. It is located at the southwest corner of Storke Road and Hollister Avenue in Goleta, CA. Major components of the development include up to 500,000 square feet of retail stores and other entertainment and commercial facilities. The development contains approximately 25 acres of recreation areas and open space, and parking spaces for approximately 3,300 cars (Figure 2.1).

The Marketplace is composed of 500,000 square feet of retail space and is located on the northern half of the project site. 14.5 percent of the approximately 46-acre Marketplace is landscaped, with the rest of the area devoted to building space and parking. The southern half of the project site is primarily comprised of playing fields, open space, the bioswale, and the natural area. This combined area is approximately 37-acres and is mostly pervious, with impervious paved areas for approximately 400 parking spaces.

The topography of the project site slopes gently towards the south at gradients ranging from one to two percent. The development site is part of a larger drainage area that consists of 159 acres that is bounded on the north by U.S. 101 and includes the K-Mart Shopping Center (east of the project site) and the

Santa Barbara Business Park (also east of the project site). All runoff from this larger drainage area is directed to the bioswale and/or natural area.

A 36.3 acre section of this larger drainage area, bounded by U.S. 101 on the north and Hollister Road on the south, consists primarily of non-native grasses. Within this area is a housing development currently under construction and a service station which are not a part of the Camino Real Development. The topography of this area slopes gently towards the southeast at an overall gradient of 1.5 percent. Approximately 33 percent of this area is impervious.

Figure 2.1
Camino Real Project Site

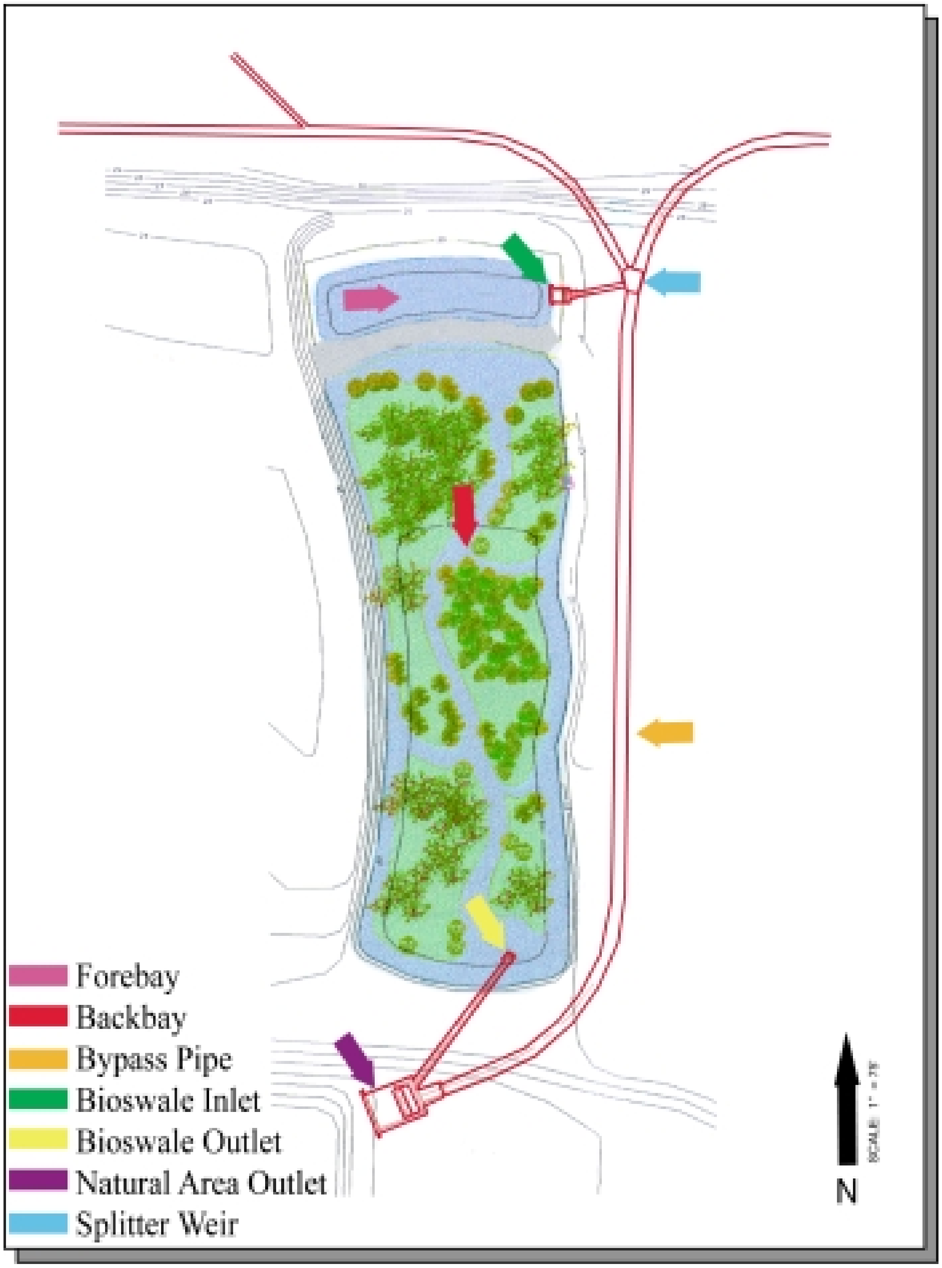
The 26.7 acre area comprised of the K-Mart Shopping Center and the Santa Barbara Business Park to the east of the project also drains to the project site. The K-Mart Shopping Center consists of commercial buildings and parking space, with limited landscaping. The topography of this area slopes gently to the south at a slope of 0.7 percent. Approximately 95 percent of this area is impervious. The Santa Barbara Business Park is also located across Storke Road to the east of the project site. It is comprised of office buildings, parking space, and landscaping. This area slopes gently to the north at a slope of 0.8 percent and is approximately 83 percent impervious.

The existing drainage ditch on the west side of Storke Road has been replaced with a closed storm drain pipe system. Existing storm drains from the east side of Storke Road servicing the K-Mart Shopping Center and the Santa Barbara Business Park have been connected to this new system. The area to the north of the project site bounded by U.S. 101 and Hollister Road is also connected to this system. The storm drain turns westerly at the newly constructed Santa Felicia Drive and southerly through the parking lot before it drains into the bioswale splitter unit. From the splitter, stormwater is either routed to the bioswale or around the bioswale to an existing low-lying wetland depression (the "natural area"), depending upon flow volumes. Under low-flow conditions, all stormwater runoff is routed to the bioswale, which eventually drains to the natural area, while under larger flow conditions, a percentage of flows bypasses the bioswale and is routed directly to the natural area (see Figure 2.2). An additional small pipe drains an approximately 0.5 acre playing field area adjacent to the bioswale into the bioswale forebay. Flows from this pipe are relatively insignificant, reaching approximately 1 cfs during the 25 year storm event. The drainage outlet for the natural area consists of two 4.5-foot storm drains at Phelps Road that ultimately discharge into Devereux Slough. The bioswale, along with the natural area and adjacent playing fields, have the capacity for storage of a 100-year storm.

2.2 Bioswale Description

The project has resulted in changes to drainage patterns and an increase in impervious surfaces, particularly on the northern portion of the site, due to the construction of parking lots, roads, walkways, and structures. Increases in runoff will occur due to the increase in

Figure 2.2
Plan View of the Bioswale



impervious surfaces and the increase in irrigation of landscaped surfaces and turf. Increased runoff from the project could result in decreased water quality in Devereux Slough due to the washing of pollutants from paved surfaces and landscaped areas.

To address these concerns, the project has incorporated a bioswale to aid in the control of stormwater runoff and its associated pollutants. The bioswale was designed to perform three major functions:

Improve the Quality of Stormwater Runoff – The bioswale was constructed to physically filter contaminants and facilitate the chemical and biological processes that remove pollutants from stormwater runoff. The most important processes by which the bioswale is expected to remove pollutants are sedimentation, filtration, absorption, and vegetative uptake. Of these processes, sedimentation is anticipated to be the most effective means for removing particulates and their associated pollutants (Cunningham, *et al*., 1997).

Stormwater Detention – The bioswale was designed to provide stormwater detention, which results in several benefits. The detention of stormwater reduces peak flows from the site, thereby mitigating possible downstream flood hazards. Decreased flow rates due to detention also promote the sedimentation of particulates and their associated pollutants. Furthermore, lower flow rates reduce and elongate the pollutant loading to downstream receiving waters (Cunningham, *et al*., 1997).

On-site Replacement of Riparian Habitat – The bioswale is designed to replace riparian habitat through onsite wetland mitigation. It will frequently have saturated soil conditions, even during periods of no rainfall, because of irrigation of the landscaping and washing of pavement. The plants chosen to go into the bioswale are riparian and wetland native California species. The selected plants also are expected to perform wetland functions, such as taking up nutrients, heavy metals, and organic contaminants that have settled into the soil of the bioswale (Cunningham, *et al*., 1997).

The bioswale (Figure 2.2) is located at the southern end of the Marketplace area and receives flows from the Marketplace, the area bounded by U.S. 101 and Hollister Ave., the K-Mart Shopping Center, and the Santa Barbara Business Park. The majority of the playing fields to the east and west of the bioswale drain to the natural area. The bioswale is comprised of a two-staged filtration/retention system. Runoff initially enters the bioswale structure at the storm drain splitter directly to the east of the bioswale. This structure routes low flows to the bioswale, while high flows are routed around the bioswale to the natural area. Flows routed to the bioswale enter its forebay through an 1.5-foot diameter pipe. The forebay is 26 feet wide, by 110 feet long and stores water to a depth of approximately 2 feet. The primary purpose of the forebay is to provide stormwater detention and particulate settling.

If the water depth in the forebay is below 2 feet, water is primarily conveyed to the bioswale backbay through eleven 0.33-foot diameter pipes. These pipes provide evenly distributed flows from the forebay to the backbay. Once the water depth is above two feet, water from the forebay also flows over a broad, crested weir to the backbay. The backbay is approximately 75 feet wide, by 290 feet long, with a depth of approximately 4.5 feet (Figure 2.3)

Figure 2.3

Bioswale Backbay

When flow enters the backbay it moves along a series of meandering channels which were designed to slow runoff velocity, carry runoff through riparian habitat, and promote sedimentation, filtration, absorption, and vegetative uptake of stormwater pollutants. This flow eventually ponds in a micropool at the far end of the backbay, before leaving the bioswale through a 2-foot diameter pipe.

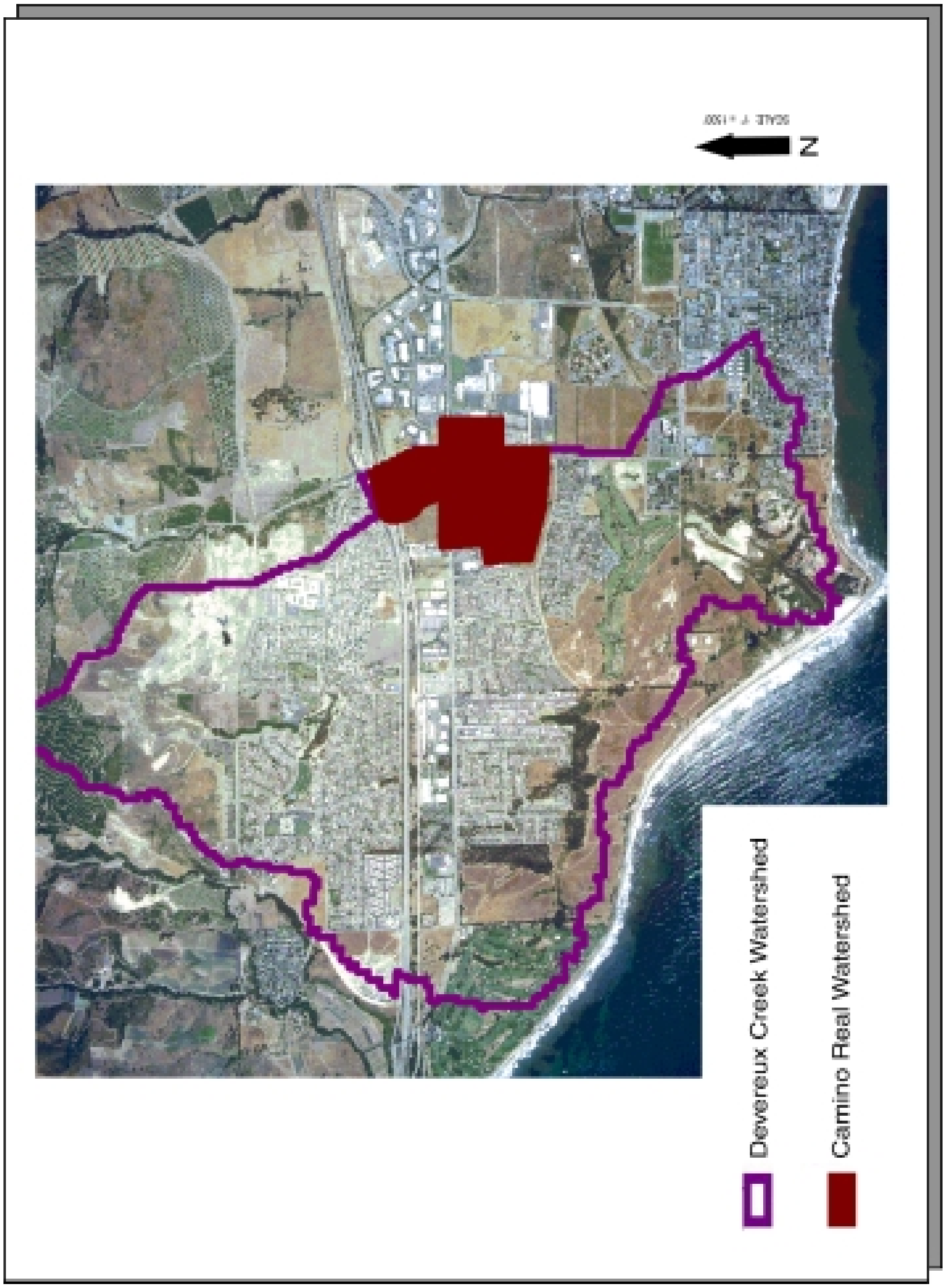
Flow leaving the bioswale enters the natural area. This area is a topographical depression at the southern project site boundary adjacent to Phelps Road and covers approximately 1.05 acres. It contains a stand of willow scrub and coastal freshwater marsh that existed before development occurred (Cunningham, *et al*., 1997). Due to its low gradient, detention storage capacity, and vegetative cover, the natural area is expected to act similarly to the bioswale in terms of improving the quality of stormwater runoff from the project site.

2.3 Devereux Slough

The Camino Real development lies within the Devereux Creek watershed (Figure 2.4). This watershed covers an area of approximately 2,732 acres and stretches northward from the mouth of Devereux Creek at sea level to the Santa Ynez Mountains at an elevation of 525 feet (de la Garza and Ryan, 1998). Devereux Creek empties into Devereux Slough which, including the area south of El Colegio Road and the north and south fingers of Devereux Slough, contains 70 acres of wetland habitat. The quantity and quality of habitat within the slough are currently threatened by: sediment loading, which reduces the capacity of the slough to retain water; its total size; continued residential development in the Devereux Creek Watershed, which increases contamination of runoff; and exotic plant species, which displace native plants and alter habitats.

All runoff from the Camino Real Development exits through drainage pipes, then passes underneath a housing area located to the south of the development, and subsequently surfaces at Ocean Meadows Golf Course south of the housing area. Water then flows through a vegetated channel within the golf course, undergoing further filtration, and then drains to Devereux Slough.

Figure 2.4
Camino Real within the Devereux Creek Watershed



2.4 Study Description

Our analysis is divided into four main sections: Hydrological Processes, Chemical Processes, Biological Considerations, and Economic Considerations. Following is a brief description of each section, and the intended goals.

This analysis focuses heavily on the hydrologic and hydraulic aspects of the bioswale. Hydraulics and hydrology, along with site geology, are fundamental in choosing a stormwater treatment system, as they provide the foundation for what methods are feasible given the site conditions. This information is also required to quantify how the bioswale functions and its overall effectiveness. Water samples from the development site were collected from several rain events and chemically analyzed. These data were used to calibrate the Storm Water Management Model, which was then used to simulate possible future storms and show how the bioswale and natural area would perform.

The chemical section describes which chemicals are regarded as potential problems in surface runoff according to literature reviews, and then lists the chemicals we tested in our analysis. An explanation is provided on why these potential pollutants were chosen, followed by a description of our sampling regime and analysis. This section pinpoints which pollutants are of most concern given the particular site conditions.

The biological section focuses on phytoremediation, which is the use of plants to remediate polluted water or soil, and summarizes relevant literature. The bioswale is vegetated, mostly with wetland plant species that are expected to aid in pollutant degradation. Included is a list of plant species in the bioswale and known information on their role in phytoremediation. Also discussed are limits to the establishment and growth of vegetation within the bioswale and the classification of the bioswale as on-site wetland mitigation.

The economic section evaluates the cost-effectiveness of the bioswale given certain requirements such as wetland mitigation, minimization of pollutant-loading offsite, and flood containment. The potential for aesthetic enhancement and maintenance of good community relations were also a priority. We present a summary of costs associated with bioswale construction and discuss benefits of the bioswale versus alternative treatment options. This information provides information for future land planning decisions.

We complete the analysis with conclusions and recommendations based on current data. The study was conducted during the construction phase of the project therefore several of our findings are preliminary. Ongoing research should be conducted to fully understand and assess the performance of the bioswale as a stormwater runoff management practice.

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3.0 Hydrologic and Hydraulic Processes

3.1 Climate

Santa Barbara County has a Mediterranean climate with warm, dry summers and cool, often wet winters. Inland, weather tends to be more seasonal. Temperatures in the county can drop into the 20s in the northern interior during winter nights, although coastal temperatures remain mild - with highs in the mid-60s and lows in the 40s. Spring starts the warming trend toward summer when average temperatures range from the low-70s along the coast to the mid-80s in the valleys and the low-90s further inland. Precipitation falls predominantly between November and March. Monthly temperature and precipitation data are listed in Table 3.1.

Table 3.1

Climatic Information for Santa Barbara, California

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Average Daytime Temp (°F)	63	65	65	68	69	71	74	75	75	73	69	65	69
Average Precip (in)	3.8	3.4	2.8	1.2	0.2	0.1	0.1	0.1	0.3	0.4	1.8	2.4	16.1
24 Hour Maximum Precip (in)	4.0	4.0	4.5	1.7	1.2	0.4	0.9	1.0	3.0	2.4	2.9	2.6	4.5

3.2 Hydrology of the Site

The Camino Real watershed, which drains the Camino Real Development and the surrounding area, is 159 acres. The majority of the 159 acres is largely impervious commercial and residential development with extensive parking lots. Forty-one acres are primarily composed of playing fields, which will drain directly to the natural area. The primary purpose of the bioswale is to mitigate pollutants associated with parking lot runoff. Stormwater is routed to the bioswale from the surrounding area through a pipe network. Near the bioswale forebay, a flow splitter in the piping system divides flow. A 1.5-foot diameter pipe conveys flow to the bioswale, and a 5.5-foot diameter pipe is placed directly above this pipe to route additional flow directly to the natural area in the case of a high flow event. This split flow design has two functions: 1) It directs all low flow events, small storms, irrigation, and site washdowns to the bioswale and 2) It directs the first portion of a high flow event, large storms to the bioswale. Since the bioswale can only treat a limited volume of stormwater runoff, this split flow design maximizes its pollutant filtration capacity by treating highly concentrated low flows and the first flush of larger storms. The two primary means of mitigating stormwater runoff in the bioswale will be through the settling of particulates and plant filtration. Both of these removal mechanisms are more efficient the longer the water is present within the bioswale. Therefore detention times were calculated for a number of storm events in order to determine the effectiveness of the bioswale.

The Storm Water Management Model was used to determine the routing and volume of runoff from the Camino Real project site, and a Fuscoe engineering report (1997) was consulted to determine the amount of flow discharging from the natural area. For the storm events sampled flows were measured at the inlet and outlet of the bioswale and the outlet of the natural area (Figure 2.2). The purpose for taking these measurements was to determine a mass loading for problematic pollutants associated with stormwater runoff, and the effectiveness of the bioswale and natural area in mitigating these pollutants. All of the flow measurement results are included in Appendix D.

3.2.1 Measurements and Calculations of Observed Flow

This section describes the methodology used for determining field measurements. In evaluating the design of the bioswale it was important to get a quantitative understanding of the conveyance of water to the bioswale, through the bioswale, and to the natural area. Currently, a one-foot orifice plate is placed over the 1.5-foot inlet pipe to the forebay to help aid in flow measurements (Figure 3.1).

3.2.1.1 Flow Entering the Bioswale

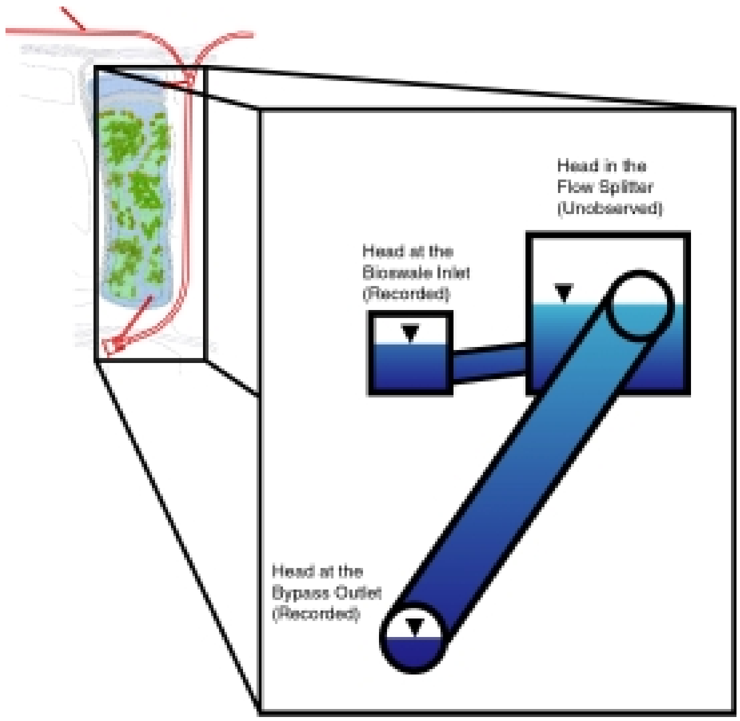
To calculate the flow entering the bioswale, the height of water with respect to the orifice plate was recorded, and a chart provided by Fuscoe Engineering was then consulted to determine the amount of water entering the bioswale. However, the orifice plate proved to be useful only in very low flows because measurement markings became covered by ponded stormwater. Consequently, the flow to the bioswale had to be calculated based on the upstream head and the head at the exit of the inlet pipe (Figure 3.2).

Figure 3.1

Orifice Plate at the Forebay Inlet

Figure 3.2

Water Elevation in the Bypass Pipe Causing the Inlet Pipe to be under a Pressure Head



The velocity leaving the orifice plate is assumed to be similar to that of a submerged jet (Daugherty, *et al*., 1985). Therefore, the following equation was used to calculate the velocity of water entering the bioswale.

(3-1) $$V_0 = (2 * g * \Delta H)^{1/2}$$

Where:
V_0 = the velocity of the discharge (ft/s)
g = gravitational acceleration (32.2 ft/s^2)
ΔH = the change in head (ft)

The height of water was measured at the entrance to the forebay and at the exit of the bypass pipe using a dipstick. It was the intention of the bioswale group to measure the upstream head where the bypass pipe and inlet pipe to the bioswale meet. Unfortunately, the parking lot adjacent to the bioswale went under construction a few days before the first rain event and the manhole where measurements could be taken was temporarily paved over. As a result, inflow to the bioswale had to be estimated. The height at the exit of the bypass pipe was extrapolated back to where it would cause the inlet pipe of the bioswale to be under a pressure head (Figure 3.2). For the January 24th and February 9th rain events this height was assumed to be 0.33-feet (2"), higher than the height recorded at the exit of the bypass pipe. There will be further discussion as to why adding two inches is a valid estimate for these sampling events when the estimation of head water for large flows from the bypass pipe is discussed. The following equation was then used to calculate the resulting flow to the bioswale.

(3-2) $$Q = K*A_0*(2*g*\Delta H)^{1/2}$$

Where:

Q = the discharge in (ft^3/s)

K = coefficient

A_0 = area of the orifice plate (ft^2)

g = gravitational acceleration (32.2 ft/s^2)

ΔH = the change in head (ft)

The coefficient (K) was determined from tables relating it to the Reynolds number of approach and the orifice to pipe diameter ratio (Daugherty, *et al.,* 1985). This calculation is provided in Appendix A. Table A.1 in Appendix A illustrates flows to the bioswale and bypass pipe as well as the height changes between the bypass pipe and the inlet pipe for a number of flow events.

3.2.1.2 **Flow Exiting the Bioswale, Bypass Pipe and Natural Area**

In determining the amount of flow leaving the bioswale backbay, Manning's equation was used when the flow was not under a pressure head. In all storm events sampled the flow leaving the backbay behaved as open channel flow. This same theory was applied for the bypass pipe and the outlet pipes of the natural area. The Manning equation is:

(3-3) $$V = 1.49 * R^{2/3} * S^{1/2} / n$$

$$Q = V * A$$

Where: V = velocity (ft/s)

R = hydraulic radius (ft)

S = slope of the hydraulic grade line (ft/ft)

n = Mannings roughness coefficient ($s/ft^{-1/3}$)

A = area of the pipe (ft^2)

Q = discharge (ft^3/s)

The slope of the bioswale exit pipe, the bypass pipe, and the outlet pipes of the natural area were determined from consulting Fuscoe Engineering's design plans. Manning's roughness coefficient values were determined from consulting a table which provided Manning's roughness coefficient values for a wide range of surface and channel types (Daugherty, *et al.,* 1985). A dipstick was used to determine the height of water leaving the bioswale exit pipe, the bypass pipe, and the outlet pipes of the natural area. In determining the hydraulic radius and area for flow in a partially filled pipe, a table consisting of geometric relationships for circular pipes was consulted (Hammer, *et al.,* 1993).

3.2.1.3 **Observed Backflow from the Energy Dissipator to the Bioswale**

During the sampling of storm events, we observed that the water leaving the bypass pipe and bioswale exit pipe was accumulating in the energy dissipator. Because the timing of sampling at the exit of the bioswale was based on previously calculated detention times, a concern was raised that due to water accumulating in the energy dissipator an exit loss could significantly increase the detention time of the bioswale. There was also a concern that in the case of a heavy rain event, runoff would accumulate so rapidly in the energy dissipator that a reverse pressure gradient could form, thereby causing water to flow back into the bioswale. Therefore calculations had to be performed which took water accumulation in the energy dissipator into consideration.

To calculate the flow leaving the energy dissipator it was necessary to determine its precise dimensions. Onsite measurements revealed that the length of this device was approximately 21 feet, with a width of 16 feet. Water leaves the energy dissipator through three 0.5-foot openings (Figure 3.3). Once the water in the energy dissipator reached a height of 2.75-feet it would leave through the whole width of 16 feet. It was determined that the equation for a suppressed rectangular weir would be most appropriate to calculate flow through the three 0.5-feet openings. If the height of water exceeded 2.75-feet, the equation for a broad-crested weir would be used to determine the flow of this additional water. Considering the effects of the velocity of approach will yield the following equation for a suppressed rectangular weir (Daugherty, *et al.,* 1985, and U.S. Bureau of Reclamation, 1984).

(3-4) $$Q = 3.33*L*[(H + h)^{3/2} - h^{3/2}]$$

Where:

Q = discharge (ft^3/s)

L = length of the weir (ft)

H = height of water relative to the crest (ft)

$h = V^2/2g$ (ft)

The length of the weir was measured in the field, and the height of water relative to the crest was measured in the field while sampling, but could also be determined theoretically based on the amount of flow entering the energy dissipator. This is possible, since the flow is expected to reach a steady state very quickly because the device is so small. The height of water should be measured at a distance upstream at least four times that of the maximum head employed due to drawdown (Daugherty, *et al.,* 1985). This was taken into consideration in field measurements as well as theoretical calculations. Since the velocity approaching the sharp-crested weir will be critical before it moves over the weir, the Froude number is one (Daugherty, *et al.,* 1985). Therefore the velocity of approach can be calculated from the Froude number as follows:

(3-5) $$F = V/(g*H)^{1/2}$$

Where: F = Froude number (1 for critical flow)

V = velocity of approach (ft/s)

g = gravitational acceleration (32.2 ft/s^2)

H = the depth of the water (ft)

From these values it is possible to calculate the discharge of the energy dissipator for any value of H as well as the amount of water that will accumulate in it (Figure3.3).

Figure 3.3

Energy Dissipator Discharge to the Natural Area

Table A.2 in Appendix A indicates the height of water in the energy dissipator, the resulting discharge to the natural area, and field observations. It was concluded that a reverse pressure gradient would form causing the bioswale to begin filling at the outlet even in the case of a small rain event. Currently, the total flow from the site would only have to be about 10 ft^3/s for this to occur. On February 9, 1999 a reverse pressure gradient was observed and the bioswale began filling at its outlet. As a result, calculations of detention times for observed conditions in the bioswale were only made for small rain events, as it would be difficult to incorporate this phenomenon.

3.2.1.4 Calculation of Observed Detention Times

Once discharge relationships for associated heights and volumes within the bioswale were determined, it was possible to estimate detention times for water in the forebay and backbay. The capacity of the forebay before the weir begins to transfer flow to the backbay is roughly 6000 ft^3. For the purpose of calculating its detention time, it was assumed that the water entering the forebay was leaving at the same rate unless otherwise observed. The following equation was used to estimate the detention time of the forebay.

(3-6) $$t_d = V/Q$$

Where: t_d = the detention time of the forebay (seconds)

V = the volume of the forebay (ft^3)

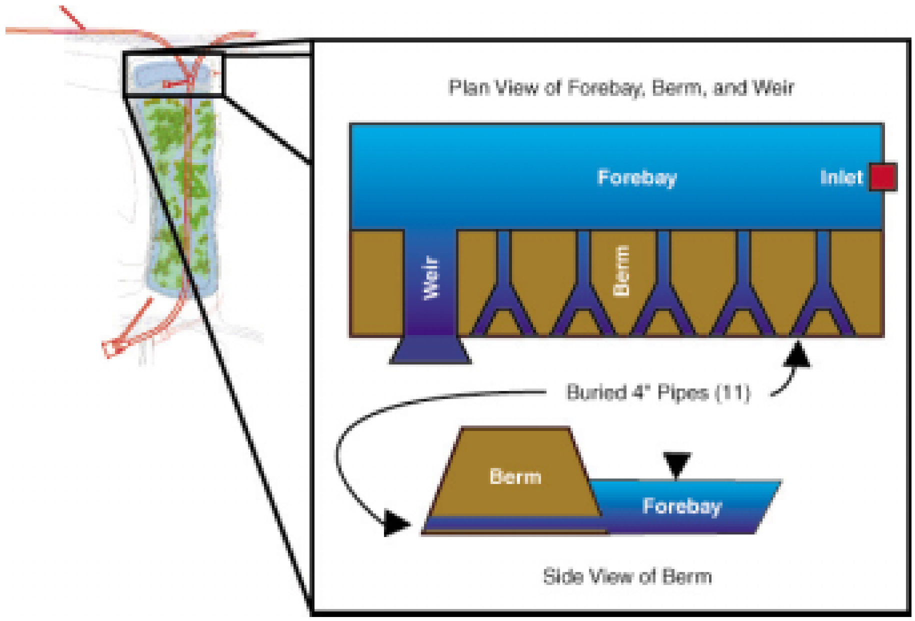
Q = outflow (ft^3/s)

As noted above, it is very likely that the weir will be discharging water to the backbay, thus it is likely that a steady state will be reached in the forebay. However, if the weir was not activated, flow to the backbay would have to be measured leaving the eleven 0.33-foot diameter pipes (Figure 3.4), and the height of water would have to be measured in the forebay to determine its volume at partial capacity. With these measurements the above equation could still be employed to determine the detention time of the forebay.

The detention time of the backbay is estimated by measuring the height of water at the outlet pipe. For this height, the volume of water present in the backbay can be determined as well as the rate at which it is discharging. The volume of water that has ponded was determined from consulting the Fuscoe Engineering plans (1997) for variations of elevation in the backbay. The ponding elevations derived from the Fuscoe Engineering plans matched well with visual observations while sampling. The water present in channels flowing to the ponded area was also considered in calculating the detention time. The speed at which this water reached the ponded area was determined to be irrelevant, since the time for the ponded area to discharge was much greater than the time of travel through the backbay. In calculating the detention time of the backbay equation 3-6 can be used.

Figure 3.4

Forebay, Berm, and Weir



The total detention time of the bioswale was determined by adding the detention time of the forebay and backbay. In a storm event the amount of water entering the forebay will vary over time, as will the amount of water exiting the backbay. For this reason this calculation becomes iterative when attempting to characterize a real storm event. When a parcel of water enters the forebay with a given flow, the amount of time it stays in the bioswale is determined by its flow rate upon entrance, the discharge of the backbay, and how these flow rates change over its expected detention time upon entrance. As a result, the calculated detention time of a parcel of water will have to be adjusted after entrance unless the flow rates stay constant at the entrance and exit of the bioswale. This method for determining the detention time of the bioswale was used while sampling.

In calculating the flow leaving the natural area a dipstick was used at the outlet pipes to determine the height of water at exit in this detention basin. The height measurements at the outlet area of the natural area were approximate as the pipe was not readily accessible and the dipstick had to be read from a distance of about ten feet. Manning's equation was used to calculate the resulting discharge.

3.2.2 Methodology for Calculations of Predicted Flows without the orifice plate

3.2.2.1 Removal of the Orifice Plate

The purpose of this section is to provide flow calculations for the bioswale for how it is expected to perform in the future. In studying the bioswale, it has become apparent that the orifice plate will have to be removed for optimal bioswale performance. Although the orifice plate is a useful tool in flow measurement, it is a flow impediment. The orifice plate is causing a significant amount of flow to be routed around the bioswale that would otherwise have been treated. Since the main purpose of the bioswale is to catch the first flush of pollutants associated with stormwater runoff, the orifice plate is detrimental to the effectiveness of the bioswale. Consequently, we have recommended the removal of the orifice plate and calculated flows without the orifice plate. However, without the orifice plate, different methods have to be employed for determining the hydrological processes within the bioswale.

The effect of removing the orifice plate on the conveyance of flow to the bioswale was significant. As stated earlier, it was not possible to calculate large flow events for the bioswale with the orifice plate as the energy dissipator would accumulate too much water, thereby causing the bioswale to receive water at both its inlet and outlet. Without the orifice plate it was possible to calculate flows up to the twenty-five year storm.

3.2.2.2 **Flow at the Bioswale Inlet**

The bioswale inlet pipe will behave as open channel flow until it becomes ponded to an elevation above the height of the 1.5-foot diameter pipe. Since the forebay fills up quickly, the flow to the bioswale will frequently be under a pressure head (Figure 3.2). To calculate this flow the energy equation was employed.

(3-7) $$\rho_1/\lambda_1 + V_1^2/2g + z_1 = \rho_2/\lambda_2 + V_2^2/2g + z_2 + h_L$$

Where:

ρ/λ = pressure head (ft)

$V^2/2g$ = velocity head (ft)

z = elevation head (ft)

h_L = head loss (ft)

ρ = pressure (lb/ft^2)

λ = specific weight (lb/ft^3)

v = velocity (ft/s)

g = gravitational acceleration (ft/s^2)

When flow to the bioswale is under a pressure head several terms in this equation are negligible. The pressure heads at both the inlet of the forebay and the splitter are zero since they are measured at the water surface (Figure 3.2). The velocity head at the inlet to the forebay is zero since it is measured at the water surface of this reservoir. The velocity head at the splitter is zero since the flow to the bioswale is perpendicular to flow coming into the splitter, it is flowing in the y direction and the concern is the amount of flow to the bioswale which is in the x direction. Thus, for this application equation 3-7 can be rewritten as follows:

(3-7) $$\Delta Z = h_L = f*L*V^2/D*2g$$

Where: ΔZ = the change in elevation between points one and two (ft)

f = the friction factor (dimensionless)

L = the length of the pipe (ft)

V = the velocity (ft/s)

D = the diameter of the pipe (ft)

g = gravitational acceleration (32.2 ft/s^2)

The change in elevation the upstream head was estimated from consulting a culvert capacity chart for a circular concrete pipe with a diameter of 5.5-feet (U.S. Bureau of Public Roads, March 1965). The length of the bypass pipe is 420 feet, however, the 5.5-foot diameter bypass pipe has a broken slope. For the first 23 feet the slope is 0.146 and for the last 397 feet it is 0.002. Since all the other requirements for the use of the culvert capacity chart were met, the chart can still be used even if a broken slope is present within the pipe (U.S. Bureau of Public Roads, March and December 1965). Following the procedure outlined for the use of the culvert capacity charts with a broken slope, it became apparent that the effect of the broken slope present on the upstream headwater for a given flow exiting the bypass pipe is negligible. Manning's equation with a slope of 0.002 was used to calculate the flow leaving the bypass pipe, and a culvert capacity chart was consulted to obtain the height of the water upstream (Figure 3.2). Thus, for a given amount of flow bypassed around the bioswale the upstream head can be calculated. The results of this analysis and are presented in Appendix A in Table A.1. The culvert chart does not provide upstream head estimates for low flows. However, for low flow events, the height change estimate given by the culvert chart between the exit of the bypass pipe and its upstream water surface would be between zero and 0.33-feet (4-inches). Since it is not known if the subsequent decrease in height change is linear, a value of 0.17-feet (2-inches) was estimated for flows that the culvert capacity chart does not provide. The amount this would change the flow to the bioswale is not significant.

For the bioswale inlet head a flow to the bioswale was estimated for the change in elevation between the head at the inlet and the upstream head at the splitter (Figure 3.2). Since the forebay is expected to reach a steady state under such conditions, a trial and error process could be employed to determine the flow to the bioswale for a given upstream head. The application of Moody's diagram shows that the Reynolds number was significant enough to cause a constant friction factor for the flows in question.

3.2.2.3 Flows From the Forebay to the Backbay

In determining the amount of flow from the forebay to the backbay, the equation for a broad crested weir was used (Daugherty, *et al.,* 1985).

(3-8) $$Q = L*g^{1/2}*(2/3)^{3/2}*H^{3/2}$$

Where: Q = flow in ft^3/s
L = length of the weir (ft)
g = gravitational acceleration (32.2 ft/s^2)
H = height of flow over the weir (ft)

The elevation throughout the forebay was assumed to be constant. This assumption matched well with observed conditions. During one storm event the elevation at the bioswale inlet was measured at 19 feet above mean sea level, while an elevation of 19.15 feet would be expected from calculations. This discrepancy is small and may be due to the weir not being constructed exactly as the site plans indicated or possibly an error in field measurements.

Determination of the flow from the forebay to the backbay through the eleven 0.33-foot pipes was difficult since the pipes branch out into twenty-two pipes before exiting into the backbay. These pipes will initially be under a pressure head and then once they branch out, will start behaving as open channel flow. The pipes should each convey a similar amount of flow to the backbay. However, during sampling events it was evident that flow exiting these pipes was inconsistent. Some pipes were approximately half full, while others were conveying a trickle of water. Therefore, the amount of discharge through these pipes had to be estimated based on field observations. The discrepancy in flow through these pipes may have been due to clogging from sediment.

3.2.2.4 **Flow from the Backbay to the Natural Area**

In estimating the amount of flow leaving the backbay, Manning's equation was used if the flow was behaving as open channel flow. However, for rain events up to the 25-year storm, this pipe will be under a pressure head. The energy equation was used in calculating this flow. The pressure head at the exit of the backbay and the entrance to the energy dissipator will be zero since they are measured at the water surface. The velocity head at the exit of the backbay should be zero since it is measured at the water surface of this reservoir. In the energy dissipator the velocity head is assumed to be negligible because it is measured at the water surface directly above the 2-foot exit pipe of the backbay. In estimating the change in height between the bioswale exit and the energy dissipator, a trial and error process was once again necessary. In calculating the detention time for design rain events, a discharge through the bypass pipe was assumed. From this discharge the upstream headwater and the subsequent flow to the bioswale can be calculated as outlined above.

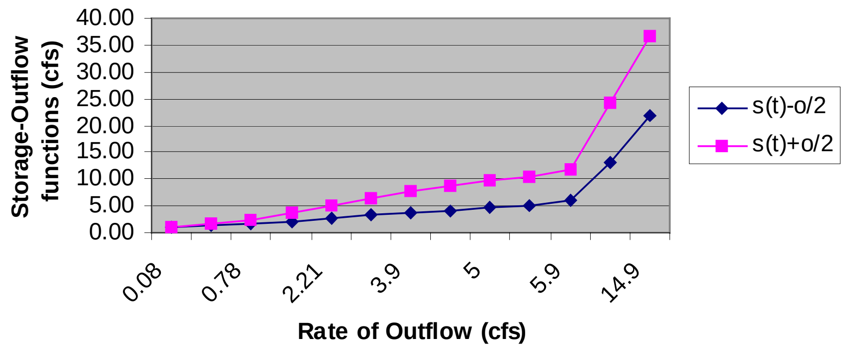
3.2.2.5 Backflow to the Bioswale in Large Flows

Since the flow out of the bypass pipe and the flow leaving the bioswale is known, the energy dissipator chart can be consulted to determine the height of water in this device to achieve the outflow desired. If the height of water in the energy dissipator is known, the height of water necessary for the correct conveyance of flow from the bioswale can be calculated through a trial and error process. With the orifice plate removed the possibility of a reverse pressure gradient in the energy dissipator is unlikely since the amount of flow into the bioswale is significantly increased. Due to the iterative nature of this calculation, it cannot be completely ruled out, but if a reversal of flow was to occur it would most likely be in a heavier storm after the problematic first flush had already been captured by the bioswale. Even if a reverse pressure gradient were to occur, it would be overcome in a few minutes as flow builds up in the bioswale.

3.2.3 Reservoir Routing

The purpose of performing reservoir routing on the bioswale for a design storm is to determine if the Storm Water Management Model (SWMM), discussed in Section 4 is properly routing stormwater through the bioswale. The discussion of reservoir routing follows Dunne and Leopold's reservoir routing method (1978). To apply reservoir routing to the bioswale it was necessary to first determine its storage-outflow relationship. The height of water in the bioswale and its associated volume and discharge have been derived earlier in this report. Calculations for storage-outflow relationships are included in Appendix A, Table A.3. In this example the chosen time increment was 15 minutes. Figure 3.5 illustrates the storage-outflow relationship for the bioswale.

Figure 3.5 Storage-Outflow Relationship for the Bioswale



Once the storage-outflow relationship has been derived it is possible to route stormwater through the bioswale. The Storm Water Management Model was used to produce an inlet hydrograph. A 0.15 in/hr, two-hour storm was the design storm used in this example. The values for hydrograph routing through the bioswale are presented in Table A.4 in Appendix A. From the inlet hydrograph it was possible to determine the inflow into the bioswale for 15-minute time steps. The average inflow rate is calculated for each 15-minute time step. At the beginning of an interval the outflow is taken from the previous interval to determine ($S_1/\Delta t - O_1/2$) in column 4 in Table A.4, by consulting Figure 3.5. In column 5, ($S_2/\Delta t + O_2/2$) is determined by adding the average inflow for this interval to ($S_1/\Delta t - O_1/2$). Figure 3.5 can be consulted again to determine the outflow rate at the end of the time interval. This process is repeated as illustrated in Table A.4 in Appendix A.

The expected outlet hydrograph of the bioswale from the Storm Water Management Model closely matches with the outlet hydrograph obtained from reservoir routing (Figure 3.6). Therefore, according to reservoir routing the Storm Water Management Model appears to be producing a fairly accurate outlet hydrograph for the bioswale.

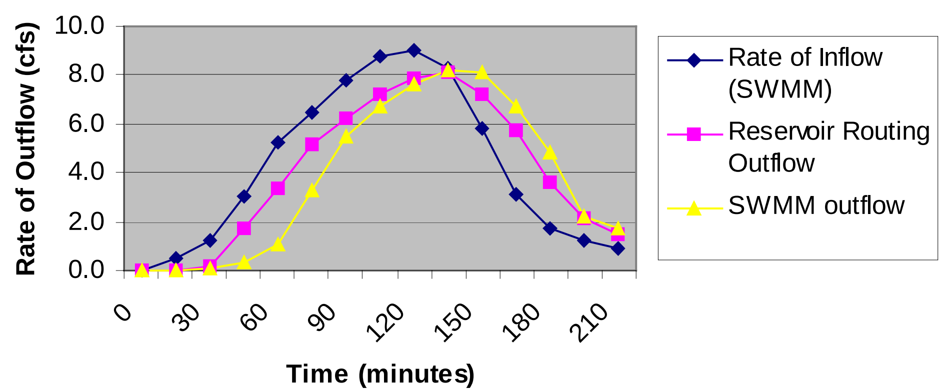


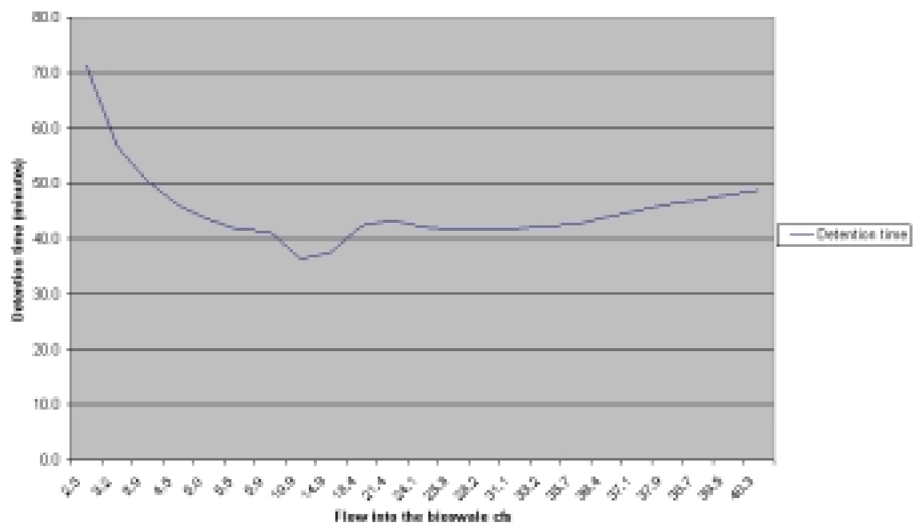
Figure 3.6 Hydrograph Routing through the Bioswale for a 0.15 in/hr 2 hour storm

3.2.4 Detention times

In calculating the detention times, the bioswale is assumed to be at a steady state, so the flow that is going to the bioswale should be leaving the bioswale at the same rate. With a hydrograph, reservoir routing can be used to determine the amount of outflow and its timing for a given amount of inflow. The determined outflow can then be used to calculate the detention time for a parcel of water. The steady-state assumption does not consider that outflow will be changing over time for a parcel of water as reservoir routing does. But, for the purpose of illustrating how the bioswale will perform for a number of outflows the steady-state assumption was used. Figure 3.7 plots expected detention times of the bioswale without the orifice plate using a steady-state assumption. In applying this plot to a storm event, outflows would have to be recorded throughout the storm and then averaged for the expected time a parcel of water stays within the bioswale. The Storm Water Management Model, which is further discussed in Section 4, could also be used as it produces a similar outlet hydrogaph to the one obtained from reservoir routing.

Figure 3.7

Detention Times of the Bioswale



The detention time will decrease for inflows up to about 15 ft^3/s, and then begin to slowly increase for inflows up to 40 ft^3/s (Figure 3.7). While intuitively the detention time of the bioswale would be expected to decrease as the inflow increases, the design of the bioswale causes an increasing detention time with increasing inflow. As with most detention basins, the residence time will be high in low flow events, but as the volume of the detention basin increases due to inflow, the drop off in detention time becomes less dramatic (Figure 3.7). However, in the case of the bioswale at Camino Real, once the inflow begins increasing above 15 ft^3/s, there is a significant increase in the amount of flow that is routed through the bypass pipe, thus increasing the height of water in the energy dissipator. Since the flow exiting the bioswale will be under a pressure head, the elevation in the bioswale will have to increase more than expected to make up for the increased height in the energy dissipator. The kink in Figure 3.7 around an inflow of 15 ft^3/s is when the effect of the energy dissipator becomes noticeable. The energy dissipator causes the flow to level out from an inflow of about 20 ft^3/s to an inflow of about 35 ft^3/s. From an inflow of 35 ft^3/s to an inflow of 40 ft^3/s, the detention time begins to increase at a linear rate. The second kink in the curve is due to a changing control mechanism for the height of water in the forebay. Up to this point, flow was being transferred from the forebay to the backbay over a broad crested weir. With an inflow of greater than 35 ft^3/s the backbay will pond to the same elevation of the forebay. Therefore, the elevation of water in the bioswale became constant throughout. The detention time of the forebay began to increase from this time step forward as discharge of water to the backbay had become less efficient. Consequently, the result is a slight increase in detention time when inflows increase from 35 to 40 ft^3/s.

3.3 Hydraulic Design

The purpose of the following section is to discuss the hydraulic design of this bioswale, and possible improvements that could have been made given the limited space available. In studying the hydraulic design of the conveyance of water through the bioswale and around it, we emphasize the following areas for discussion: hydraulic design, the slope of the bypass pipe, and the use of an energy dissipator. The overall sizing of the bioswale will not be discussed in this section, as there was a limited amount of space available for its design.

The use of a forebay and backbay in the design of the bioswale is recommended in a number of studies, and is instrumental in increasing the detention time of the bioswale (Wanielista, *et al.,* 1986). The use of a bypass pipe is recommended and since the purpose of a detention basin is to catch the first flush of pollutants, if a bypass pipe is not present the detention basin would be overrun with water, therefore causing it to be less effective. The fundamentals of an effective detention basin design for the treatment of urban stormwater runoff are present in the design of this bioswale. However, there are a few areas in the design of this bioswale, which are not optimal for bioswale performance.

If the capacity of the forebay were increased, this could significantly increase the detention time of the bioswale for smaller rain events, thereby causing it to be more effective in its ability to remove pollutants. See the modeling results (Section 4.7) for further discussion of this subject.

Another area of concern is the slope of the bypass pipe and the use of an energy dissipator. As noted above a break in the slope exists in this 5.5-foot pipe. Flow leaves this pipe with a slope of 0.002, yet the average slope for the whole pipe is 0.01. The optimum slope of a culvert of this size can be calculated by the following formula (Simon, 1986).

(3-9) $S_{optimum} = 111*n^2/D^{1/3}$

Where: n = Manning's roughness coefficient ($s/ft^{-1/3}$)
D = diameter of the pipe (ft)
S = the slope of the pipe (ft/ft)

It should be noted that these units do not cancel out, so it is assumed that the coefficient will remedy this discrepancy. For the 5.5-foot concrete culvert the optimum slope for the conveyance of water is 0.01. But, as noted above the water is discharged to the energy dissipator with a slope of only 0.002. Therefore, the culvert is not discharging the optimum amount of water due to its smaller gradient and resultant slower velocity.

The impetus behind putting an energy dissipator at the discharge points of culverts is to slow down the velocity to prevent erosion. However, this energy dissipator is designed so that it accumulates water, because flow is allowed to only discharge through a very small area. As flow is ultimately discharged through these three 0.5-foot openings, the energy dissipator actually increases the velocity, thereby defeating its ability to mitigate erosion processes (Figure 3.3). However, the same characteristics of the energy dissipator that cause it to increase the velocity, also cause it to accumulate water. This has the effect of increasing the detention time of water within the bioswale for reasons outlined earlier in Section 3.2.2.

3.4 Sediment Transport

As sediment accumulates in the bioswale there is the possibility that it could be scoured up in a heavy rain event, causing pollutants originally removed by the bioswale to be loaded to the natural area and possibly to Devereux Slough. In determining if such an event will occur it is necessary to obtain the distribution of sediment sizes that have been deposited, where it accumulates, as well as the velocity that would cause particles of a certain size to become mobile. Since the possibility of sediment transport is most likely in the case of a heavy rain event, the bioswale would be functioning as one channel as it would be entirely submerged in water. Therefore, it is possible to calculate the velocity of water through the bioswale by applying Manning's equation using a width of 75 feet, a slope of 0.0045 and the depth that would convey the flow in question. To determine where and how particles will accumulate in the bioswale further field work would be necessary, although it is likely that most sediment particles will accumulate in the forebay or the back of the backbay as this is where stormwater ponds within the bioswale. Since most pollutants are trapped in fine grain sediments, the transport of this type of sediment is of most concern. The deposition rates of sediment and fine-grained particles could be estimated based on the removal efficiency of the bioswale for the rain events sampled. However, the bioswale is currently under construction and the size of the particles that are currently being loaded could change significantly once construction has been completed. Due to the inherent inaccuracy of sediment transport equations and the fact that construction of the site will be completed later this year, it would be inappropriate to make the number of estimates listed above and apply this year's sampling data to the possibility of future sediment transport events

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4.0 Modeling

4.1 Purpose of Modeling Hydrologic and Chemical Quality Processes

The bioswale group project used a computer-based model to simulate the hydrology and chemical quality of stormwater runoff for the Camino Real Project site. Use of a model was necessary due to the limited time frame and funding of the group project. A wide range of different sized storm events, needed to accurately characterize the performance of the bioswale, were not available for field observation and sampling from December 1998 through February 1999. Storms which occurred in the study area during this time were generally small. Furthermore, funding was not available for an extensive flow gauging and chemical sampling program. As a result, it was not possible to determine the functioning of the bioswale and project site for varying storm sizes through a field observation and sampling program alone. Modeling was therefore used by the bioswale group project to determine the functioning of the bioswale and project site for a wider range of storms of varying sizes than could be sampled during this project.

The model was used for a broad range of applications and analyses, including:

- Determination of output values such as total flow volumes, total pollutant loads, hydrographs, and pollutographs for a wide range of storm events. The bioswale inlet and outlet flows were calculated, together with the outlet of the whole project site. These output values allowed for the assessment of changes in stormwater runoff quantity and quality resulting from the presence of the bioswale for different sized storm events. Changes in runoff quantity and quality due to the routing of runoff through the natural area at the southern end of the project site were also determined.

- Analysis of the design of the bioswale and the project site. Design parameters such as the length, width, depth, and depth-volume-discharge relationships of the bioswale forebay and backbay were altered within the model in order to assess their impacts on the effectiveness of the bioswale.

- Analysis of environmental impacts to the Devereux Slough resulting from the development of the Camino Real Project, including anticipated impacts from the project if the bioswale had not been utilized.

4.2 Screening Models

We conducted a literature search to determine which models with both hydrologic and water quality capability were available. Three models were identified as meeting the requirements: the United States Geological Survey Source Loading and Management Model (SLAMM) (Pitt and Voorhees, 1993), the P8 Urban Catchment Model (Walker, 1990), and the United States Environmental Protection Agency Storm Water Management Model Version 4.0 (SWMM) (Huber and Dickinson, 1988). After investigating the models and performing short sample runs on them, we determined that SWMM would be the most effective model. We based this decision on the following:

- SWMM is capable of modeling inter-storm event buildup of pollutants for any given land use. Other models were only capable of modeling inter-storm event pollutant buildup for street surfaces. Since the a large fraction of the Camino Real project is comprised of parking lots, modeling of pollutant buildup on parking lot surfaces is necessary. Parking lots can accumulate pollutant buildup at different rates than street surfaces (Manning, *et al.*, 1977), making the distinction necessary.

- SWMM is capable of modeling the piping of the project site's storm sewer system. This capability is necessary because of a splitter structure found on site. This splitter structure diverts some water around the bioswale during large flows. To determine the effectiveness of the bioswale, it is necessary to model the amounts of water routed through the bioswale and diverted around the bioswale for a given storm event.

- SWMM is flexible in the level of modeling detail it allows. SWMM can be used as a planning tool or as a design tool. As a planning tool, it can be used for an overall assessment of an urban runoff problem. As a design tool, it can be used to simulate all aspects of urban hydrologic and quality cycles, including rainfall, surface and subsurface runoff, flow routing through a drainage network, storage, and treatment.
- SWMM allows for the use of site-specific parameters rather than pre-assigned parameters. Parameter values can vary widely from site to site. By allowing for the entry of site-specific parameters, SWMM provides the potential for higher levels of modeling accuracy.

- SWMM is the most common water quality model used in engineering practice. This results in a large technical support base. Questions regarding the model can be directed to the model's designer or other e-mail forums. In addition, SWMM is Windows-based, making it the most user-friendly model. The other models were DOS-based, with limited access to technical support.

4.3 Description of SWMM

The EPA's SWMM is a comprehensive hydrological and water quality simulation model developed primarily for urban areas (Huber and Dickinson, 1988). It is capable of both single-event and continuous simulation for almost all components of rainfall, runoff, and water quality processes within a catchment. SWMM is comprised of various modules or blocks, which can simulate different components of the hydrological cycle (Tsihrintzis and Hamid, 1998).

The RUNOFF block was used in this study for stormwater runoff simulations. Surface runoff is computed in SWMM for any rainfall hyetograph, considering land use type and topography, and accounting for infiltration losses to pervious areas, surface detention, overland flow, and channel/pipe flow. The RUNOFF block can also simulate the quality of stormwater runoff within a drainage basin, and the routing of flows and contaminants along storm drainlines, leading to the calculation of a number of hydrographs and pollutographs (Tsihrintzis and Hamid, 1998).

In the RUNOFF block, the drainage area to be modeled is divided into subcatchments based on predominant land use and overland drainage patterns. Values for parameters such as topography, infiltration capacity of pervious areas, width of flow, Manning's roughness, and surface detention are entered into the model for each subcatchment. When provided with a hyetograph, the model then uses these parameters to calculate overland flow. Each subcatchment's overland flow is calculated based on the Horton infiltration equation, surface detention, and nonlinear reservoir routing using Manning's equation (Huber and Dickinson, 1988). For a designated time step, overland flows from each subcatchment are summed to determine the total overland flow. Plotting summed overland flows for each time step provides a hydrograph of runoff for the study site.

SWMM simulates the chemical quality of overland flow based on linear or exponential buildup of pollutants during dry weather preceding the simulated storm event. Built-up pollutants are suspended in overland flow based upon an exponential washoff equation dependent on subcatchment runoff rates. Pollutant loads for various subcatchments are routed and summed with their associated overland flow.

Overland flow data from the subcatchments is then entered into the TRANSPORT block to simulate flow routing. The TRANSPORT block routes flows through a simulated sewer system. It is capable of simulating the functioning of conduits of various sizes and shapes, including flow dividers such as the bioswale splitter system described in Section 3.0. Flow routing proceeds downstream through the designated sewer system for each incremental time step. Flow for each time step is computed by the model through the use of a kinematic wave approach which assumes a cascade of conduits, in which disturbances are allowed only to propagate in the downstream direction (Huber and Dickinson, 1988). Division of flow is simulated based on a series of data sets provided by the user, which describe diverted and undiverted outflows for a given inflow quantity. Chemical quality of flows through the TRANSPORT block is simulated by advection and mixing (Huber and Dickinson, 1988).

SWMM is also capable of simulating the storage of flows and their associated pollutants, such as the storage that occurs in the bioswale and natural area of the study site. The STORAGE block performs this function. Flows enter the STORAGE block from the TRANSPORT block and proceed through the storage unit based on model computations derived from the Puls method (Huber and Dickinson, 1988). Flows leave storage units as dictated by depth-volume-outflow relationships provided by the model's user.

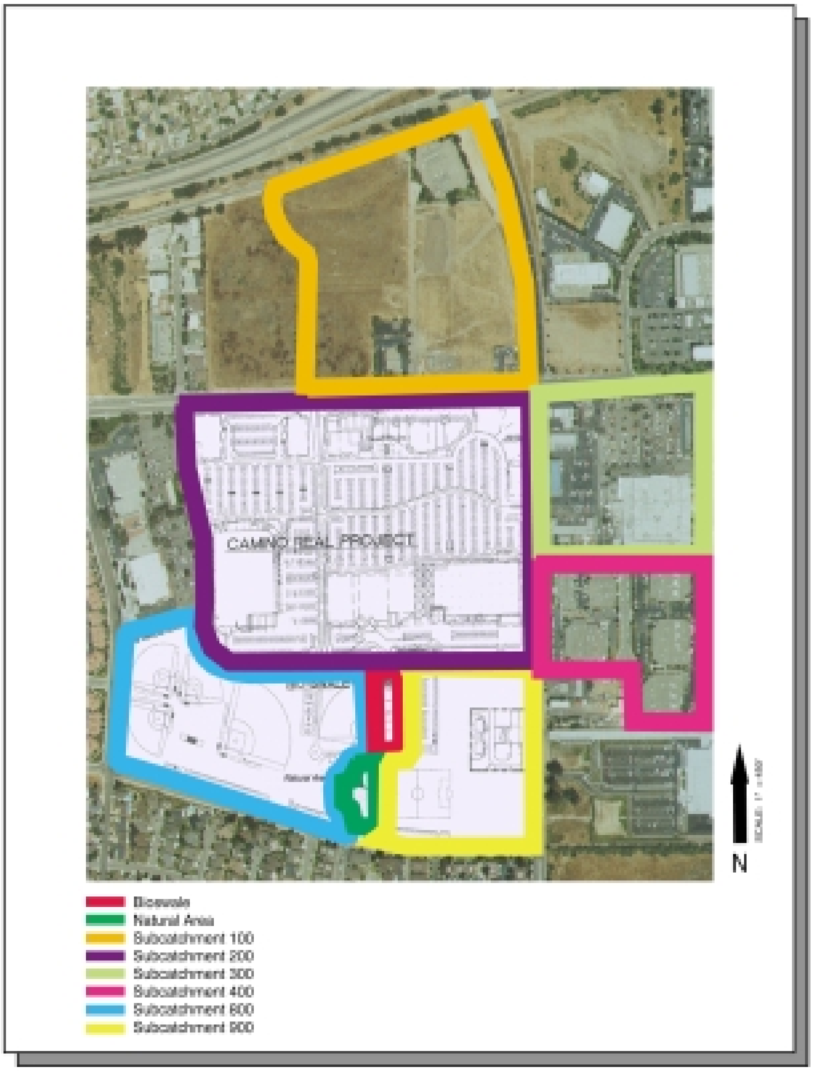
Pollutants are removed from flows within storage units based on the depth-volume-outflow relationship within the storage unit and settling velocities of suspended particles. Within the model, pollutants are assumed to be sorbed onto suspended particles of various size ranges. This assumption is based on the observation that significant amounts of pollutants are commonly associated with the street dust which is carried in suspension by street runoff (Novotny, 1981). Direct runoff measurements by the Nationwide Urban Runoff Program also support this finding, as suspended solids in stormwater runoff were found to carry nutrients, metals, and other pollutants (U.S. EPA, 1983). As flows are detained within a SWMM storage unit, particle settling is simulated based on the proportion of particles found in various settling velocity ranges. The proportion of TSS or a pollutant found in each settling velocity range is provided by the model user. Settling velocity distributions for TSS and other pollutants in stormwater runoff have been measured by the Nationwide Urban Runoff Program (U.S. EPA, 1983). Particles and their associated pollutants which settle out during the detention period are removed from flows. SWMM calculates the total loads of a pollutant entering a storage unit and total loads which are detained by the storage unit due to settling. Pollutographs for the inlets and outlets of storage units are also calculated.

4.4 Designating Subcatchments

SWMM's data requirements make it necessary to divide the study site into subcatchments. This division was based predominantly on surface flow patterns and areas of similar land use. As construction of the site has yet to be completed, the site's hydrologic design plans were used to identify surface flow patterns, while plans for the finished site were used to determine predominant land uses. Six subcatchments were identified. See Figure 4.1 for the location and relative size of the subcatchments. The housing development across Hollister Road, north of the Camino Real Project, was designated as

Subcatchment #100. The main parking areas and commercial developments of the Camino Real Project were designated as Subcatchment #200. The K-Mart and its associated parking areas across Storke Road were designated as Subcatchment #300. The business park area located south of K-Mart was designated as Subcatchment #400. The playing fields to the west of the bioswale and natural area were designated as Subcatchment #800, while the playing fields and fire station to the east of the bioswale and natural area were designated as Subcatchment #900. While Subcatchment #100, 300 and 400 are not part of the Camino Real Project, they are included in the modeling because their runoff is routed to the bioswale and natural area of the Camino Real Project.

Figure 4.1
Modeling Runoff Subcatchments



4.5 Parameterization

SWMM requires parameterization of the following characteristics for each subcatchment: area, percent of area which is impervious, width of predominant flow pattern, slope, Manning’s roughness coefficient, depression storage, infiltration parameters, pollutant buildup rates, and pollutant washoff rates. These parameters are used by the model to calculate overland flow from the subcatchment for a given storm event. SWMM calculates overland flow for each subcatchment based on infiltration, surface detention, and nonlinear reservoir routing using Manning's equation.

The quantity of overland flow for each subcatchment is determined by SWMM using the area, percent impervious, infiltration, and surface detention parameters. The area of each subcatchment controls the amount of rain which falls on it during a model run, thereby dictating quantity of overland flow generated by each subcatchment. The area of each subcatchment was determined from the Fuscoe Engineering plans.

The percent of each subcatchment that is impervious was determined from onsite inspections and consultation of the engineering plans. Due to the irregular shape of landscaping in the developed subcatchments, it is believed that there is the potential for an approximate $\pm$5% error in the estimation of this parameter. The percent impervious parameter is used by SWMM to determine how much area of a subcatchment is influenced by infiltration. Infiltration is considered by the model since it influences quantities of overland flow. The time variation of infiltration rates were calculated in the model runs. Infiltration rate calculations performed by the model were based on the Horton infiltration equation, shown below:

(4-1) $F_p = f_c + (f_o - f_c)e^{-kt}$

Where: F_p= infiltration capacity of the soil (ft/sec)

f_c = minimum or ultimate value of F_p (ft/sec)

f_o = maximum or initial value of F_p (ft/sec)

t = time from beginning of storm (sec)

k = decay coefficient (sec^{-1})

Infiltration parameter estimations for the pervious areas of subcatchments were made based on soil type, soil moisture and vegetation cover. Soil Conservation Service Soil Maps were consulted to determine soil types for the study area. The Soil Conservation Hydrology Handbook (1972) was then consulted to determine that the hydrologic classification of the soils of the study site was type “D”. The soil moisture and the amount vegetation cover were estimated based on site plans. From this information it was possible to consult tables in the SWMM User's Manual and estimate the minimum (f_c) and maximum (f_o) value of the infiltration capacity of the soil (Huber and Dickinson, 1988). A default decay coefficient (k) of 0.00115 sec^{-1} was used as an estimate, as no field data was available (Huber and Dickinson, 1988).

The surface detention parameter (in inches) also impacts the quantity of overland flow, as it represents the amount of water which does not run off the subcatchment surface. In SWMM, water stored as surface detention on pervious areas is subject to infiltration, while surface detention stored on impervious areas is depleted only by evaporation (Huber and Dickinson, 1988). Surface detention was determined for both pervious and impervious areas of subcatchments based on the slope and surface type of the subcatchment. The SWMM User's Manual provided typical surface detention data, based on these parameters. Surface detention values for each subcatchment were interpolated from this data set

(Huber and Dickinson, 1988). Since the surfaces and slopes of the subcatchments were not entirely uniform, the percentage of error in the determination of the surface detention parameter values is expected to be approximately ±10%.

To determine the timing of flows from each subcatchment, SWMM utilizes nonlinear reservoir routing using Manning's equation. Parameters that impact the timing of overland flows in SWMM include width of flow, average slope, and Manning's roughness for each subcatchment.

To determine the width of flow of each subcatchment, the location and length of the main drainage channel in each subcatchment was first identified from the site engineering plans, which plotted their locations. This information was used to determine a skew factor, which is calculated to account for the impact of irregularly shaped subcatchments on the widths of flow from the subcatchments (Di Giano, *et al.,* 1977) (eq. 4.2). The skew factor was then used with the length of the main drainage channel to determine the width of flow of the subcatchment (eq. 4.3). Variables and calculation of the skew factor and subcatchment width of flow are exhibited below.

(4-2) $$S_k = (A_2 – A_1)/A$$

Where: S_k = skew factor

A_1 = Smaller area to one side of the main drainage channel

A_2 = Larger area to the other side of the main drainage channel

A = Total Area

(4-3) $W = (2 - S_k)*L$

Where: W = Width of flow

L = Length of the main drainage channel

S_k = skew factor

Calculations of width of flow for a subcatchment are dependent upon identifying the location of the main drainage channel and measuring its length. While this was measured from site engineering plans, secondary channels and meanders could not be identified. The potential for error in this measurement is believed to be approximately ±10%.

The average slope of each subcatchment was determined from the Fuscoe Engineering plans. Manning's roughness coefficients were determined from consulting a table which provided average Manning's roughness coefficient values for a wide range of surface and channel types (Chow, 1959).

To determine the amount of a pollutant available for suspension in stormwater runoff, SWMM considers pollutant buildup rates for the various land uses in a study area. The amount of pollutant available is dependent upon the subcatchment land use and length of the preceding dry weather period. Total Suspended Solid (TSS) buildup rates (lbs/acre-day) for each subcatchment were calculated based on the subcatchment's predominant land use (Lager, *et al*., 1977). An exponential build-up equation was used:

(4-4) $L_t = QFACT(2) *(1-e^{-QFACT(1)t})$

Where: L_t = constituent quantity at time *t* (lbs/acre)

t = preceding dry weather period (days)

QFACT(1) = build-up parameter exponent (day^{-1})

QFACT(2) = build-up parameter coefficient (lbs/acre)

Values for the parameters QFACT(1) and QFACT(2) were derived from average buildup rates of TSS for various land uses provided in the SWMM User's Manual (Huber and Dickinson, 1988).

Pollutant buildup rates for copper and phosphorus were estimated as a percentage of the buildup of total suspended solids as provided in the SWMM User's Manual (Huber and Dickinson, 1988). As these percentages can be highly site specific, these values can be modified for calibration purposes (Huber and Dickinson, 1988). Calibration of this parameter is discussed in Section 4.6.2.

In spatially variable subcatchments, weighted average parameter values were calculated to get the most reasonable estimate for that parameter. Tables 4.1 - 4.2 illustrate the values that were used as input in SWMM to simulate the as-built functioning of the bioswale and project site.

Table 4.1
Subcatchment Parameter Values

Sub-catch-ment	Area (Acres)	Imperviousness (%)*	Slope	Width of Flow (Feet)*	Manning's n of Impervious Areas	Manning's n of Pervious Areas	Infiltration Parameters of Pervious Area, f_c and F_o (inches/hr)
100	36.3	33.0	0.0150	3322	0.012	0.030	0.02 and 1.5
200	52.2	97.5	0.0096	1400	0.012	0.030	0.02 and 1.5
300	13.5	99.0	0.0072	1760	0.012	0.020	0.02 and 1.5
400	15.2	89.5	0.0083	1552	0.012	0.035	0.02 and 3.0
800	19.1	7.0	0.0100	2585	0.014	0.030	0.02 and 3.0
900	14.1	33.0	0.0170	750	0.014	0.030	0.02 and 3.0

* = Values altered for calibration purposes in Section 4.6.1.

Table 4.2
Subcatchment Parameter Values

Sub-catchment	Depression Storage of Impervious Areas (Inches)	Depression Storage of Pervious Areas (Inches)	Buildup Rates for TSS (lbs/acre*day) QFACT(2)	Buildup Rates for Copper (lbs/acre*day) QFACT (2)	Buildup Rates for Phosphorus (lbs/acre*day) QFACT(2)
100	0.06	0.25	0.82	0.00014	0.03
200	0.03	0.15	1.04	0.00018	0.04
300	0.04	0.10	1.04	0.00018	0.04
400	0.03	0.15	1.04	0.00018	0.04
800	0.06	0.25	0.02	0.000003	0.0008
900	0.06	0.25	0.02	0.000003	0.0008

To determine the amount of built-up pollutants which will become suspended in stormwater runoff for a given storm event, SWMM considers the washoff of the pollutants. Washoff is the process of transport of constituents from a catchment surface during the period of runoff (Warwick and Tadepalli, 1991). In SWMM, the rate of washoff of pollutants is dependent upon the subcatchment runoff rate and two washoff parameters, WASHPO and RCOEF. The following wash-off relationship was used by the model, which describes wash-off at each time step to be proportional to the runoff rate Q_t to a power WASHPO:

(4-5) $$M_t = RCOEF*Q_t^{WASHPO}$$

Where: M_t = constituent load washed off at time *t* (lbs/sec)

Q_t = catchment runoff rate (cfs)

WASHPO = wash-off parameter (dimensionless)

RCOEF = wash-off parameter coefficient (lbs/sec*$[cfs]^{-WASHPO}$)

The original pollutant washoff rate coefficients (RCOEF and WASHPO) were estimated based on a typical range of values provided in the SWMM User's Manual for urban runoff (Huber and Dickinson, 1988). These parameters are generally used as calibration parameters, to be altered to fit observed field values (Huber and Dickinson, 1988). Calibration of these parameters is discussed later.

To simulate flow and pollutant routing through the splitter structure, a flow divider was modeled in SWMM. Runoff from the developed areas of the study site is routed to the splitter structure. The splitter structure then routes flows to the bioswale, or around the bioswale to the natural area when flow conditions to the bioswale exceed the bioswale inlet's flow capability (Figure 2.2). Within the model, runoff and its associated pollutants from the developed areas of the study site were routed to the flow divider to simulate this condition. Division of flow within the flow divider was simulated based on a series of data sets provided to the model. These data sets described the quantity of flows to be routed to the bioswale or bypassed to the natural area for a given inflow quantity. Calculation of these data sets is discussed in Section 3.0. Runoff from the playing fields (Subcatchments 800 and 900) was routed directly to the natural area within the model, as this is what occurs at the study site (Figure 4.1).

To calculate the effect of detention in the bioswale and the natural area on the flows and chemical quality of stormwater runoff, the bioswale forebay, bioswale backbay, and natural area were modeled as separate storage facilities within SWMM. Modeling of these areas in this manner was necessary in order to simulate their detention properties, and the impacts these properties have on the chemical quality of stormwater runoff. Detention within each storage unit (bioswale forebay, bioswale backbay, and natural area) was modeled by providing the model with up to 16 data sets describing the units' geometry and hydraulics. Each data set represented a depth of ponded water within the storage unit. Parameters for each data set included the corresponding surface area of the ponded water, corresponding volume of the ponded water, and the corresponding depth-treated outflow relationship from the storage unit. Due to the irregular shape and contours of the bioswale forebay and backbay, the level of error in calculating these units' volume capacity for a given depth of ponded water is estimated to be approximately $\pm$10%. The depth-treated outflow relationship dictates the detention time of flows through the storage unit.

Calculations used in determining the values of these data sets for the bioswale forebay and backbay are discussed further in Section 3.0. Table A.6 includes the values used. The values of these data sets for the natural area were obtained from Fuscoe Engineering's site plans and are also included in Table A.6 (Fuscoe Engineering, 1997).

To model the pollutant removal characteristics of the bioswale forebay, bioswale backbay, and natural area, SWMM utilizes particle size and settling velocity distributions. Significant amounts of pollutants are commonly associated with street dust which is carried in suspension by street runoff (Novotny, 1981). Suspended solids carry nutrients, metals, and other substances in stormwater runoff (U.S. EPA, 1983). SWMM therefore characterizes pollutants by their association with suspended solids of various particle size ranges.

In SWMM, settling velocities in stormwater runoff are assigned to each particle size range based on settling column tests using urban runoff (Driscoll, 1983). Removal of a particle size range by a storage unit (bioswale forebay, bioswale backbay, and natural area) is then based on the settling velocity of the particle size range and the detention time of the unit. If flows are detained in a storage unit long enough for a particle size range to settle out, the proportions of TSS and pollutants found in this particle size range are removed from the runoff by the storage unit. The proportion of TSS and other pollutants found in each settling velocity range in stormwater runoff was determined based on values used in the P8 Urban Catchment Model (Walker, 1990). These values are based on results of the Nationwide Urban Runoff Program (U.S. EPA, 1983). The settling velocity distributions of pollutants modeled in SWMM are included in Table 4.3 below.

Table 4.3
Pollutant Settling Velocity Distribution

	Pollutant Settling Velocity Distribution (% by weight)		
Settling Velocity (ft/hr)	**TSS**	**Copper**	**Total Phosphorus**
0 (Dissolved Particles)	0	40	30
0.00 – 0.03	20	20	23.3
0.03 – 0.30	20	20	23.3
0.30 – 1.50	20	20	23.3
1.50 – 7.00	40	0	0

Though the proportions of pollutants found in the various settling velocity ranges were derived from results from the Nationwide Urban Runoff Program, the proportions can be site specific (Walker, 1990). For this reason, the proportions of pollutants found in various settling velocity ranges were used as calibration parameters where necessary. Calibration is discussed in the next section of this report.

4.6 Calibration

The objectives for the calibration of the modeled stormwater runoff quantity included the following:

- Matching the simulated hydrograph timing and shape with measured field values; and
- Matching the simulated peak discharge with measured peak discharge in the field.

4.6.1 Calibration of Stormwater Runoff Quantity

To calibrate the stormwater runoff quantity aspect of the model, the predicted hydrographs were matched with values observed in the field to achieve the required timing and magnitude of the flow peak and shape of the modeled hydrograph. Rainfall was generated in the model by input of Santa Barbara County rainfall data from the Goleta Fire Station located adjacent to the site. This site records the duration of time between every 0.04 inches of rainfall. This rainfall data was extrapolated to 10-minute interval rainfall intensities for use in the model. Model generated hydrographs based on this rainfall were then calibrated to field observations by adjusting the quantity and timing input parameters reported in the SWMM User's Manual (Huber and Dickinson, 1988). These parameters were adjusted within the estimated range of error used in their original measurement (Huber and Dickinson, 1988). Measured and simulated hydrographs were matched by plotting both of the hydrographs on the same graph and altering calibration parameters to achieve the best visual fit.

Stormwater runoff quantity calibration was based on two storms of relatively small magnitude. During the period of study (December 1998 through February 1999) there were few significant storms for field measurement. Calibration of the quantity aspect of the model for the simulation of large storm events would have benefited from additional field measurements of larger storms.

The hydrographs calibrated represent runoff from the developed areas of the study site. These areas are the housing development north of Hollister Road (Subcatchment 100), the Marketplace of the Camino Real Project (Subcatchment 200), the K-Mart Shopping Center (Subcatchment 300), and the business park (Subcatchment 400) (Figure 4.1). These areas represent all of the areas that drain to the splitter structure located directly upstream from the bioswale (Figure 2.2). The splitter then directs flows to the bioswale and around it to the natural area during large flows. Hydrographs were calibrated for the splitter structure inlet, the bioswale inlet, and bioswale outlet (Figure 2.2).

To calibrate the hydrographs generated at the splitter structure, the two parameters adjusted were the "percent impervious" parameter and the "width of flow (W)" parameter. The "percent impervious" parameter was adjusted to calibrate the magnitude of the flow peak and the shape of the hydrograph, while the "width of flow" parameter was adjusted to calibrate the timing of the peak of the hydrograph. The percent of each subcatchment that was impervious was originally measured from site plans and by field inspection. Due to the complicated and irregular landscaping of much of the study area, the error in the original measurement was estimated to be approximately ∈5%. Preliminary predicted hydrograph peaks and volume at the splitter structure were higher than observed values. The "percent impervious" parameter was therefore decreased for each subcatchment by 5% from its original measurement in order to match simulated and measured hydrograph peak flow and volume.

The width of flow measurement derived earlier in this section applied only to the main drainage channel. Since the width of flow measurement did not originally include secondary drainage channels or account for channel meanders, the error in the original measurement was estimated to be at least ∈10%. Preliminary model-generated hydrographs for runoff at the splitter structure peaked later than the observed values in the field. The width of flow parameter was therefore reduced by 10% to match the simulated and measured timing of the flow peak.

Once the stormwater runoff quantity aspect of the model was calibrated, the average error in peak flow timing of runoff from the developed areas between simulated and observed values was approximately 10 minutes. This was for calibration based on two storm events, where rainfall lasted for approximately 3.3 – 4.5 hours. The error in peak flow magnitude was approximately 1.1 cfs for the 1/24/99 storm, when peaks flows in the field were observed at 5.8 cfs (an error of 19% of observed values). The error in peak flow magnitude was approximately 0.3 cfs for the 2/9/99 storm, when peaks flows in the field were observed at 6.9 cfs (an error of 4% of observed values). It should be noted that relatively few field observations of flow were made due to lack of flow gauging instruments.

Figures 4.2 and 4.3 show the 1/24/99 hyetograph and the 1/24/99 calibrated hydrograph for runoff at the splitter structure. Figures 4.4 and 4.5 show the 2/9/99 hyetograph and the 2/9/99 calibrated hydrograph for runoff at the splitter structure. Table 4.4 exhibits original estimates of parameter values and calibrated parameter values for developed area subcatchments.

Figure 4.2
Hyetograph from Goleta Fire Station (1/24/99)

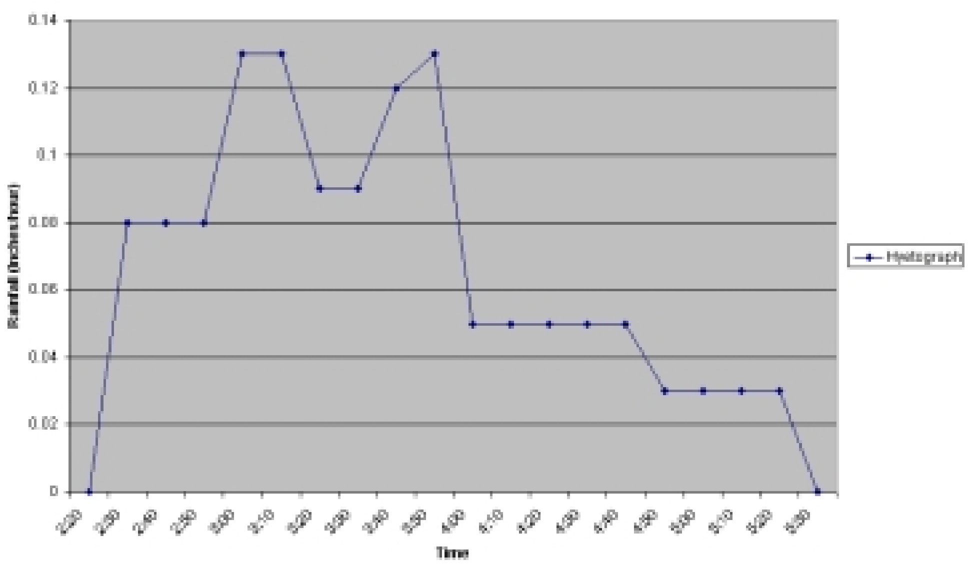


Figure 4.3
Calibrated Hydrograph and Observed Values for Flow Routed to Splitter Structure from Developed Areas (1/24/99)

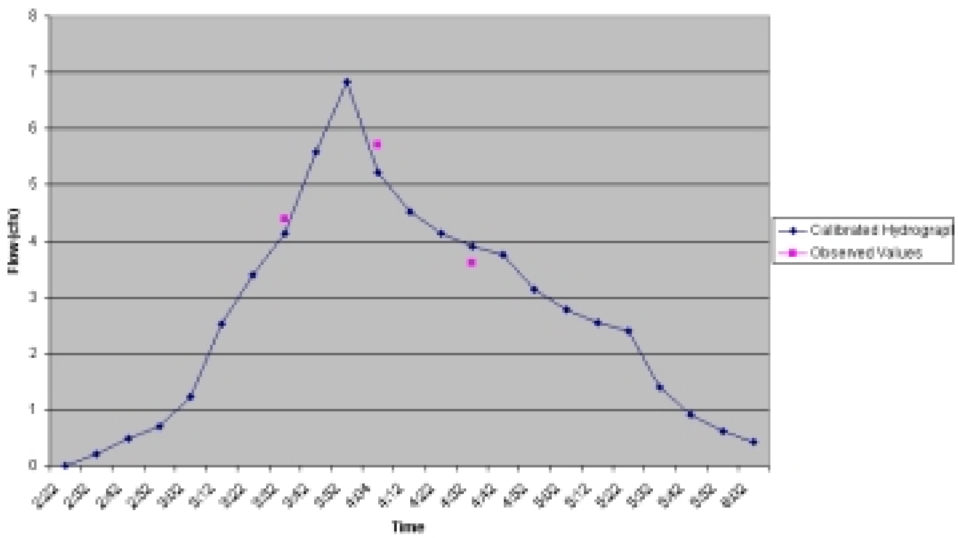


Figure 4.4
Hyetograph from Goleta Fire Station (2/9/99)

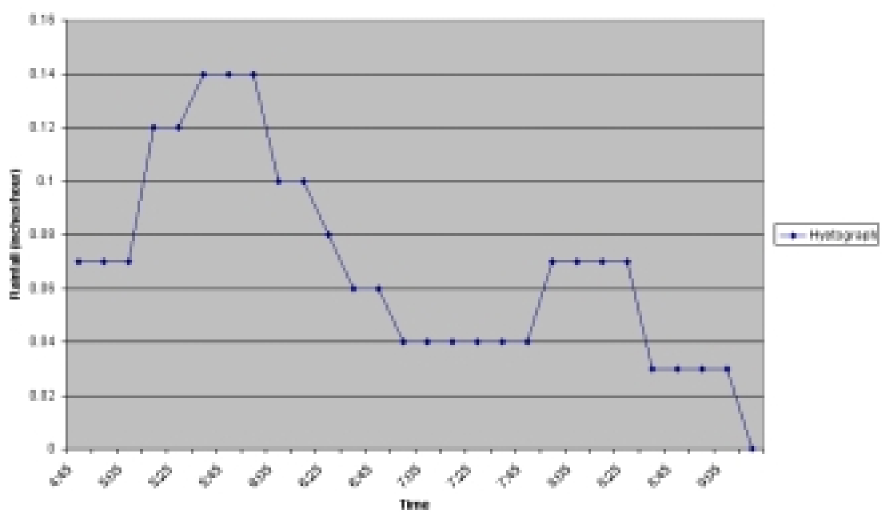


Figure 4.5
Calibrated Hydrograph and Observed Values for Flow Routed to Splitter Structure from Developed Areas (2/8/99)

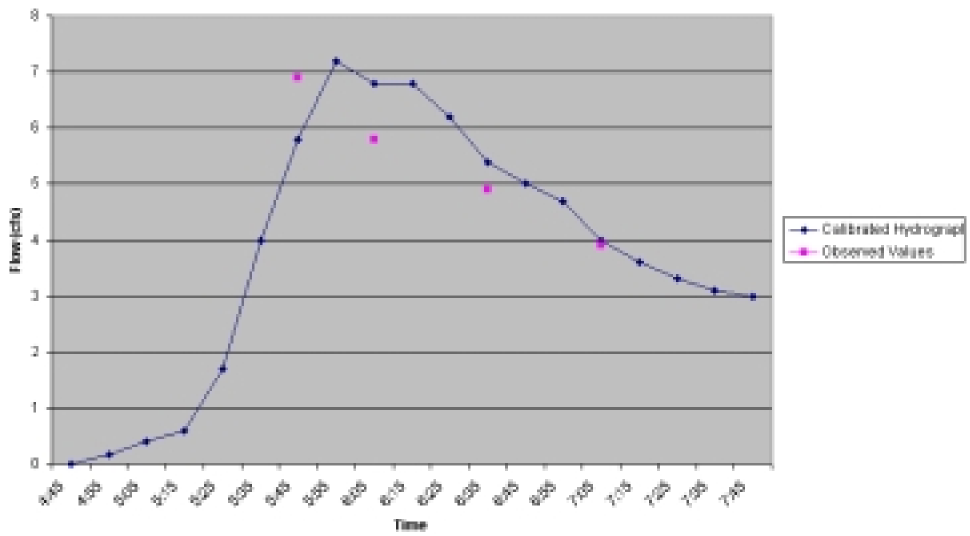


Table 4.4

Comparison of Preliminary Estimates and Calibrated Values of Parameters

	Estimated Percent Impervious	Calibrated Percent Impervious	Estimated Width of Flow	Calibrated Width of Flow
Subcatchment 100	33.0	31.3	3322	2990
Subcatchment 200	97.5	92.6	1400	1260
Subcatchment 300	99.0	94.1	1760	1584
Subcatchment 400	89.5	85.0	1552	1396

With the runoff from the developed areas of the study site (Subcatchments 100 – 400) calibrated, calibration of hydrographs for flow routed to the bioswale inlet was not necessary. Error for the timing of the peak flow of the 1/24/99 event was approximately 10 minutes, while no error was observed in the timing of the of the peak flow of the 2/9/99 event. The error in modeling the magnitude of the peak flow for both events was approximately 0.1 cfs for peak flows of 3.5 and 3.6 cfs.

Figures 4.6 and 4.7 show values observed in the field with calibrated hydrographs for the bioswale inlet.

Figure 4.6
Calibrated Hydrograph and Observed Values for Bioswale Inlet (1/24/99)

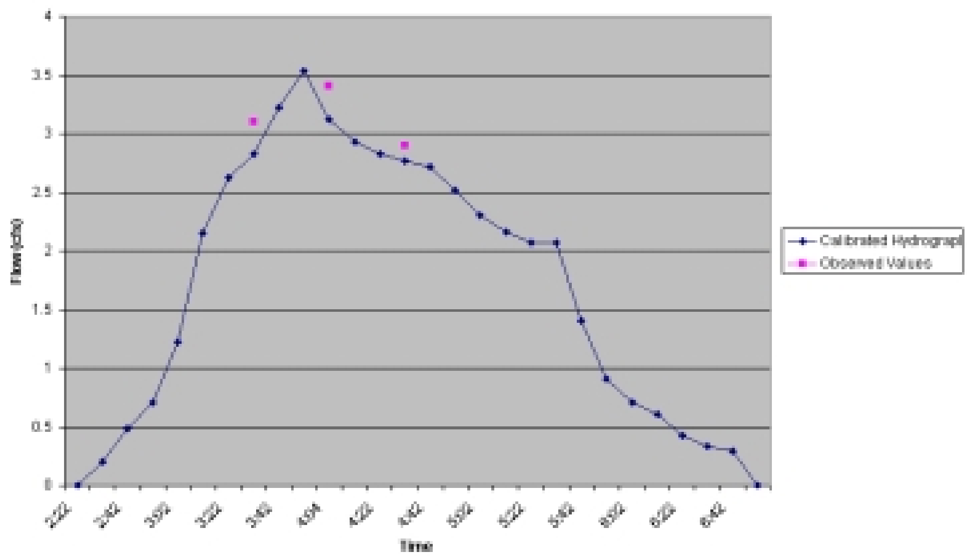


Figure 4.7
Calibrated Hydrograph and Observed Values for Bioswale Inlet (2/8/99)

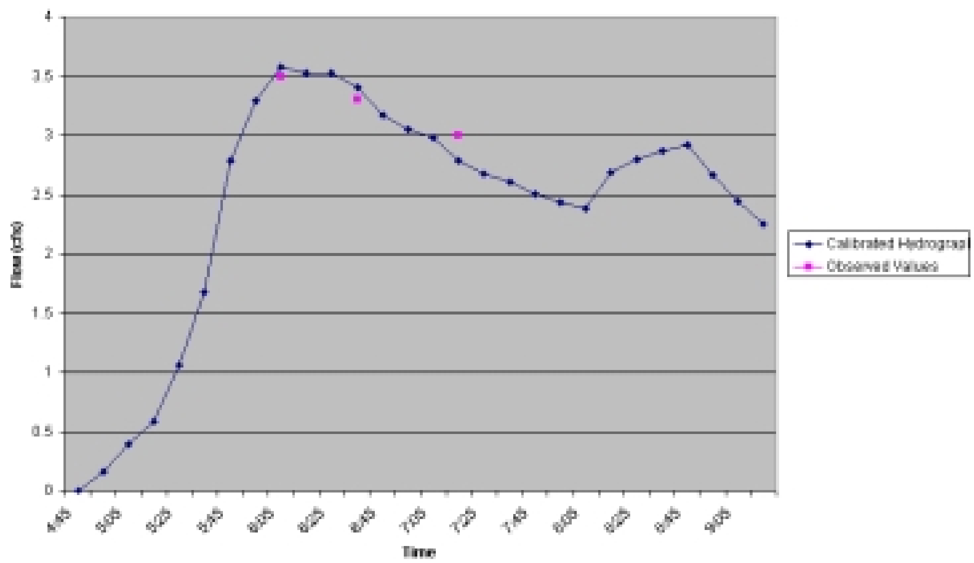


Figure 4.8
Calibrated Hydrograph and Observed Values for Bioswale Outlet (1/24/99)

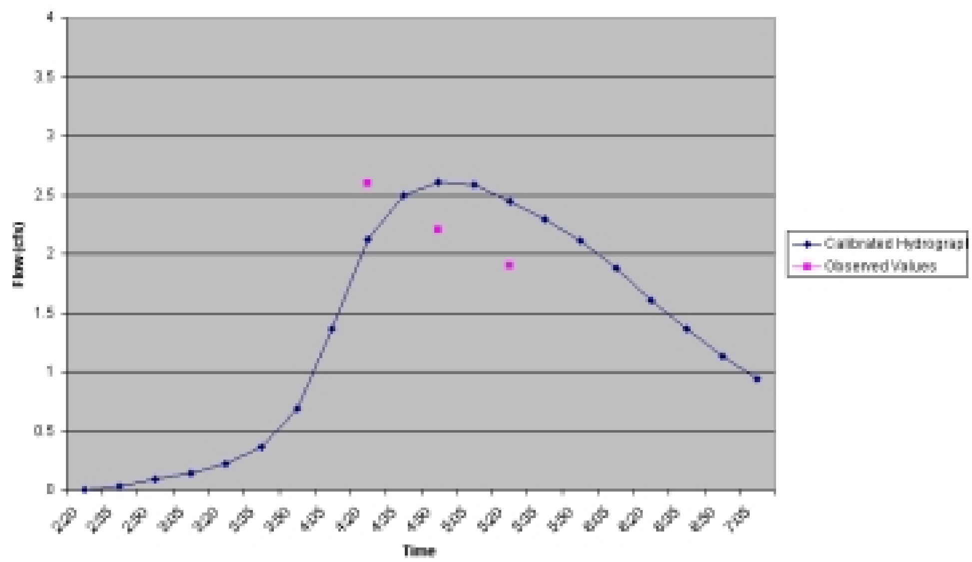
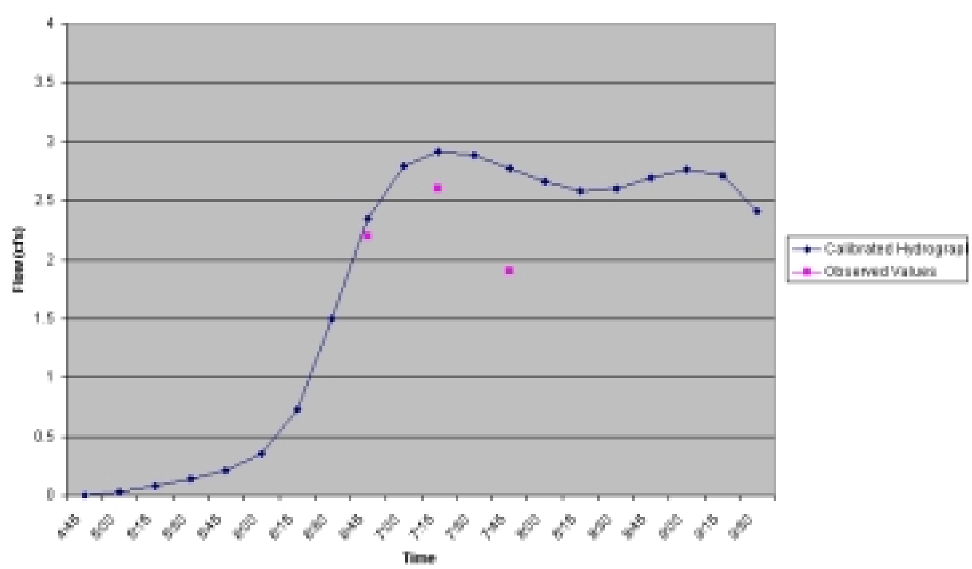


Figure 4.9
Calibrated Hydrograph and Observed Values for Bioswale Outlet (2/9/99)



For the bioswale outlet, the predicted hydrograph for the 1/24/99 storm event peaked approximately 45 minutes after the observed peak. No error was observed for the magnitude of this peak, however. For the 2/9/99 storm event, no error was observed in the timing of the peak of the modeled hydrograph. The magnitude of the modeled peak was 0.3 cfs higher than the observed peak of 2.6 cfs. Modeled flow values for this storm event were an average 22% higher than observed values. Figures 4.8 and 4.9 show values observed in the field with calibrated hydrographs for the bioswale outlet.

It is believed that the error seen between the predicted hydrographs and observed values at the bioswale outlet may be due to infiltration within the bioswale. The model does not account for infiltration within storage units such as the bioswale forebay, bioswale backbay, and natural area. The lack of infiltration in the modeled bioswale may account for a higher magnitude of the modeled hydrograph for the bioswale outlet.

Calibration of predicted hydrographs for the bioswale outlet was attempted by altering the volume parameter in the depth-volume-outflow relationship used by SWMM. Modeled outflows from the bioswale forebay and backbay are based on this relationship, which is discussed above in Section 4.5. Due to the irregular shape and contours of the bioswale, determination of the volume of runoff held by the bioswale for a given ponded depth was estimated to have an error of ±10%. Since the magnitude of modeled hydrographs was greater than that of the observed values, the volume held by the bioswale was decreased by 10% within the model. Alteration of this parameter had minimal impact on timing and magnitude of flows. Likewise, the Manning's roughness value for the bioswale forebay and backbay was increased and decreased. This parameter also had very little impact on modeled hydrographs for the bioswale outlet.

The insensitivity of the model to calibration of storage unit parameters prevented further calibration of the hydrographs for the bioswale outlet. The modeled hydrograph for the 1/24/99 event peaks approximately 45 minutes later than the observed values, while the magnitude of the 2/9/99 modeled hydrograph is an average 22% higher than the observed values. While more accurate calibration was desired, the present level of calibration is believed to be adequate for the following reasons:

- The higher magnitude of flows for the modeled hydrographs suggests that the model predicts flows leave the bioswale faster than observed. The modeled detention times of the bioswale are therefore shorter that those observed in the field. With shorter detention times, the model is predicting less settling of pollutants in the bioswale. The model therefore under-predicts the effectiveness of the bioswale in removing TSS and other pollutants from stormwater runoff. As a result, modeled pollutographs for the bioswale outlet can be seen as worst-case scenarios. The actual performance of the bioswale is expected to be somewhat more effective.

- Though detention times for the bioswale are under-predicted by the model, other parameters are available for calibration of the effectiveness of the bioswale in removing pollutants from stormwater runoff. For example, the proportion of pollutants found on various particle size ranges can be altered. The proportions can be changed so that more of a pollutant is partitioned to larger particles within the model. A greater proportion of the pollutant would thereby be associated with a greater settling velocity. The pollutant will then settle out in a shorter time period, countering the effect of shortened detention time used by the model. This method of calibration is discussed further in Section 4.6.2.

- Comparison of a SWMM generated hydrograph for the bioswale outlet and a reservoir routing generated hydrograph for the bioswale outlet proved to be very similar. The magnitude and timing of the peaks were identical. Total flow volume also appeared to be very similar, based upon visual fitting of the two hydrographs. This comparison between the two hydrographs corroborates the SWMM bioswale outlet hydrograph results. Both modeling methods calculated similar hydrographs for the bioswale outlet, indicating that the SWMM calculations are relatively accurate. Furthermore, the hydrographs help confirm that the SWMM model conserves mass of flows through the bioswale. See Section 3.0 for further discussion of the calculation of the reservoir routing generated hydrograph.

- When the error of the modeled hydrographs of the two storm events are averaged together, the magnitude of the error is not prohibitive. The average error in the magnitude of the modeled peak flows of the two storms is approximately 6%. The average error of the modeled average flows of the two storms is approximately 15%. The average error in the modeled timing of the peak flows is approximately 22.5 minutes.

Flows routed to the splitter structure and bioswale are from the developed areas of the study site (Subcatchments 100, 200, 300, and 400). The playing fields to the east and west of the bioswale and natural area (Subcatchments 800 and 900) do not drain to the bioswale. These areas drain directly to the natural area at various locations along the natural area's length. Though outflow from the natural area was modeled, the entrance of flows to the natural area at various locations along its length made modeling of its outflows difficult to incorporate. For this reason, calibration of the natural area outflow hydrographs was not conducted.

4.6.2 Calibration of Stormwater Runoff Quality

During the period of this study, the bioswale had been recently constructed. The soil of the bioswale and its surrounding slopes was disturbed, and the vegetation within the bioswale had not yet become established. As a result, the bioswale had not reached its full potential in removing pollutants from stormwater runoff. However, the model was calibrated to simulate the bioswale's present effectiveness in removing pollutants. This helped to create an accurate model, as modeling results could be checked against results observed in the field. Modeling runs conducted with calibrated parameters are useful in exhibiting the effectiveness of a bioswale in its early stages of development. Furthermore, calibrated modeling runs provide the means for comparison between present bioswale performance and bioswale performance in the future. During the comparisons, the level of improvement of the bioswale's effectiveness could then possibly be attributed to particular changes within the bioswale that were observed in the field.

Calibration of the modeled stormwater quality was performed in a manner similar to the stormwater quantity calibration. Simulated pollutographs for a variety of constituents were compared with values observed in the field. The constituents modeled in SWMM were TSS, copper, and phosphorus. Measured and simulated pollutographs were matched by plotting both of the pollutographs on the same graph and altering calibration parameters to achieve the best visual fit.

TSS was the first constituent to be calibrated. As discussed previously in Section 4.5, the model considers pollutants in stormwater runoff to be sorbed to TSS. The quantity of pollutants present in stormwater runoff is determined to be a fraction of the TSS load. The build-up and wash-off of these pollutants is therefore dependent on the build-up and wash-off of TSS. The quantity of TSS built-up is dependent upon the subcatchment land use and length of the preceding dry weather period. Values for the parameters used to derive average buildup rates of TSS for various land uses were provided in the SWMM User's Manual and were not altered for calibration (Huber and Dickinson, 1988).

The 2/9/99 data set was used to calibrate the TSS pollutographs. This data set was used because it is representative of runoff from the whole project site in its present state, and includes data for both the inlet and outlet of the bioswale. It was also chosen because the TSS values were similar to those collected during a storm event on 1/31/99. 1/31/99 data was not used because reliable flow data is not available for this date. Data from 1/24/99 were not used because laboratory analysis was performed by a different laboratory and results varied from the 2/9/99 and 1/31/99 results by over an order of magnitude, even though all storm events were similar in size, intensity, duration, and length of preceding period of dry weather.

Two quality parameters (WASHPO and RCOEF) were used to calibrate the magnitude and timing of the TSS pollutograph routed to the bioswale inlet from the developed areas of the study site. During calibration, these parameters can be widely modified, as they "may be varied in order to calibrate the model to observed data" (Huber and Dickinson, 1988). RCOEF and WASHPO were calibrated until the TSS pollutograph magnitude and timing matched measured values, based on visual fitting of the graphs. These parameters are used in the following equation to simulate washoff from a subcatchment:

(4-5) $$M_t = RCOEF*Q_t^{WASHPO}$$

Where: M_t = constituent load washed off at time *t* (lbs/sec)

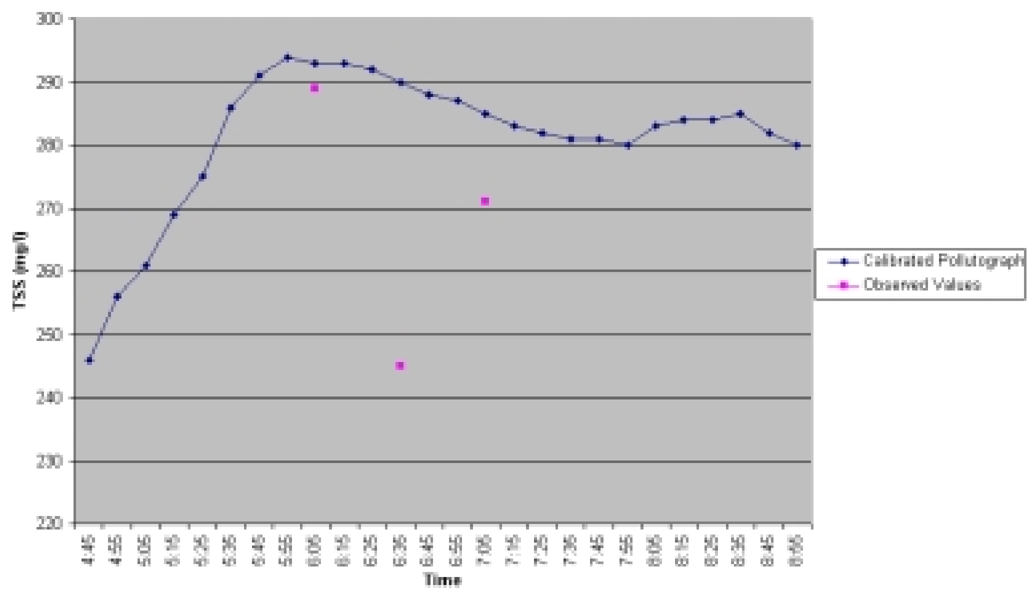
Q_t = catchment runoff rate (cfs)

WASHPO = wash-off parameter (dimensionless)

RCOEF = wash-off parameter coefficient bs/sec*$[cfs]^{-WASHPO}$)

Preliminary values suggested by the SWMM User's Manual for WASHPO and RCOEF are 2.0 and 1.0, respectively. The calibrated value for WASHPO was 1.05, while the calibrated value for RCOEF was 0.075. Calibrated values may vary from preliminary values due to the unfinished nature of portions of the study site. Preliminary values represent values for completely developed sites, while the study site was partially under construction during the study period.

Figure 4.10
Calibrated Pollutograph and Observed Values at Bioswale Inlet (2/9/99)



At the bioswale inlet, timing of the peak of the calibrated pollutograph had an error of approximately 10 minutes from the peak observed in the field. Magnitude of the calibrated peak varied from that of the observed peak by approximately 2% of the observed peak. Calibrated values of TSS varied from observed values by an average of approximately 8% of the observed values. Figure 4.10 shows the calibrated pollutograph and observed values for bioswale inlet for the 2/9/99 storm event.

In addition to the calibration of the coefficients RCOEF and WASHPO, it was also necessary to calibrate the proportion of TSS found in various particle ranges within the model. Calibration of this parameter was performed due to the unfinished nature of the bioswale. It is an effective means for modeling the effects of the presence or lack of aquatic vegetation in detention ponds and wetlands (Walker, 1990). At the time of sampling, the bioswale had recently been graded and planting was not yet completed. The soil was therefore bare and disturbed in many areas of the bioswale. This bare and disturbed soil may have become easily suspended, explaining the relatively small difference between TSS levels observed in the field at the bioswale inlet and outlet. In addition, the bare soil slopes surrounding the bioswale could have been a source of loading of suspended sediments within the bioswale. Erosion of these slopes during storm events was observed (Figure 5.2).

In order to calibrate the model to illustrate the functioning of the unfinished bioswale, the proportion of TSS found in various settling velocity ranges was altered. The P8 Urban Catchment Model (1990) provided typical values for the partitioning of TSS into various settling velocity ranges in stormwater runoff. These values were based on measurements made by the Nationwide Urban Runoff Program (U.S. EPA, 1983). The settling velocities for the various particle size ranges of TSS in stormwater runoff were based on settling column test using urban runoff (Driscoll, 1983). This parameter was calibrated by increasing the proportion of stormwater runoff TSS found in the lower settling velocity ranges, while decreasing the proportion found in the higher settling velocity ranges. By altering the settling velocity distribution of the TSS found in the stormwater runoff, the total averaged settling velocity of TSS was lowered, and the model removed less TSS from the stormwater runoff in the bioswale due to settling. This allowed for the model to more accurately predict the pollutograph for TSS leaving the unfinished bioswale. Calibration of this parameter countered the apparent resuspension or loading of TSS within the unfinished bioswale.

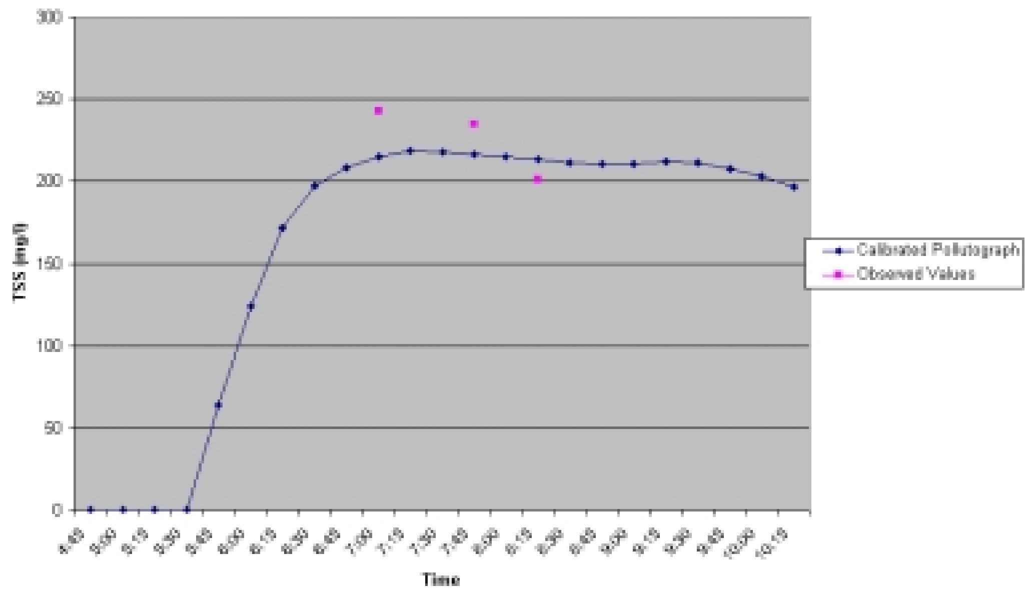
The typical settling velocity distribution of TSS in stormwater runoff, based on Nationwide Urban Runoff Program measurements (U.S. EPA, 1983), and the calibrated settling velocity distribution of TSS are shown in Table 4.5. The documented TSS settling velocity distribution was used during modeling to represent the bioswale's anticipated effectiveness in removing TSS from stormwater runoff in the future, when the bioswale's soil and vegetation have become established. The calibrated TSS settling velocity distribution was used to represent the bioswale's effectiveness during the study period.

Table 4.5
TSS Settling Velocity Distributions

TSS Settling Velocity Distribution (% by weight)		
Settling Velocity (ft/hr)	**Documented Settling Velocity Distribution**	**Calibrated Settling Velocity Distribution**
0 (Dissolved Particles)	0.0	0.0
0.00 – 0.03	20.0	40.0
0.03 – 0.30	20.0	40.0
0.30 – 1.50	20.0	15.0
1.50 – 7.00	40.0	5.0

Using the calibrated settling velocity distribution for TSS, the pollutograph generated by the model at the bioswale outlet for the 2/9/99 storm event had an error in peak time estimation of 10 minutes. The concentration of TSS at the peak of the calibrated hydrograph varied from the observed concentration by approximately 10% of the observed concentration. The average error of calibrated concentrations of TSS was 8.3% of the observed concentrations. Figure 4.11 shows the observed values and calibrated pollutograph of TSS leaving the bioswale outlet for the 2/9/99 storm event.

Figure 4.11
Calibrated Pollutograph and Observed Values at Bioswale Outlet (2/9/99)



To model removal of pollutants other than TSS, SWMM assumes the pollutants are sorbed onto TSS in stormwater runoff. This indicates that build-up rates and wash-off rates of pollutants are the same as those assigned to TSS. The only parameter to be calibrated for pollutants is the amount of pollutants present per gram of TSS. This parameter was modified until modeled pollutographs matched the values observed in the field. Pollutographs and observed values were matched by altering the calibration parameter until the best visual fit was obtained.

Copper and phosphorus were chosen for modeling because they are pollutants representative of metals and nutrients, respectively. Copper in stormwater runoff from the site was observed to be at levels that approached U.S. EPA Water Criteria Toxicity Levels (Table 5.4). Total Petroleum Hydrocarbons were also originally planned for modeling, but were not detected in runoff from the study site.

Analytical laboratory results for copper and phosphorus samples collected in the field were provided as dissolved copper and phosphate. Since SWMM provides no mechanism for the removal of dissolved pollutants from stormwater runoff, values for dissolved copper and phosphate were converted to total copper and phosphorus values for calibration purposes. In stormwater runoff, a typical value for the dissolved fraction of copper is 40% by weight (Walker, 1990). A typical value for the dissolved fraction of phosphorus is 30% by weight (Walker, 1990). For calibration purposes, the other 60% of copper and 70% of phosphorus were assumed to be particulate and sorbed onto TSS. Analytical laboratory results for the dissolved fractions of copper and lead were used to derive the concentrations of the particulate fractions of copper and phosphorus in the stormwater runoff. These values were then used for calibration purposes.

The amount of copper and phosphorus present per gram of TSS built-up was the parameter used for the calibration of the pollutants. The SWMM User's Manual provided typical values, in milligrams of copper or phosphorous per gram of TSS. The values were then calibrated until the resulting pollutograph matched observed values by visual fitting. The calibrated value for copper is 0.17 mg per g of TSS. The calibrated value for phosphorous is 39 milligrams per gram of TSS.

The 2/9/99 data set was used to calibrate copper and phosphorous. This data set was used because it is representative of runoff from the whole project site in its present state, and includes data for both the inlet and outlet of the bioswale. Table 4.6 shows the level of error of the calibrated pollutographs for both copper and phosphorous for the bioswale inlet on 2/9/99. Figures 4.12 and 4.13 show calibrated pollutographs and estimated field values of copper and phosphorous for the bioswale inlet on 2/9/99.

Figure 4.12
Calibrated Pollutograph and Estimated Field Values for Copper at Bioswale Inlet (2/9/99)

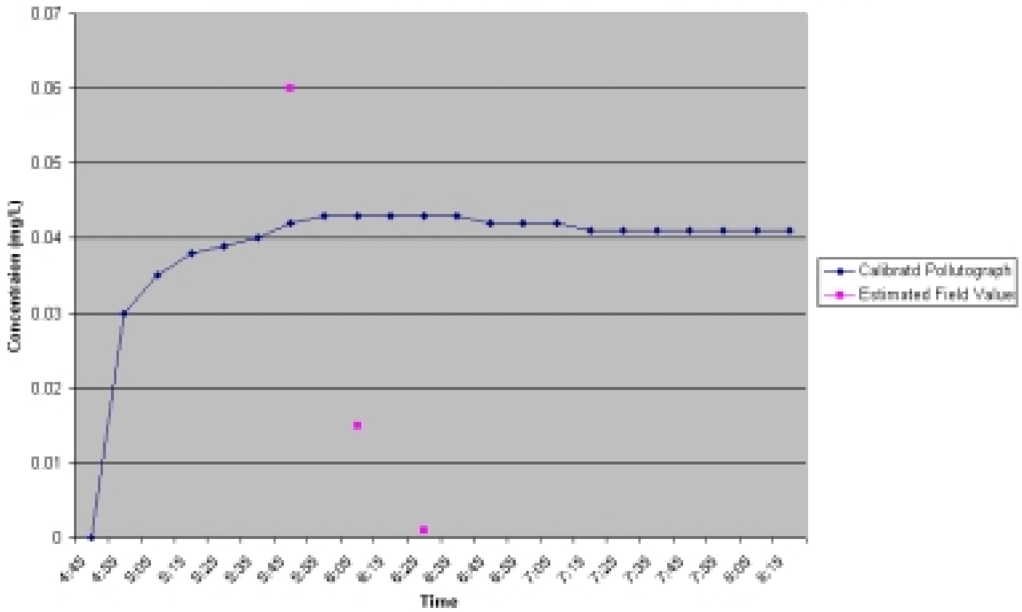


Figure 4.13
Calibrated Pollutograph and Estimated Field Values for Phosphorous at Bioswale Inlet (2/9/99)

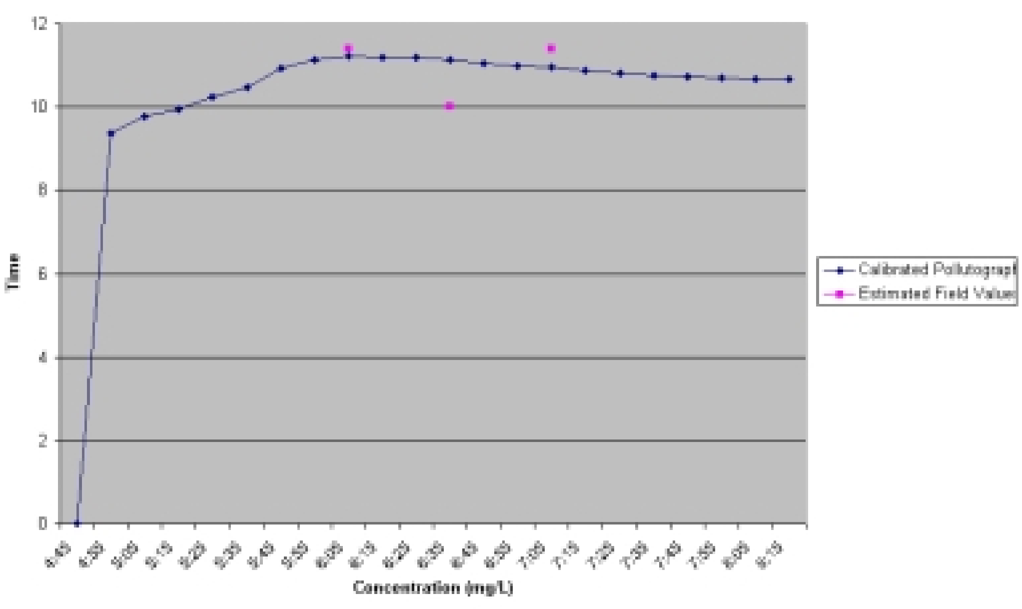


Table 4.6
Error Between Calibrated Pollutographs and Estimated Field Values for Copper and Phosphorous (2/9/99)

		Peak Timing Error (Minutes)	Peak Magnitude Error (%)	Average Error (%)
Bioswale Inlet	Copper	20	28	107
	Phosphorous	0	1	6

Calibration of copper and phosphorous pollutographs for the bioswale outlet was not performed. Laboratory analysis of collected field samples provided data for the dissolved fraction of copper and phosphorus. It is not expected that the dissolved fraction of pollutants will be removed by the bioswale (U.S. EPA, 1983). Measured concentrations of dissolved fractions of copper and phosphorus at the bioswale outlet could therefore not be used to estimate the concentrations of the non-dissolved fractions of copper and phosphorus at the bioswale outlet. Without concentrations of non-dissolved copper and phosphorus, bioswale outlet concentrations of these pollutants could not be calibrated. Additionally, unlike TSS, the unfinished bioswale is not seen as a potential source of copper and phosphorus. For this reason, calibration of the bioswale's removal of non-dissolved copper and phosphorus should not be necessary. Calibration of the settling velocity distributions of copper and phosphorous was therefore not conducted to simulate the bioswale's removal of these pollutants.

Modeled pollutographs and total loads of copper and phosphorous should only be considered for qualitative assessment. Calibration for these pollutants was based on estimated field values and the level of error in their calibration is high. Model runs of these pollutants should prove useful in the qualitative assessment of the effectiveness of the bioswale in removing these pollutants from stormwater runoff.

4.7 Modeling Results

Once SWMM was calibrated, it was possible to run storms of different magnitude through the model to determine the expected effectiveness of the bioswale under storm conditions not observed in the field. It was also possible to make modifications to the bioswale design within the model to discern if any improvements could be made in its ability to affect runoff hydrographs and remove pollutants.

TSS was the primary pollutant that was run through the bioswale and the natural area during modeling. TSS was used in most scenarios because it has a settling velocity that is faster than any of the other pollutants included in this study. Since the settling of pollutants is the primary removal mechanism of the bioswale, total suspended solids should indicate a more drastic change in pollutant removal efficiency, thereby making it easier to discern whether or not a modification in the bioswale would prove it to be more or less effective.

It was not possible to study the bioswale with its designed pollutant removal capability. During the period of this study, the bioswale had been recently constructed. The soil of the bioswale and its surrounding slopes was disturbed, and the vegetation within the bioswale had not yet become established. As a result, the bioswale had not reached its full potential in removing pollutants from stormwater runoff. The slopes of the unfinished bioswale may even have been a source of TSS due to observed erosion (Figure 5.2).

While modeling runs with calibrated TSS removal parameters were performed, other modeling runs were conducted without calibrated TSS removal parameters. Uncalibrated TSS removal parameters utilized documented settling velocity distributions for TSS in stormwater runoff. These settling velocity distributions were obtained from the P8 Urban Catchment Model (Walker, 1990) and are based on measurements made by the Nationwide Urban Runoff Program (U.S. EPA, 1983). It is believed that these modeling runs will better represent the bioswale's effectiveness in the future, when vegetation has become fully established. The documented settling velocity distributions for TSS provide for quicker overall settling of the TSS load, leading to more TSS being removed by the bioswale. This is the anticipated condition when the bioswale's soil and vegetation become established. Vegetation can increase particle removal rates by increasing the effective surface area for settling, stabilizing bottom sediments, and/or through biological mechanisms (Walker, 1990).

Copper and phosphorous were also modeled for several storm events. Calibrated parameter values were used for modeling the washoff of these pollutants. These parameter values are the same values as those calibrated for washoff of TSS, as the pollutants are treated within SWMM as being sorbed to TSS particles. However, unlike for TSS, the bioswale was not anticipated to be a source of copper and phosphorus. For this reason, use of calibrated settling velocity distributions for the pollutants was not necessary (see Section 4.6.2 for further discussion). The proportion of the pollutants sorbed to various particle size ranges of TSS did not need to be altered in order to simulate the present functioning of the bioswale. Parameter values used for copper and phosphorus are therefore believed to represent the behavior of the pollutants in the bioswale at present and in the future.

A number of different storms were modeled for the bioswale and natural area without the orifice plate to indicate their effectiveness in both small and large storms. Most scenarios were not modeled with the orifice plate in place because we recommend that it be removed to increase bioswale performance (Section 3.0). It is assumed that the plate will be removed, as it is a relatively simple operation that will greatly improve the effectiveness of the bioswale. In addition, SWMM was not capable of modeling reverse pressure gradient conditions within the bioswale. These conditions occurred during large storms due to the presence of the orifice plate. Simulation of large storm events could therefore not be conducted with the orifice plate in place.

One small storm was modeled with the orifice plate in place, however, to exhibit the present operation of the bioswale. This scenario also shows the benefit of the removal of the orifice plate (Table 4.7). For a relatively small design storm of 0.15 in/hr over two hours, the model indicated that the bioswale and natural area's effectiveness in reducing the TSS loads leaving the site increased by 2-6% with the orifice plate removed. This was due to the increase in the amount of flow routed to the bioswale with the orifice plate removed. The percent of flow from the site treated by the bioswale increased from 50% to 84% without the orifice plate in place. The difference in the amount of water treated by the bioswale with and without the orifice plate increases as the magnitude of storm increases. Impacts of the removal of the orifice plate are also discussed in Section 3.0.

Table 4.7
Comparison of Bioswale Functioning With and Without Orifice Plate

0.15 in/hr 2 hour storm		**Total Flow Received (cu. ft.)**	**TSS Removal** with anticipated bioswale performance (Documented TSS Settling Velocity Distribution)	**TSS Removal** with present bioswale performance (Calibrated TSS Settling Velocity Distribution)
With Orifice Plate	Bioswale by itself	32,780	31%	17%
	Bioswale and the natural area	66,057	73%	42%
Without Orifice Plate	Bioswale by itself	56,910	46%	21%
	Bioswale and the natural area	67,890	79%	44%

Table 4.8 lists the efficiency of the bioswale in removing pollutants from the stormwater runoff for four design storm events. The values used in the table do

not account for water diverted around the bioswale by the splitter structure. Only water reaching the bioswale was considered.

Table 4.8
Removal Efficiencies of the Bioswale

	Constituent	0.03 in/hr, 2 hr Storm	0.15in/hr, 2 hr Storm	2 yr, 2 hr Storm	10 yr, 2 hr Storm
TSS with present bioswale performance (Calibrated Settling Velocity Distribution**)**	TSS Received (lbs)	43	1039	3568	5207
	TSS Removed (lbs)	33	266	553	685
	% TSS Removed	77%	26%	15%	13%
TSS with anticipated bioswale performance (Documented Settling Velocity Distribution**)**	TSS Received (lbs)	43	1039	3568	5207
	TSS Removed (lbs)	37	600	1750	2413
	% TSS Removed	86%	58%	49%	46%
Copper	Copper Received (lbs)	0.007	0.16	0.5	0.8
	Copper Removed (lbs)	0.005	0.05	0.09	0.1
	% Copper Removed	71%	31%	18%	13%
Phosphorus	Phosphorus Received (lbs)	1.7	40	256	578
	Phosphorus Removed (lbs)	1.4	14	39	71
	% Phosphorus Removed	82%	35%	15%	12%

As the table exhibits, the bioswale is effective in its removal of TSS and pollutants for very small storms (0.03 in/hr), retaining 71–86% of the pollutants it receives. This is to be expected, as the bioswale was designed to control pollutants associated with the relatively low flow conditions found during first flush situations. The effectiveness of the bioswale decreases as flows increase.

From Table 4.8, it is observed that bioswales have the potential to significantly reduce TSS and pollutant loads leaving a developed site, particularly for small storm events. Developed areas could benefit from their application, especially in areas with no other means of runoff control. The effectiveness of bioswales is somewhat dependent upon their capacity to receive and retain flows, however.

Bioswales are limited in the amount of water they can process. Within the frame of runoff from a large area, their impact may be relatively small, depending upon the size of the bioswale. In addition, other means for reducing TSS and pollutants in stormwater runoff may already be in place.

Table 4.9 addresses the above issues. It shows the modeled percentages of TSS and pollutants that were removed by the bioswale and natural area. Percentages provided in the table indicate the percentage that was removed of a total load generated by the study site. To determine the percentage of a constituent that was removed by the natural area by itself, the bioswale was assumed not to exist. Within the model the bioswale was replaced by a playing field, and all flows from the study site were routed directly to the natural area. This modeled scenario represents the study site's stormwater runoff conditions if the bioswale had not been constructed.

Table 4.9
Removal Efficiencies of the Bioswale and Natural Area in Percentage of TSS Generated by the Study Site

	Location	**TSS Removal** with anticipated bioswale performance (documented settling velocity distribution**)**	**TSS Removal** with present bioswale performance (calibrated settling velocity distribution**)**	**Copper Removal**	**Phosphorous Removal**
10 year, 2 hour storm	Bioswale by itself	18%	4%	4%	4%
	Bioswale and Natural Area	55%	16%	16%	16%
	Natural Area by itself	47%	12%	ND	ND
2 year, 2 hour storm	Bioswale by itself	25%	8%	8%	8%
	Bioswale and Natural Area	61%	21%	22%	22%
	Natural Area by itself	48%	14%	ND	ND
0.15 in/hr, 2 hour storm	Bioswale by itself	46%	21%	24%	24%
	Bioswale and Natural Area	79%	44%	51%	51%
	Natural Area by itself	60%	27%	ND	ND
0.03 in/hr, 2 hour storm	Bioswale by itself	73%	63%	67%	67%
	Bioswale and Natural Area	98%	92%	94%	94%
	Natural Area by itself	88%	77%	ND	ND

ND = Not Determined

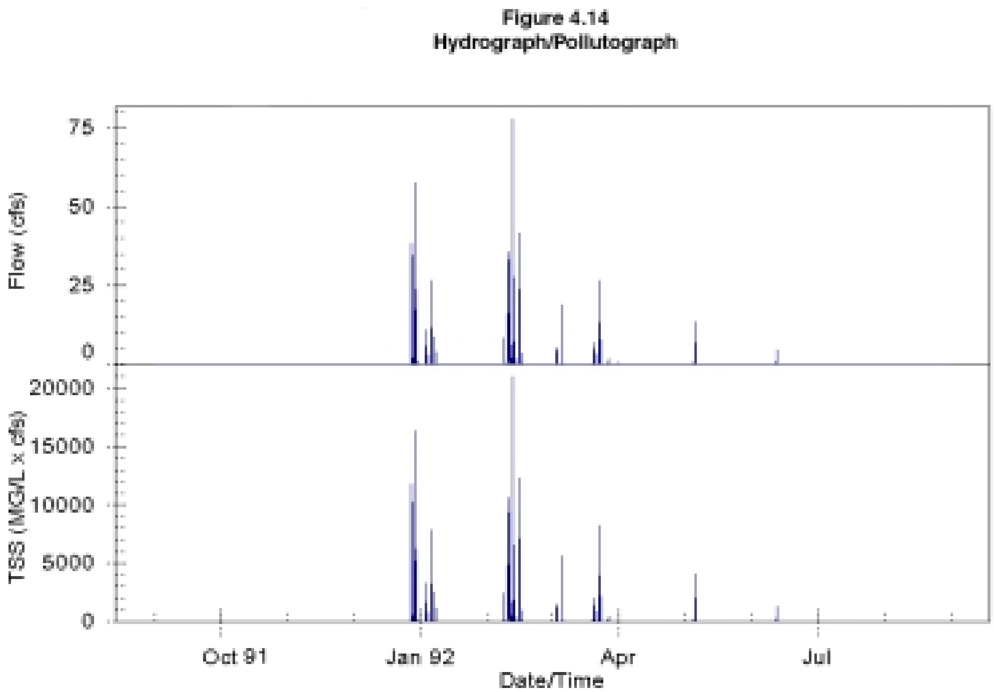
As summarized in Table 4.9, the model indicates that the natural area, because of its larger area, lower gradient, and thicker vegetation, is a more effective mechanism for the removal of TSS than the bioswale in its current, unvegetated state. This holds true even when documented settling velocity distributions for TSS are used within the model to simulate the bioswale's future functioning. The model also indicates that the natural area is almost as effective at removing TSS by itself as when it is coupled with the bioswale. For example, for a 2-hour, 10-year design storm, the model indicates that the natural area would remove 47% of the total TSS load generated on site assuming documented TSS settling velocity distributions. With the bioswale in place, however, the natural area and bioswale remove 55% of the total TSS load; an increase of 8%. The bioswale's effectiveness improves as storm intensity decreases, with the model indicating that its best performance is an increase in the removal efficiency of the site of 17-19% for documented and calibrated settling velocities, for a 2-hour 0.15 in/hr storm. The model indicates that the bioswale improves the overall removal of TSS by about 4-19% of the total load generated by the study site. It has a similar effect on the pollutants copper and phosphorous.

The natural area is almost as effective in reducing TSS loads by itself as it is when coupled with the bioswale, particularly for larger storm events. Modeling indicates that the bioswale improves removal efficiencies up to 19%. If the natural area is valued as a habitat that needs protection from stormwater runoff, however, the bioswale will significantly reduce the loading to the natural area. For example, even for a 10-year storm event the bioswale would reduce loading of TSS to the natural area by up to 18%.

The bioswale’s ability to reduce the peak flow leaving the natural area in large storms is minimal. A two-hour, 10 -year storm was run in SWMM to determine the effectiveness of the bioswale in reducing peak flows. By the time the 2-hour, 10-year storm peaks in magnitude, the bioswale is close to a steady state.

Therefore, the timing of the peak flow to the natural area is similar whether or not the bioswale is present. Thus, the timing of flow leaving the natural area will be about the same as well. The results from SWMM simulation indicate that with the bioswale, the peak flow leaving the natural area will be reduced by approximately ten percent for this design storm.

SWMM was also used to run a continuous simulation for the bioswale and study site. Hourly rainfall data for the rain year of 1992 from Santa Barbara County's Santa Barbara Road Yard rain gauge was used for this simulation. Rainfall data for this year was used because it is similar in magnitude to an average year of rainfall for the Santa Barbara area. 1992 received 18.94 inches of rain, while the average annual rainfall for the Santa Barbara Road Yard gauge is 17.06 inches. A hydrograph and pollutograph for TSS for the simulation are shown in Figure 4.14. This simulation was run to predict the sedimentation of the bioswale forebay. The model indicates that for the rain year of 1992, 70,100 lbs of TSS would enter the bioswale forebay, with 12,700 lbs remaining in the forebay. A bulk density range of 1200-1500 kg/m^3 (Brady and Weil, 1996) was used to determine the volume of this sediment within the forebay. Assuming an annual influx of this volume of sediment, it was calculated that the pipes draining the forebay would begin to clog with sediment in approximately 3.9-4.8 years. It is estimated that the pipes would be completely covered with sediment in 7.7-9.6 years.



In an attempt to determine if a modification in the bioswale design could improve its removal efficiencies, two other scenarios were modeled. In the first scenario the area of the forebay was doubled, and the backbay was reduced by an appropriate amount so the overall space that the bioswale occupied did not change. It was thought that this might improve the bioswale removal efficiency, as an increase in the size of the forebay would give pollutants more time to settle out in this region. The second scenario modeled was a design bioswale recommended by the King County Surface Water Design Manual (1997). Table 4.10 illustrates the effectiveness of only the bioswales in these two scenarios. Removal percentages are for total loads of TSS generated by the study site, including TSS bypassed around the bioswale and TSS routed directly to the natural area.

Table 4.10
Removal Efficiency of the Bioswale in Percentage of TSS Generated by the Study Site

	Design Storm	**TSS Removal** with anticipated bioswale performance (documented settling velocity distribution**)**	**TSS Removal** with present bioswale performance (calibrated settling velocity distribution**)**
Forebay Doubled	0.15 in/hr, 2 hour storm	55%	30%
	2 year, 2 hour storm	27%	10%
King County Bioswale	0.15 in/hr, 2 hour storm	54%	27%
	2 year, 2 hour storm	30%	13%

According to SWMM, a doubling of the forebay will increase the bioswale's ability to remove TSS fairly significantly in small rain events, but in the case of a heavier rain event a larger forebay will do very little to augment TSS removal. For a 2-hour 0.15 in/hr storm, doubling of the forebay increased the percent of the total load of TSS removed by the bioswale from 46% to 55% for documented TSS settling velocity distribution, and from 21% to 30% for calibrated TSS settling velocity distribution. For a 2-hour 2-year storm, the larger forebay only improved from 25% to 27% removal for documented TSS settling velocities, and from 8% to 10% removal for calibrated TSS settling velocities. In a heavy storm the forebay will discharge rather rapidly to the backbay and its increased storage capacity will have little effect on pollutant removal. However, in the case of small rain events, the extended capacity of forebay allows for more settling time within the bioswale, thereby increasing its effectiveness.

The King County scenario utilized a bioswale 2.4 times the size of the Camino Real bioswale. This size of bioswale is recommended by the King County Surface Water Design Manual (1997), based on 60% of the peak flow from the study site for a 2-year, 2-hour storm. The manual provides recommended sizes for bioswales based on the value of 60% of the peak flow for a 2-year, 2-hour storm event. The King County bioswale removes about the same amount as the bioswale currently in place in small storms, yet in larger storms it proved to be more effective. It was thought that the King County bioswale would be much more effective in both large and small storms as it required more than twice the surface area that the present bioswale occupies. The King County bioswale was designed as one detention basin without a forebay. The results obtained from this model run further confirm that dividing the detention basin into two components will increase its ability to remove pollutants in smaller rain events. For example, increasing the size of the bioswale by 2.4 times did not improve the effectiveness of the bioswale as much as doubling the forebay size for smaller storms. For larger storms, the King County bioswale's effectiveness improved, but at the expense of using a larger area. Including a forebay to the King county bioswale should make it even more effective for both large and small storms.

5.0 Chemical Processes

This section provides chemical information that supports the evaluation of pollutant processes that will occur in the bioswale, including degradation, volatilization, and the transport & fate of pollutants. While the Bioswale Group Project did not perform detailed analyses of these processes, it is important to remember how the chemical information generated by this study can be used to evaluate the long-term performance and significance of the bioswale. Section 5.1 presents a review of common pollutants in stormwater runoff. The group selected four of the eight major categories for sampling during the study. Section 5.2 explains the sampling regime and describes the chemical analyses that were performed on stormwater samples collected at the Camino Real bioswale. Section 5.3 summarizes the chemical sampling results for the four rain events sampled by the group during the course of the study. Section 5.4 discusses the significance of the chemical results in relation to established water and sediment quality criteria. Section 5.5 completes the chemical processes section with an overview of the transport and fate of contaminants at Camino Real.

5.1 Pollutants in Stormwater Runoff

The investigation of chemical processes in the bioswale required research on the types of pollutants commonly found in stormwater runoff and why they are of concern. A large source of information was the final report of the Nationwide Urban Runoff Program (NURP), a study conducted by the US Environmental Protection Agency (U.S. EPA, 1983) over a five year period during the late 1970s and early 1980s. This study listed the prevalence of pollutants from several major categories, including solids, nutrients, oxygen-consuming constituents, and heavy metals. Other pollutants of concern include hydrocarbons, pesticides and herbicides, bacteria, and floatable debris. The scope and time frame of the bioswale group project did not allow for sampling and analyses of all the pollutant types listed below. The discussion below illustrates the wide range of pollutants that are stormwater pollutant concerns, potential sources at Camino Real, and the eventual impacts these pollutants may have on the environment. It is important to note that the natural area acts in conjunction with the bioswale to filter pollutants, and plays a key role in reducing the amount of contamination that exits the development site. The discussion addresses potential aquatic environmental impacts because all runoff eventually reaches Devereux Slough, a coastal estuary.

5.1.1 Sediment

Potential sediment sources at Camino Real include erosion of landscaped areas, deposition of dust, and sediment from open areas that drain to the site. Physical effects of sediment on aquatic plants and animals can include: 1) reduction of light penetration in the water column, which interferes with visual feeding and photosynthesis, 2) particulates clog gills and filter systems in aquatic organisms which may result in retarded growth, systemic dysfunction, and asphyxiation in extreme cases, and 3) sediment deposition on bottom-dwelling organisms which reduces juvenile habitat and interferes with egg deposition and hatching (U.S. EPA, 1983). Chemical effects of sediment in stormwater are related to the effects of associated nutrients, metals, and hydrocarbons that are attached to sediment particles.

5.1.2 Nutrients

Sources of nutrients at Camino Real may include fertilizer application on landscaped areas and playfields and organic debris such as leaves and grass clippings. Although nutrients such as nitrogen and phosphorus are essential for life, adverse effects may occur when they are present in excess amounts in aquatic ecosystems. Inputs of nitrogen or phosphorus from fertilizers, both agricultural and domestic, can increase the amount of nutrients in an aquatic system. Algal blooms may occur and reduce light penetration in the water column, thus causing larger submerged aquatic vegetation to die and reduce habitat for aquatic animals. When algae and other aquatic vegetation die, dissolved oxygen is utilized during the decomposition process and the amount of oxygen available for aquatic organisms is reduced.

Phosphorus is often associated with sediment in agricultural and urban runoff, with 40 to 80% of the total phosphorus in the particulate form (Ng, *et al.*, 1993). Because particulate phosphorus is less bioavailable than dissolved phosphorus, burial and sequestration of phosphorus occurs at high rates of sedimentation. Even after deposition, however, sediment may be disturbed through bioturbation, storms, or flooding, thus releasing nutrients into the water column where they may again be available for biological growth (Mueller, *et al.*, 1995).

5.1.3 Metals

Sources of metals at Camino Real are primarily from cars (copper and zinc from brake pad dust). Many metals are essential to life in small amounts. High levels of exposure can lead to death, and lower levels can produce a variety of sub-lethal effects. An important consideration in the assessment of potential toxicity from metals in stormwater is related to the bioavailability of these metals (Moffa, 1996). In general only the dissolved form of heavy metals is toxic, and the high levels of suspended solids in stormwater tend to bind with most available metals, thus rendering them inactive. Copper and zinc in urban runoff have typical soluble fractions of about 50 percent, whereas lead has a typical soluble fraction of 10 percent or less (U.S. EPA, 1983). Metals bound to sediment particles may later desorb into the water column or surrounding sediments and become bioavailable. This process leads to the possibility for ongoing problems related to the presence of metals in the environment, in particular the Devereux Slough and its aquatic inhabitants.

5.1.4 Hydrocarbons

Hydrocarbon sources at Camino Real include crankcase oil, brake fluid, and gasoline leaking from automobiles, as well as from the two nearby gas stations. Most work on the effects of hydrocarbons on aquatic life has been conducted relative to major oil spills (Stenstrom, *et al.*, 1984). The form and amount of hydrocarbons in the urban environment is substantially different from those observed during oil spill events and, subsequently, have different effects on the environment. A study in San Francisco Bay (Whipple, *et al.*, 1981) observed that the accumulation of monoaromatic hydrocarbons in fish tissues may be a contributing factor to the decline of striped bass populations. The association of hydrocarbons with suspended sediments in stormwater runoff has been established for high molecular weight polycyclic aromatic hydrocarbons (PAHs) which have low water solubility (Makepeace, *et al.*, 1995). Accumulation of hydrocarbons in bottom sediments of lakes and estuaries may exert adverse impacts on benthic organisms, but few toxicity tests have been performed to examine the effect of urban runoff hydrocarbon loads under typical exposure conditions found in urban areas (Dennison, 1996).

5.1.5 Pesticides and Herbicides

Sources of pesticides and herbicides at Camino Real include lawn care products. While pesticides and herbicides may be detected in urban runoff, the number of constituents detected is usually low and most often at levels below analysis detection limits (EOA, 1996). Many laboratory studies have determined experimental toxicity levels for various pesticides and herbicides, but less is known about environmental effects on aquatic organisms. Analysis of herbicides and pesticides is expensive, and potential for contamination of field samples is high, so that routine testing of stormwater samples for these compounds is not recommended.

5.1.6 Oxygen-Demanding Substances

When organic matter in water decomposes, dissolved oxygen levels become depleted, particularly in lakes, estuaries, or slow-moving streams (Dennison, 1996). Measures of oxygen-demanding substances include the Biological Oxygen Demand (BOD_5) test, which measures the amount of oxygen consumed during biochemical oxidation of matter in an enclosed water sample over a 5-day period. Depleted levels of dissolved oxygen will adversely affect respiration of aquatic organisms. Problems associated with oxygen-demanding substances are most prevalent in older urban areas, where storm runoff can mix with overflows from sanitary sewers.

5.1.7 Bacteria

It is common for bacteria levels in undiluted urban runoff to exceed federal public health standards for water contact recreation and shellfish harvesting (Dennison, 1996). Potential sources of bacterial contamination (in the known absence of contamination from sanitary sewage systems) may include sources such as animal excrement and leaking septic tanks. These sources are not commonly associated with human health risk, and it is suggested that fecal coliform may not be consistently reliable in identifying human health risks from urban runoff pollutants (Moffa, 1990). Even so, bacterial contamination often has the most widespread public exposure due to its immediate environmental consequences (beach closures and shellfish harvest restrictions). It is therefore an important contaminant because it can promote public dialogue about the necessity for stormwater pollution prevention and treatment.

5.1.8 Floatable Debris

Floatable debris in stormwater runoff may include plastic, paper, tires, and glass and metal containers. Vegetation in receiving waters may be adversely affected by debris that prevents or slows its establishment. Larger aquatic organisms are also adversely affected due to ingestion or entanglement with the debris. Finally, aesthetics may be severely impacted in receiving waters and along riverbanks and shorelines (Dennison, 1996).

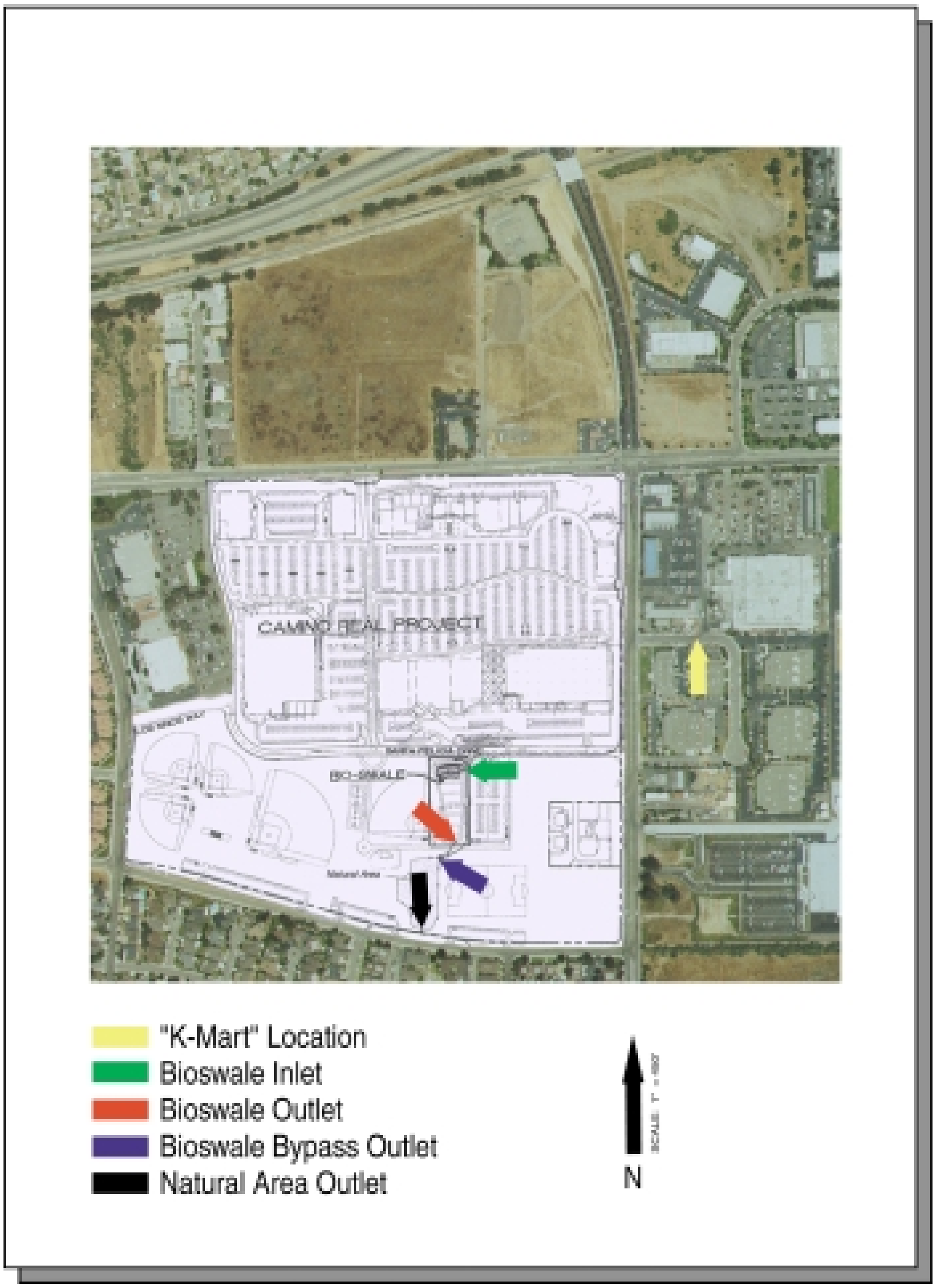
5.2 Sampling Regime and Chemical Analysis of Stormwater at the Camino Real Bioswale

Our hypothesis was that for a given amount of stormwater runoff originating from the project site, the bioswale and natural area would reduce the amount of pollutants that would otherwise reach Devereux Slough through settling of sediments and filtration. In order to test this hypothesis, the group collected stormwater samples for analysis of pollutants that may have a detrimental impact on Devereux Slough. The collection of stormwater data also supported calibration of the Storm Water Management Model (SWMM). The group did not propose to quantitatively investigate plant uptake of pollutants because, although the bioswale structure was completed in the middle of December, 1998, the vegetation was not yet well established and minimal uptake was expected to occur within the short time frame designated for this project (Mazer, 1998). We determined that suspended solids, nutrients (nitrate and nitrite, ammonia, phosphate), dissolved metals (zinc, copper, lead), and hydrocarbons (total petroleum hydrocarbons) would be an adequate, achievable list of sampling objectives addressing the major areas of concern about stormwater runoff pollutants. The group also collected a composite sediment sample from the forebay of the bioswale to establish baseline metals, phosphorus, and hydrocarbon information.

For each storm event, the group collected three samples per sampling location for each sample parameter. The three locations at which the group collected samples were at the inlet and outlet of the bioswale, as well as the outlet of the natural area at the southern end of the project site (Figure 5.1). The sample locations were chosen to provide data to answer the group's hypothesis regarding the improvement of water quality routed through the bioswale, as well as the relative effect of the bioswale on water quality in runoff generated within the developed area's watershed. Pollutant concentrations obtained from samples taken at the inlet and outlet of the bioswale were analyzed to determine if and to what extent the bioswale reduced pollutant concentrations of stormwater routed through the bioswale. Pollutant concentrations obtained from samples collected at the outlet of the natural area were compared to bioswale samples to determine the extent of the bioswale's impact on runoff leaving the entire project site.

During the course of any individual rain event, the critical time period for sample collection is the "first flush" which occurs within the first 10 to 60 minutes, depending upon rainfall intensity of the storm event. The first flush contains the majority of the pollutants in the stormwater runoff generated during the rain event (Line, *et al.*, 1997). Samples collected several hours after the rain begins are not representative of the total concentrations of pollutants contained in the stormwater runoff. Several samples must be collected during the rain event in order to calculate Event Mean Concentration values (U.S. EPA, 1983). The bioswale group project therefore collected three samples at each location for each storm event. The first set of samples was collected at the inlet to the bioswale 10 minutes after runoff was first observed at this location. The next two samples at this location were collected at thirty-minute intervals. This allowed for the "first flush" to be represented in the sampling.

Figure 5.1
Stormwater Sampling Locations



The time of collection for the first sample at the bioswale outlet was determined using the detention time of water routed through the bioswale during the storm event. Detention times were calculated based on flow estimates obtained in the field during the storm event. For example, if the detention time was determined to be 15 minutes, the first sample collected at the bioswale outlet was collected 15 minutes after the first sample was collected at the bioswale inlet.

The bioswale group project collected stormwater samples for four rain events. The first set of samples was collected on 11/7/98. Because the bioswale was not yet completed and flow was not being routed through the structure, the group collected runoff samples from the K-Mart parking lot (Figure 5.1). Runoff collected from this area is routed through the completed bioswale, and was expected to represent typical first flush concentrations of stormwater runoff from the first major rain event of the season after several months of pollutant loading. The next rain event the group attempted to sample occurred on 1/19/99, but the group discovered that although the structure was completed, stormwater runoff was not yet being routed through the bioswale and so could not collect stormwater samples. Just before the beginning of this rain event, the group collected a composite sediment sample from the forebay of the bioswale to establish baseline soil conditions prior to any additional loading (the sample was analyzed for total petroleum hydrocarbons, total phosphorus, and trace metals).

The other three sampling events occurred in January and February 1999 (Table 5.1), with the length of time between each storm event varying, thus affecting the amount of pollutant loading. In Table 5.1, total rainfall is the amount of rain occurring in each rain event, and does not represent only the amount of rainfall during sampling. Each time a sample was collected, water heights were also measured in order to establish flow discharge necessary for the calculation of pollutant Event Mean Concentrations (EMCs), a flow-weighted measure of pollutant concentration for a given storm event.

Table 5.1
Date, Location and Total Rainfall of Each Sampling Event

Date	Location	Rainfall (inches)
November 7, 1998	K-Mart Parking Lot	0.32
January 24, 1999	Bioswale	0.24
January 31, 1999	Bioswale	0.47
February 9, 1999	Bioswale	0.70

All samples were collected in polyethylene containers (for nutrients, metals, and total suspended solids) or amber glass bottles (for total petroleum hydrocarbons) and refrigerated before being transported to the analytical laboratory in iced coolers. All analyses were conducted according to standard EPA methods as outlined in Standard Methods (Clesceri, 1989). The project developer, Wynmark Company, provided a portion of funding for analyses. Additional grant funds from the University of California Toxic Substances Research and Teaching Program, Coastal Component were used to purchase supplies and laboratory analysis services for a portion of our field sampling efforts.

It is important to note that at the time of all sample collection, the bioswale structure was complete but vegetation throughout the structure had not been established. While the primary treatment process for pollutant removal in the bioswale is gravitational settling and removal of particulates, vegetation is expected to provide additional physical filtration of stormwater and dissolved pollutant uptake. The following chemical sampling results are therefore considered a preliminary data set that does not completely reflect all the processes the bioswale and its plants will eventually exert on stormwater runoff.

5.3 Chemical Sampling Results

Results of chemical analyses of stormwater samples collected at K-Mart on 11/7/98 are presented in Table 5.2. Total dissolved solids and chloride were not routinely measured for every sampling event of this project, but are included here to provide potential levels of contaminant loading prior to the first major rain event of the winter season.

Table 5.2

Summary of Event Mean Concentration (EMC) Values (milligrams per liter) for Selected Pollutants of Samples Collected at the K-Mart Location.

Date	Pollutant	EMC (mg/L)
11/7/98	TPH	6
"	Total P as Phosphate	30
"	Nitrate + Nitrite	3
"	Lead	0
"	Total Suspended Solids	24
"	Total Dissolved Solids	1209
"	Chloride	329

EMCs for nutrients, total suspended solids, and dissolved metals are summarized in Table 5.3. No samples were collected for analysis from the outlet of the natural area on 1/31/99, because the rain event was too small to generate flow through the entire system. Flow measurements are summarized for each sampling event in Appendix D.

Table 5.3

Summary of Event Mean Concentration (EMC) Values (milligrams per liter) for Selected Pollutants for Three Rain Events.

Date	Pollutant	Bioswale Inlet	Bioswale Outlet	Natural Area Outlet
1/24/99	Total Petroleum Hydrocarbons	nd	nd	nd
1/31/99		NM	NM	NM
2/9/99		nd	nd	nd
1/24/99	Total P as Phosphate	NM	NM	NM
1/31/99		12	7	NM
2/9/99		5	6	5
1/24/99	Nitrate + Nitrite (NO3-N +NO2-N)	nd	nd	nd
1/31/99		70	50	NM
2/9/99		17	24	18
1/24/99	Ammonia (NH3-N)	NM	NM	NM
1/31/99		157	132	NM
2/9/99		130	124	132
1/24/99	Copper (dissolved)	nd	nd	nd
1/31/99		0.01	0.01	NM
2/9/99		0.02	0.00	nd
1/24/99	Lead (dissolved)	NM	NM	NM
1/31/99		0.10	0.03	NM
2/9/99		nd	nd	nd
1/24/99	Zinc (dissolved)	nd	nd	nd
1/31/99		0.042	0.031	NM
2/9/99		0.019	0.023	0.010
1/24/99	Total Suspended Solids	28	47	22
1/31/99		346	495	NM
2/9/99		269	233	219

nd = not detected
NM = not measured

5.4 Discussion of Chemical Results

Results for all field sampling conducted during the course of this group project are preliminary. Interpretation of water quality field data is necessarily cautious when based on only a few sampling events that had variable rain intensities and different periods of pollutant loading prior to rain events. Similar cautions apply to the soil analysis results that are presented for a single composite soil sample.

Several samples collected on 1/31/99 demonstrated apparent differences in Event Mean Concentrations between the bioswale inlet and outlet. Total phosphorus, nitrate plus nitrite, ammonia, lead, and zinc all appeared to have decreased in samples collected at the bioswale outlet, while total suspended solids appeared to have increased relative to inlet concentrations. For samples collected on 2/9/99, nitrate plus nitrite and total suspended solids appeared to have decreased at the outlet compared to their inlet concentrations. A Student's t-test revealed, however, that none of the differences in Event Mean Concentration were statistically significant (Table 5.4). In no case would we reject the null hypothesis (H_0) that the means are equal. This result is not unexpected because the low number of samples results in low degrees of freedom. According to this statistical analysis, the apparent decreases in pollutant concentrations cannot be attributed to bioswale processes, but rather are interpreted as the variability between individual sample results at any given sample location.

Table 5.4

Summary of Student's t-test of Apparent Differences in Event Mean Concentrations for Samples from Bioswale Inlet and Outlet (Samuels, 1986)

Date	Parameter	n	d.f.	p(0.05)	t-statistic	Reject H_0?
1/31/99	Total P	4	3	3.182	2.192	no
	$NO_3 + NO_2$	4	3	3.182	2.805	no
	NH_3	4	3	3.182	1.471	no
	Lead	4	3	3.182	0.084	no
	Zinc	4	3	3.182	0.012	no
	TSS	4	3	3.182	-1.211	no
2/9/99	$NO_3 + NO_2$	3	2	4.303	-2.817	no
	TSS	3	2	4.303	1.882	no

5.4.1 Water Quality Criteria

Table 5.5 summarizes water quality criteria for pollutants addressed in this study, as established by the U.S. EPA (1986). Some criteria have specific numerical values, while others are narrative. Quality criteria are presented for both marine and freshwater environments. Devereux Slough is usually brackish, with freshwater inputs being modified by seasonal inputs of seawater when the slough opens to the ocean (de la Garza and Ryan, 1998). The bioswale group project did not address specific potential impacts on aquatic inhabitants of Devereux Slough. de la Garza and Ryan (1998) asserted that concentrations of stormwater pollutants could potentially exceed the EPA criteria for high end estimations of pollutant loading. Their high-end estimates of pollutant loading did not account for the stormwater management measures installed at Camino Real that reduce pollutant loads between their sources and their ultimate destination in Devereux Slough.

We observed that all samples analyzed for total petroleum hydrocarbons were at non-detectable levels, and can be interpreted as a positive result of the installation of Fossil Filters® at catch basins upstream of the bioswale. At the same time, the full extent of hydrocarbon loading onto parking lots has not yet occurred since major portions of the stores and parking lots are still under construction. There are no consistent trends in the results for total suspended solids, and this is most likely due to the incomplete vegetated state of the bioswale that existed at the time of sampling compounded by erosion of the banks of the bioswale (Figure 5.2).

Figure 5.2

Erosion of Bioswale Banks

Table 5.5

U.S. EPA Water Quality Criteria (U.S. EPA, 1986)

Pollutants	Concentrations ug/L			
	Fresh Acute Criteria	Fresh Chronic Criteria	Marine Acute Criteria	Marine Chronic Criteria
Copper	18*	12*	2.9	2.9
Lead	82*	3.2*	140	5.6
Nitrates	NE	NE	NE	NE
Petroleum Hydrocarbons (Oil and Grease)	narrative statement			
Phosphorus	NE	NE	NE	NE
Suspended Solids	narrative statement			
Zinc	120*	110*	95	86

NE = Not Established
* = Hardness-dependent criteria (100 mg/L used)

Acute effects are short-term lethal effects that occur within 4 days of exposure.
Chronic effects occur over a longer period and include changes in feeding, growth, metabolism, or reproduction in addition to eventual death.
Petroleum Hydrocarbons (as Oil and Grease): Domestic water supplies should be "virtually free from oil and grease," particularly from the tastes and odors that emanate from petroleum products.
Suspended Solids: Criteria are established for solids and turbidity primarily due to their effect on productivity by reducing light penetration. The criterion for suspended solids is that the depth of the compensation point for photosynthetic activity should not be reduced by more than 10 percent from its seasonally established norm.

5.4.2 Sediment Quality Criteria

Sediment quality criteria standards are even less well established than are those for water.
Establishment of sediment criteria standards has long been a goal of the U.S. EPA, who recently published the Contaminated Sediment Management Strategy (1998). This document does not provide specific soil quality parameters, but outlines a systematic approach to sediment monitoring and assessment. The EPA approach discusses several steps deemed necessary for the effective establishment of a nationwide management strategy, one of which is the establishment of quality criteria for the protection of benthic organisms.

Baudo, *et al.,* (1990) presented standards that are currently in use, as well as proposed sediment contaminant standards for a variety of pollutants. Table 5.6 is a compilation of proposed sediment quality criteria and includes the forebay composite soil sample results for comparison. The soil quality criteria represent best estimates of the lowest effect levels of contaminants on benthic organisms.

Of the pollutants listed in Table 5.6, total petroleum hydrocarbons in the forebay are noticeably higher than the recommended standard of 100 ppm. Total phosphorus is also high, along with some of the metals such as nickel and zinc. The three metals of highest environmental concern (copper, lead, and zinc) are all present in the forebay soil, although their concentrations do not exceed recommended criteria at this point. The results from a single soil sample do not reliably establish the pollutant levels in the forebay, and additional samples are necessary to establish a more accurate picture of mean pollutant values and their variability. We recommend further sediment sampling in the forebay and other parts of the bioswale to better establish the present soil conditions prior to additional loading. A major reason for performing additional soil analysis is that if contaminant levels exceed quality criteria, this information may be required to establish the amount of cleanup necessary before forebay soil disposal.

Table 5.6

Summary of Recommended Sediment Quality Criteria and Forebay Sample Results.

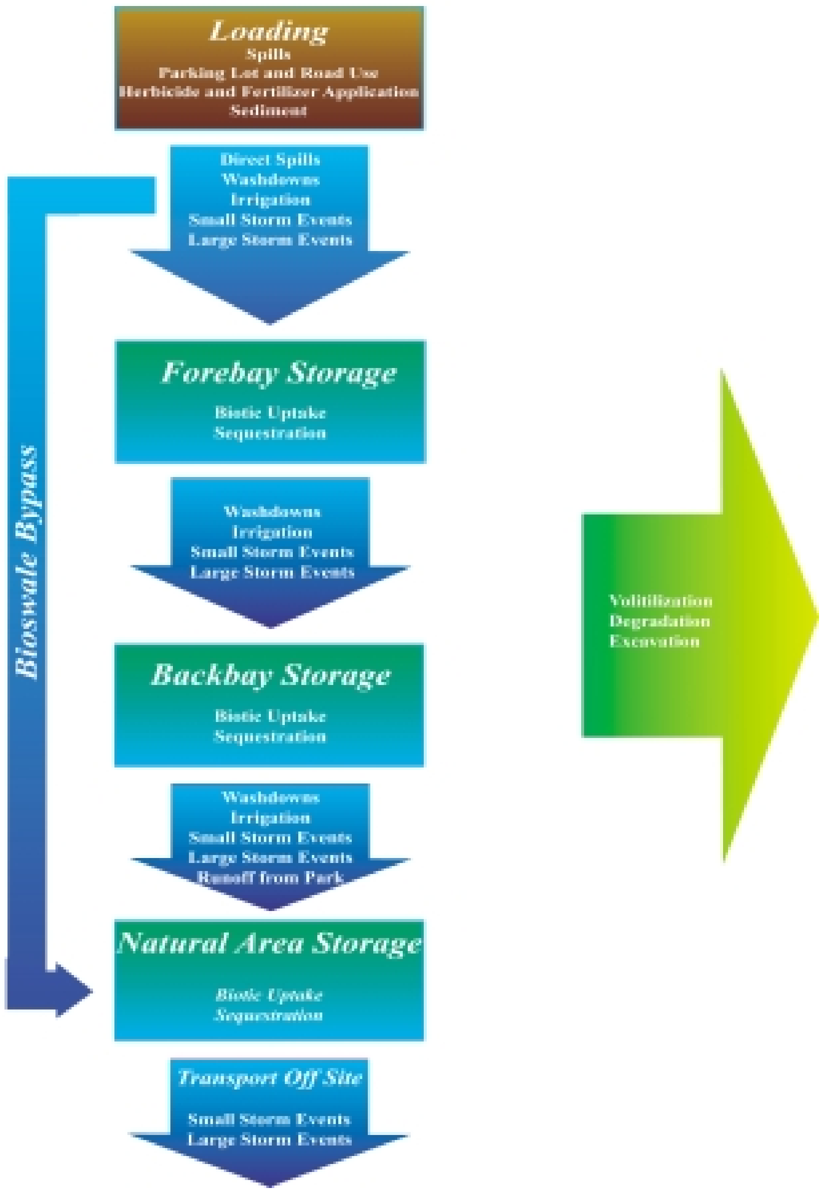
Constituent	Ontario Ministry of Environment and Wisconsin Dept. of Natural Resources Sediment Quality Critera mg/kg (ppm)	Forebay Composite Results mg/kg (ppm)
TPH	100	230
Total P as Phosphorous	600	700
Total P as Phosphate		2100
Antimony		nd
Arsenic	10	nd
Barium		61
Beryllium		nd
Cadmium	1	nd
Chromium	100	16
Cobalt	25	6.9
Copper	100	7.8
Lead	50	5.7
Mercury	0.1	nd
Molybdenum	4	nd
Nickel	100	95
Selenium	2	nd
Silver	0.5	nd
Thallium		nd
Vanadium		16
Zinc	100	44

nd = not detected
Source: Baudo, *et al.,* 1990

5.5 Transport and Fate of Contaminants at Camino Real

A logical extension of the chemical analysis addresses the transport and fate of pollutants. Figure 5.3 presents a conceptual model of potential reservoirs and transport routes for pollutants at Camino Real. Pollutants may remain sequestered in the bioswale forebay, but larger flow events have the potential to re-suspend sediment and disperse pollutants to the bioswale backbay and natural area. Plants in the bioswale can contribute to pollutant uptake, but the maximum uptake capacity of plants and the length of time required for uptake limit this process.

Figure 5.3
Fate and Transport of Contaminants at Camino Real



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6.0 Biological Considerations

The bioswale and the natural area represent a major portion of the remaining open space on the Camino Real Development site. With the construction of the development, a considerable amount of open space, considered to be a significant visual resource, was lost (Camino Real Project EIR, 1997). Therefore, the bioswale is not only a means of providing runoff treatment, but also acts to visually enhance the area. In the *Enhancement and Management Plan* for Camino Real (1997) one of the stated functions for the bioswale is "on-site replacement of riparian habitat". The Army Corps of Engineers defined the bioswale as wetland replacement, and a such provides an open vegetated area for various animal species such as, birds, frogs and possibly fairy shrimp (an endangered species associated with local vernal pools*)* as suggested by the lead biologist (Bomkamp, personal communication). It is expected that prolonged periods of ponded water will occur near the outlet of the bioswale due to the built in depression and relatively impermeable soil.

The natural area at the southern border of the development site works along with the bioswale to filter pollutants. All runoff, even that bypassed around the bioswale, is routed through the natural area before it exits the site. The natural area, therefore, acts as a vegetated continuation of the bioswale and performs many of the same functions. It is also important in enhancing the project site while providing additional wildlife habitat. The Environmental Impact Report designates this "willow grove" as an Environmentally Sensitive Habitat, classified under Riparian Woodlands/Corridor. This area was essentially left intact with some of the undergrowth and invasive species removed and the addition of native plantings both in the natural area and around the perimeter.

6.1 Phytoremediation

Phytoremediation is the use of plants to remediate polluted water or soil. The plants in the bioswale at Camino Real are expected to significantly increase degradation of pollutants by chemical alterations occurring in the root zone, or to contribute to pollutant decrease by physical uptake. Plants, particularly wetland species, have been used extensively to treat municipal and industrial wastewater, but the use of plants to treat in situ contaminated zones has only recently come into use (Anderson & Coats, 1994). Studies have shown considerable promise towards increasing use of plants to treat some polluted sites, but more information needs to be acquired. The bioswale's purpose is to treat pollutants as they arrive and accumulate, not to clean an already contaminated site. Thus phytoremediation is being used to reduce the rate of possible long-term chemical build up, as well as minimize pollutant loading off-site with potential damages to Devereux Slough.

Plant species play a large role in pollutant uptake ability, with many plants able to degrade or uptake certain pollutants occurring at various rates (Anderson 1994). Much of the recent research is focusing on creating new breeds and hybrids that will be able to accumulate more pollutants over shorter time intervals. Plants also assist in the physical removal of particles by acting as barriers to the water flow; this decrease in flow speed enhances settling of suspended sediment. Some uptake of pollutants is possible on above ground plant surfaces, this occurs mostly with organic pollutants such as PAHs (polycyclic aromatic hydrocarbons) (Simonich and Hites, 1995). For example, plant accumulation of some organic pollutants can occur through reactions between air and leaf, as well as from deposition of particles out of the water column onto exposed surfaces.

The majority of phytoremediation occurs in the root zone of plants – the rhizosphere. The rhizosphere represents a microenvironment where bacteria and fungi, along with plant roots, form a unique community that has the potential for detoxification of hazardous compounds. In natural plant ecosystems, microbial communities are found in symbiotic relations with plants. The presence of plants increases the abundance of microorganisms in the rhizosphere. This increase is commonly 5-20 times greater than in non-vegetated soils, and can be as high as 100 or more times (Kruger, 1997). The plant provides exudates to the microbial community, which stimulates activity and often leads to a build up of the organic carbon content in the soil, while the plant receives, in turn, mineral nutrients.

Plants exude a variety of compounds, both organic and inorganic, to stimulate microbial communities in their root area including sugars, amino acids, carbohydrates, acetates, carbon, esters, benzene derivatives, enzymes and essential vitamins. These exudates can mobilize essential nutrients from the soil, and act as chemo-attractants, thus stimulating bacterial activity and altering toxicant sorption, bioavailability and leachability. Fungi are the second most prevalent group of microorganisms in the soil, and grow in association with plant roots and provide unique enzymatic paths for the degradation of organics not available through bacteria alone. Mychorrizal fungi are especially important in the rhizosphere for a wide range of herbaceous and woody plants, and can improve plant success in nutrient or water limiting conditions. Though bacteria and fungi can catabolise (break down) many of the same contaminants, they do so by different mechanisms. Which process is more prevalent depends on the soil properties and its constituents. Exudates from the plant as well as the cell wall mechanisms of the plant root vary with plant species. The cell walls of the plant root are a source of fixed, non-diffusible charges that may adsorb particles in the rhizosphere and make them less bioavailable. Bioavailability is defined as the amount of a compound present in soil solution or readily exchanged off of system surfaces.

6.1.1 Phytoremediation Mechanisms of Organic Contaminants

Plants remove organic contaminants through two mechanisms: (1) direct uptake and accumulation of contaminants, and (2) degradation by stimulating the rhizosphere microbial communities through the use of exudates and enzymes from the plant. There are several important plant factors that play a role in the capacity of the plant to take up contaminants, such as: the plant species, age, vigor of rooted plant, soil properties and climatic conditions. The majority of the microbes are composed of bacteria, but there is also usually a large fungi population. Just as plant uptake is influenced by many factors, the microbial community in the soil also depends on a variety of soil parameters, such as: temperature, aeration, salinity, texture and nutrient availability. Especially critical for microbes are moisture, temperature and oxygenation.

Schnoor, *et al*., (1995) found hybrid poplars to be particularly effective at treating soils with organic contaminants. Poplars were used at several study sites, either alone or in conjunction with other plants, to degrade contaminants such as atrazine, chlorinated solvents, organics (mostly nitrate and phosphate), and metals. Poplars planted directly on top of landfills flourished and maintained growth even after several years, they immobilized organics in the soil and added to soil stability thus decreasing soil erosion. Plants with relatively deep roots and/or dense root mass can take up large volumes of water, thus decreasing downward percolation of water, along with associated pollutants, into the water table.

The accessibility of organic contaminants to plants varies greatly. Plants are highly efficient in the uptake of hydrophobic organic compounds. Hydrophobicity is expressed as the log of the 'octanol-water partitioning coefficient' K_{ow}, where contaminants with high K_{ow} can show significant root uptake. However, in organic-rich or highly textured soils, hydrophobic compounds may sorb strongly to soil particles and become unavailable for root adsorption. Once adsorbed, plant tissues sequester organic contaminates or volatize, metabolize, and mineralize the chemicals to carbon dioxide, water and chlorides (Suthersan, 1997).

6.1.2 Phytoremediation Mechanisms of Heavy Metals

Most heavy metals have several physical and chemical forms in the soil. Metals may be found dissolved in the soil solution, adsorbed to plant roots, adsorbed to insoluble inorganic matter, bonded to ion exchange sites on inorganic soil constituents, precipitated as solids, or attached to soil biomass. Plant roots help to prevent the erosion of soils and the metal contaminants associated with them, as well as engage in uptake of metal contaminants. Metals often remain in the roots of the plant, and to a limited degree are translocated to aboveground plant parts. Some species known as hyperaccumulators have been shown to uptake large quantities of metals without toxic side effects.

The amounts of metals in stormwater runoff available for biological uptake are closely approximated by the percentage of dissolved metals within the runoff. Zinc, cadmium, and copper are highly available for uptake, while lead, iron, and aluminum are frequently bound to particles and less available (Sansalone and Buchberger, 1997). Metals uptake varies widely by plant species and levels of exposure. Further investigation is required to make qualitative uptake predictions for bioswale vegetation. Biological uptake may facilitate metals introduction into the food web.

Plants have been shown to accumulate heavy metals, as well absorb and metabolize a variety of organic chemicals. Table 6.1 lists contaminants known to be suitable for phytoremediation.

Table 6.1

Contaminants Suitable for Phytoremediation

Moderately Hydrophobic Contaminants	Excess Nutrients	Heavy Metals
benzene	nitrate	chromium
toluene	ammonium	cadmium
ethylbenzene	phosphate	zinc
Xylenes		lead
Chlorinated solvents		mercury
PAH's*		arsenic
Nitrotoluene		nickel
Ammunition wastes		copper
		silver

*Polycyclic aromatic hydrocarbons

Source: Suthersan, 1997

6.1.3 Plant Selection for the Bioswale

All former vegetation has been removed from the area where the bioswale is now located. The planting of the bioswale is divided into four areas: the forebay, the backbay, the dam (separating the forebay from the backbay), and the banks. Plants in each area were selected according to expected soil moisture levels and degree of inundation. Table 6.2 summarizes the plants used in the Camino Real bioswale.

Table 6.2

Bioswale Plant List

Planting Area	**Scientific name**	**Common Name**
Forebay	*Eleocharis palustris*	Spike Rush
	Anemopsis californica	Yerba Manza
	Lilium pardolinum	Water Lilly
Backbay	*Scirpus maritimus*	Bull Rush
	Scirpus californica	Bull Rush
	Distichlis spicata	Salt Grass
	Juncus patens	Common Rush
	Cyperus eragrostis	Common Cyprus
	Juncus phaeocephalus	Brown Headed Creeping Rush
Berm	*Artemesia californica*	California Sagebrush
	Baccaris pilularis	
	Diplacus duranliucus	Monkeyflower
	Elymus condensatus	Giant Ryegrass
Bank	*Plantanus racemosa*	Western Sycamore
	Populus fremonti	Fremont Cottonwood
	Acer negundo	Boxelder
	Quercus agrifolia	Live Oak
	Prunus lyonii	Catalina Cherry
	Geteromeles arbutifolia	
	Rhus integrifolia	Lemonade Berry
	Nassella pulchra	Purple Needlegrass
	Berberis nevinii	Barkberry
	Rubus ursinus	California Blackberry
	Artemesia douglasii	Mugwort
	Rosa californica	California Wild Rose

6.1.4 Plant Specifics

There is a scarcity of information regarding the specific plant species in the bioswale and their potential pollutant uptake; this is probably due to the lack of similar water treatment systems in southern California. Selection of plant species was based on two criteria: that they are native to the area and will survive given the expected soil conditions. Plants in the main channel of the backbay were selected for their ability to survive up to a month of standing in ponded water.

Some work has been done looking at plants of the same genus as the plants in the bioswale, but of different species. While this may provide an indication of general plant functioning, caution should be used when extrapolating plant behavior among different species. This information can provide clues to the success of pollutant uptake within a given plant, but ongoing research should be conducted to analyze actual uptake ability for each plant within the bioswale. Following are some examples of research in this area that potentially indicate how plants in the bioswale will perform.

6.1.5 Synopsis of Research on the Uptake Ability of Various Plants

Rejmankova and Bayer (1995) analyzed two species of the Scirpus genus, *Scirpus acutus* and *Scirpus californicus* (the bioswale has *Scirpus maritimus*). These two species behaved similarly in regards to their metal uptake abilities, with most of the metals remaining in the roots and not being translocated to the shoots to any significant degree. In the author's heavy metal analysis, none of the five species examined had significant uptake of metals in above ground growth, with significant accumulation of metals only occurring in the roots. Their analysis was based on two natural (non-polluted) wetlands that were used as control sites and compared to four other treatment sites, with all locations in either Davis or Fairfield, California. Both *Scirpus acutus* and *Scirpus californicus* were found to allocate more of their biomass into their below-ground structure when water levels are periodically drawn down, as opposed to continual flooding. This could affect pollutant uptake since as far as metals are concerned, most of the accumulation is in the root zone. In general these two species grow well in a wide range of water depths and nutrient concentrations. They can survive occasional deep flooding as well as droughts, and are highly productive.

Breen, Mag and Seymour (1994) studied a similar system to the bioswale, which they call a flood-retarding basin, located in Melbourne, Australia. They also note that the majority of urban runoff consists of pollutants adsorbed onto mineral particulates, and thus one of the key roles of the plants is to remove these particles from the water column. This study, as well as others including data from King County, WA, deem that optimum performance in such a water treatment system is enhanced by a wide variety of species. Since each plant performs differently, and especially since data on pollutant uptake is limited, there is a better chance that performance will increase with a variety of plant species as opposed to only several. The only exception to this may be plants known as “hyperaccumulators”. Preliminary research is being conducted on special breeds that uptake pollutants, mostly metals, at several orders of magnitude higher than other observed plants (Cunningham and Ow, 1996). Also, a variety of plant species is also helpful at the beginning stages of the bioswale (or similar system), since inevitably some plants will do well while others will die.

The Australian basin uses some Juncus species in areas that are frequently inundated, which are similar to wet zones in the backbay that contain 2 species of Juncus. Though the authors do not provide any data on pollutant uptake ability by the plants, they make recommendations about which species would be appropriate given the hydrologic conditions of the area. They also recommend Eucalyptus trees in areas that occasionally are inundated, such as the higher elevations in the backbay or even on the lower slopes of the bioswale. Even though Eucalyptus trees grow well in the Santa Barbara area, they are not native and are not recommended for a small site such as the bioswale where they could easily prohibit other growth.

The King County Surface Water Design Manual (1997) lists acceptable plants for a “wet biofiltration swale”, which is similar to the Camino Real bioswale. This list includes several species of *Eleocharis*, *Juncus tenuis*, *Scirpus acutus* and *Scirpus microcarpus*, reflecting similar species planted in the bioswale. It notes that cattails (*Typha latifolia*) are not appropriate for most wet swales due to the plant’s dense and clumping growth habit, which prohibits water filtration. Also, typical wetland vegetation does not respond well to high velocity flows, which cause the plants to fall over and are subsequently unable to return upright. This problem is addressed in the bioswale where flows in the backbay are gentle.

Kemp and Cunningham (1980) studied *Distichlis spicata,* which is planted in the backbay. This particular grass occurs over a wide geographic area, thus showing itself to be fairly hardy and well able to adapt to different environments. *D. spicata* is shown to be highly salt-tolerant, which is a possible concern within the bioswale. The event mean concentration (EMC) of chloride in stormwater samples from the bioswale (1/24/99) ranged between 5 and 12 mg/L, with chloride concentration providing a good indicator of total salt levels. The sample series taken from the runoff of K-Mart parking lot exhibited a higher chloride concentration, with an EMC of 329 mg/L. This sample was taken after a long dry period and indicates a longer period of pollutant buildup. Kemp and Cunningham (1980) showed that moderate to high levels of salinity (14.6-29.3 mg/L NaCl) significantly reduced net photosynthesis given warm temperatures and bright light conditions, which would be the dominant conditions for the bioswale. Therefore, even though plants such as D. *spicata* can survive periods of high salinity, growth rates are diminished and decrease pollutant uptake. Studies show that the evapotranspiration rate plays a significant role in pollutant degradation (Burken & Schnoor, 1996). The ability of the plant to transport oxygen to the soil stimulates rhizome activity and degradation of pollutants.

6.1.6 Limits of Phytoremediation

Despite advances in technology, additional information is needed to assess the various plants and their potential to decrease or transform pollutants either by direct uptake or by their contributions to the soil to enhance microbial activity. The process of soil transformation through phytoremediation is still slow for most plant species, which has a direct effect on best management practices, policy regulations, and ultimately remedial costs. This is especially true for hydrophobic pollutants that bind tightly to soil particles and thus require a long time to remediate. One of the arguments in favor of phytoremediation is that costs are substantially lower for in situ treatments as opposed to transporting material offsite, but this benefit must be weighed against the length of time needed for treatment.

According to Cunningham & Ow (1996), research on future technologies is focusing on developing new hybrids, with new genetically modified plants able to uptake more pollutants and at a faster rate. They envision a new valuation system that selects plants "based on what they absorb, sequester, destroy and tolerate". Several aspects of a plant structure could be improved, such as deeper roots and increased root density. Deeper roots would allow the plant to filter pollutants further down in the soil column, while increased root density may make extraction more efficient. Many studies have focused on organic pollutant uptakes, which appears to happen more easily than accumulating metals into the plant structure. Again, some research is being directed towards analyzing metal uptake, for example some plant mutations have exhibited a 10 to 100-fold increase in metal accumulation compared to their non-mutant counterparts (Cunningham & Ow, 1996).

It is still unclear if a plant accumulates significant portions of pollutants in leaves and thus re-releases contaminants during litter fall; this probably varies with the type of plant. Studies so far have not emphasized this aspect and it does not appear to be of high concern, but still merits further investigation. Whether or not this is a problem has ramifications for ensuing biological consumption of toxic materials as well as re-mobilizing the pollutant. It is also uncertain whether the plants are most important for their actual uptake abilities, or whether the release of exudates and subsequent stimulation of the rhizosphere is their primary role.

It is clear that the plants in the bioswale will aid in the removal of soil particles and their associated contaminants and will contribute to contaminant degradation in the soil. The uncertainty lies in knowing to what degree these processes contribute to the overall removal of contaminated constituents from the runoff at the Camino Real development.

6.1.7 Vegetation Establishment and Growth

The successful establishment and growth of plants within the bioswale is key to the achievement of its water quality goals. Plant species have been selected for use in the bioswale based on their ability to thrive in the hydrologic regimes anticipated to be present in the bioswale. Given the high investment of time and effort in planting, successful establishment of vegetation is quite likely. The long-term growth and community composition of vegetation within the bioswale is dependent on hydrologic regimes, access to sunlight, soils, and vegetation community dynamics.

Plants within the bioswale will experience a variety of hydrologic conditions depending on season, location within the bioswale, Camino Real site usage, and management intervention. The strong seasonality of precipitation (in Santa Barbara precipitation comes predominantly from November to March) will result in a bioswale that is frequently ponded or inundated in the winter and significantly drier in the summer. The topography within the bioswale will strongly influence the hydrologic regime to which plants are exposed. The bioswale is topographically separated into wet, mid, top, and upper slope zones; forebay and backbay; and micropool. The bioswale is expected to receive some water daily from watering and washdowns on the Camino Real Shopping Center (Yean, personal communication). Since construction is not completed, the amount and variation of daily flows is not yet known. Direct watering of the bioswale may be required to maintain plant health through extended dry periods. In anticipation of extended dry conditions, sprinklers have been installed in the bioswale.

Access to sunlight is a critical component in the growth and community composition of plants within the bioswale. Moderate to high vegetation density requires abundant sunlight (Mazer, 1998). Trees planted within the bioswale will increasingly shade areas of the bioswale over time. The sandy clay soil within the bioswale is suitable for all of the plants selected for use in the bioswale (Bomkamp, personal communication). The initial soil conditions will favor some plants, and sedimentation and concentration of contaminants will change the soil conditions that will favor other plants over time.

Since the controlling factors of vegetation growth are expected to vary over time, the vegetation community composition will also vary as. The variety of plants initially planted within the bioswale provides numerous and significantly different plant species which will attempt to colonize the bioswale. Ultimately, the vegetation community will progress towards one that is dominated by those species most suited to the particular environmental conditions within the bioswale.

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7.0 Economic and Regulatory Considerations

7.1 Why a Bioswale?

The Camino Real development considered several factors in the choice of stormwater treatment system. In addition to concerns regarding water quality, permitting required that the developer address flood containment capacity and mitigate for wetland loss. This section discusses options that were considered for stormwater treatment, which were narrowed to the choice of a bioswale due to its additional benefits addressing flood containment and wetland mitigation.

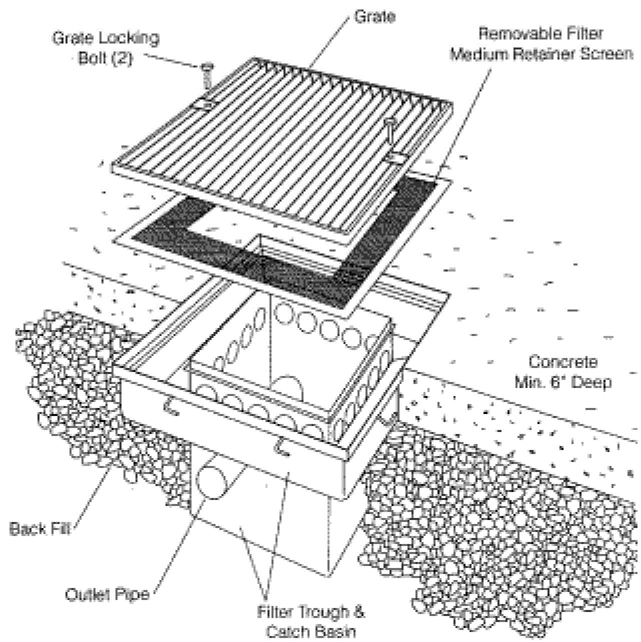
The Environmental Impact Report (EIR) for Camino Real mandated the use of oil and grease traps, or equivalent, which resulted in the installment of Fossil Filters® at each catch basin. This type of oil and grease trap provides removal of hydrocarbons, suspended sediment, and floatable debris. An alternative option was to use the Stormceptor , which provides the same water treatment as Fossil Filters®, but has a larger pollutant storage capacity. Following is a description of both Fossil Filters® and Stormceptors .

Fossil Filters® are trough structures installed under the grates of all runoff catch basins (Figure 7.1). They are principally designed to trap petroleum hydrocarbons and associated pollutants, while still allowing unrestricted flow of water into drainage pipes. They conform to EPA standards under the National Pollutant Discharge Elimination System (NPDES) program and are considered to be economically feasible and fall under the definition of Best Available Technology. These structures are made in a variety of shapes and sizes, and should catch all flow directed towards the catch basin. The non-hazardous adsorbent material in each Fossil Filter®, known as Amorphous Alumina Silicate, traps the hydrocarbons and remains effective until 50% or more of the filter material is covered with pollutants. Minimum recommended maintenance for each structure is three cleanings and one change of filter material annually. To ensure proper functioning, regular maintenance of the structures must include removal of large debris to allow unrestricted water passage.

The Stormceptor is a subsurface chamber made of precast concrete or fiberglass components that are assembled and installed in either new or existing storm sewers. The Stormceptor is designed to treat more than 80% of all storm events (Stormceptor Corporation, 1996) and directs stormwater flow into an upper bypass chamber, where a u-shaped weir diverts the flow down to the main treatment chamber (Figure 7.2). In this lower chamber hydrocarbons and floatable debris rise to the top and become trapped, while sediment settles to the bottom. The main advantage of the Stormceptor is that during high flow events, previously collected pollutants will not be scoured from the device. High flow volumes will simply pass over the u-shaped weir and continue through the bypass chamber to the downstream stormwater system. Maintenance of the Stormceptor consists of measuring accumulated sediment depths and subsequent removal of accumulated solids through the manhole access with a vacuum truck. Stormceptor® units are available in a variety of sizes, with main treatment chamber capacities ranging from 450 to 7400 U.S. gallons. Even the largest Stormceptor® unit, however, is only expected to treat a maximum impervious drainage area of 5.5 acres for 80% removal of TSS (Stormceptor® Corporation, 1996).

Figure 7.1

Schematic Design of a Fossil Filter

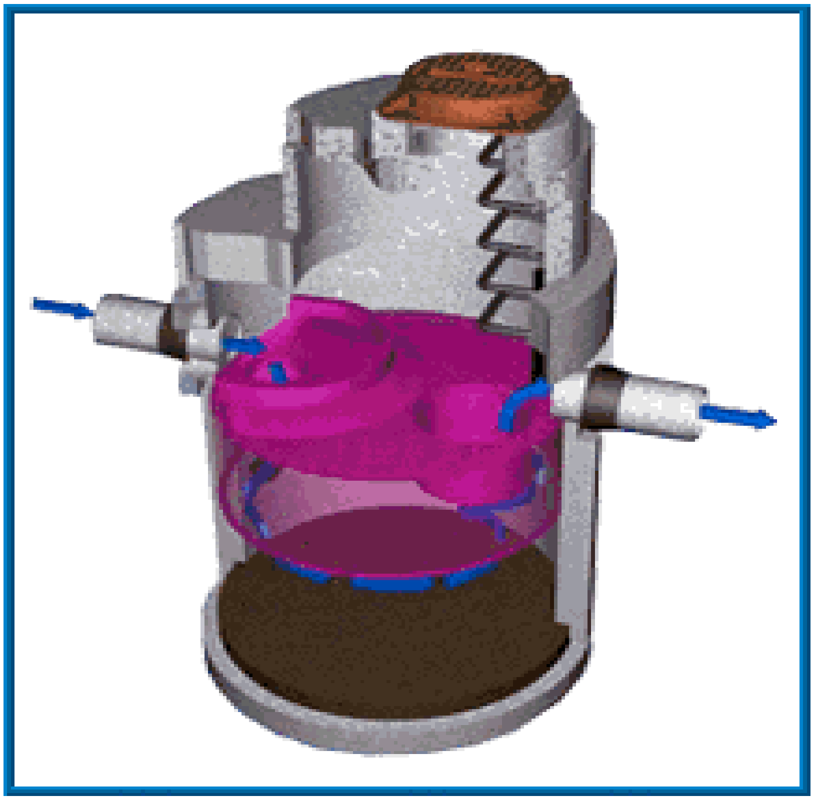


Source: KriStar Enterprises, Inc.

Figure 7.2

Schematic Design of Stormceptor® Stormwater Treatment Device.

Manhole cover at top gives rough idea of scale.



Source: Stormceptor® Corporation, 1996.

The guidelines about the maximum impervious area a single Stormceptor® unit can effectively treat, as well as flow restrictions, raised questions about the use of the Stormceptor®. It became clear that without a large number of units, the expected runoff volumes of major storms could not effectively be processed at the Camino Real development. The same number of Stormceptors as Fossil Filters® would have been required, and the large price difference eliminated Stormceptors® from further consideration. Instead, thirty Fossil Filters® were installed at all major catch basins. Including material and labor, construction cost for each Stormceptor® is approximately $150,000 and $225 for each Fossil

Filter®. Annual maintenance costs for each unit are roughly equal, although the Stormceptor® has a larger storage capacity and requires less frequent removal of collected sediments. Two additional concerns still needed to be dealt with that neither Fossil Filters® nor Stormceptors® could address: mitigation of wetland lost during construction and flood containment.

A minimum replacement ratio of 2:1 was required by the EIR for the loss of wetlands existing on the site before construction. From the beginning of the project development, the natural area was to remain and be enhanced to maintain open space, but off-site habitat restoration within the Devereux Creek watershed would still have been required. The installation of the bioswale, in conjunction with the natural area, accounted for full wetland mitigation according to the Army Corps of Engineers. An option such as the bioswale is cost-effective when compared to off-site restorations that are more expensive and more difficult to implement and monitor.

The bioswale also acts as a detention basin during high water flows, and thus increases on-site floodwater storage capacity. Maximum storage for the bioswale occurs during a 2-year flood event, and the combination of bioswale, natural area and playfields contains a 100-year flood event. Runoff is always first routed to the bioswale and then into the natural area. This avoids flooding of other open areas (mostly playfields), and increases the amount of time these areas are available for public enjoyment. With regards to pollutant loading, the forebay in the bioswale provides a small accessible collection site for concentration, and occasional removal of pollutants. In managing the area, it is much easier and less costly to have much of the pollutants located in the forebay. The natural area increases the efficiency of the bioswale to filter out sediment and pollutants, but it is preferable to concentrate as much of the pollutants as possible in one area. All these considerations influenced the selection of a Best Management Practice (BMP) for the Camino Real development, and the use of a bioswale provided a cost efficient method for addressing every concern. Following is a discussion of the components related to the implementation of the bioswale and how these relate to its long-term maintenance.

7.1.1 Costs

Table 7.1

Construction Costs of the Bioswale

Structure or Process	Cost
Grading work (excavated soil kept onsite)	$15,000
All drainage structures / energy dissipater	$47,200
Landscaping / includes fencing	$25,700
TOTAL COST	**$87,900**

The major costs associated with the bioswale include the construction costs (Table 7.1) and operations and maintenance costs. To ensure continual upkeep of the bioswale and surrounding area, including monitoring of plants and removing all refuse, Wynmark will establish a separate company in charge of managing the open areas. The new company's expenses will be paid for by the monthly fees collected from the retailers at Camino Real. Recommendations for a maintenance management plan follow later in the report. Before Wynmark decided to install the bioswale, the area was slated to be a parking lot, but this loss of additional parking space does not impose a significant cost. There is still plenty of parking available at the site to accommodate the expected number of shoppers.

We recommend occasional monitoring of the soil and the plants in the bioswale to find out if there is toxic accumulation, especially in the first several years as the system establishes itself. Information from similar water treatment systems in Washington State indicates the need for periodic dredging and removal of polluted sediment. Therefore, some expense will be directed at monitoring potential areas of pollutant buildup (notably the forebay), with additional disposal and treatment costs for the removed sediment.

In conclusion, the bioswale addresses the following considerations: (1) flood containment capacity, (2) wetland mitigation, and (3) reduction of pollutant loading off site. In comparison to the Stormceptor®, the bioswale is more expensive to operate and maintain, but Stormceptors® would have been much more costly to install and only addressed the third consideration listed above. The bioswale was therefore the most cost-effective option for addressing Wynmark's concerns and obligations.

7.1.2 Benefits

Table 7.2

Comparison of Benefits Between the Bioswale and Stormceptors

BENEFITS:	Bioswale	Stormceptors
Improved water quality	Yes	Yes
Enhancement of area	Yes	No
Flood Containment	Yes	No
Public Relations	Yes	Possible / not strong
Education/Research tool	Yes	No

Table 7.2 is a summary of the benefits of the bioswale and how they compare to using an alternative such as the Stormceptor . We discuss in further detail each of the five benefits and how they contribute to the development site, as well as

the practicality of using such water treatment systems in Santa Barbara County and elsewhere.

Improved water quality refers to decreasing pollutant loading from the site. If improved water quality were the only concern, there are several options to treat surface runoff. In this case, the use of Fossil Filters® would be sufficient and the additional expense of a bioswale would not be contemplated. Both systems trap a portion of the pollutants that are generated in the Camino Real watershed, thus improving the quality of water exiting the site. Modeling results indicated that the bioswale's TSS removal efficiency decreases as rain event size increases (Table 4.8). The Stormceptor® also provides decreasing TSS removal efficiency as flow rate to the unit increases (Stormceptor® Corporation, 1996), but high rates of removal efficiency are only true for a small treatment area (approximately 5 acres) for each unit.

Examination of the remaining benefits reveals that the bioswale is clearly preferable to the Stormceptor . The bioswale provides flood storage capacity for a two-year storm event, while the Stormceptor® provides no additional storage capacity. After several years the plants in the bioswale will be established and the bioswale will be an attractive open area, which contributes positively to the community. Stormceptors® are underground and provide no additional visual enhancement to a developed area. If the bioswale had not been installed this area would have become an extension of the parking lots. The bioswale can also serve as an education and research tool. Wynmark plans to install informational signs near the bioswale and natural area to educate the public about why they are there and how they function. The bioswale at Camino Real also provides several additional areas for potential research. Sediment re-suspension and vegetative pollutant uptake are two processes that were not extensively evaluated during the course of this project. Both processes are interesting and useful research areas because they relate to long-term questions about successful functioning of the bioswale.

Finally, the bioswale has a greater potential to improve public relations than an unseen underground treatment device such as the Stormceptor®. In recent months citizens of Santa Barbara County have voiced concerns about polluted runoff in creeks and the resultant beach closures. Establishment of local programs such as Project Clean Water and Save Our Shoreline represent the county government's response to citizen demand for action. The county is also federally required to address pollution in urban runoff under the requirements of the National Pollutant Discharge Elimination System (NPDES).

Implementation of Phase II of NPDES began in Santa Barbara County March 1, 1999, with stormwater discharge permits likely being required beginning May 31, 2002 (City of Monterey, *et al.*, 1998). While Phase II does not specifically require discharge permits for existing commercial facilities, Santa Barbara County may enact more stringent requirements if it develops its own urban runoff program. Wynmark knew about the upcoming regulations, and their installment of an advanced water treatment system that meets NPDES specifications reduces future uncertainty. Therefore, the bioswale becomes a benefit to the developer by avoiding potential problems such as expensive retrofitting of storm sewer systems. The following section provides more detailed information about the NPDES permit process and how it relates to urban runoff programs. An urban runoff program for Santa Barbara County is a natural extension of the NPDES permit application process, and will contain guidelines that regulate future development practices.

7.2 Regulatory Framework for Stormwater Management

The U.S. Congress amended the federal Clean Water Act (CWA) in 1987 to require stormwater discharge permits under the U.S. EPAs National Pollutant Discharge Elimination System (NPDES). This was known as Phase I of NPDES, and since 1990 it has required permits for stormwater discharges from municipalities with populations over 100,000, specific industrial activities, and construction activities disturbing 5 or more acres of land. Phase I of NPDES was intended only to minimize combined sewer overflows (CSOs). CSO technically refers to an overflow event from combined stormwater and sewage discharge, but does not assume that sewage systems frequently overflow into storm drain systems. Polluted discharge from stormwater drainage is considered enough of a problem by itself to warrant the establishment of urban runoff programs (City of Monterey, *et al.*, 1998). In 1993 the EPA published an expansion of the original policy under Phase II of NPDES. Phase II of NPDES expands the original program to include all municipalities within designated urbanized areas, and small municipalities outside of urbanized areas with a population of at least 10,000 and/or a population density of at least 1,000 persons per square mile (City of Monterey, *et al.*, 1998). Phase II also includes construction sites that disturb between 1 and 5 acres.

The expansion of NPDES under Phase II include goals for much stricter regulation of CSOs, including a wet weather management plan for CSOs such that specific water quality standards would be achieved. Phase II of NPDES is considered a landmark policy in two respects. First, Phase II resulted from a joint collaboration of U.S. EPA, environmental groups, and municipalities. Second, the policy contains a presumptive clause with respect to meeting water quality standards (Roesner and Traina, 1994). The presumptive approach is the major tool for evaluation of alternatives to be used for a long-term CSO program, as outlined in Roesner and Traina (1994). If any of the following criteria are met by a CSO control plan, the program is “presumed” to provide an adequate level of control to meet CWA requirements. 1) No more than four overflow events per year for urban areas (5 for rural areas) are permitted, although the permitting authority may allow up to two additional overflow events per year. 2) On a system-wide annual average annual basis, no less than 85% by volume of combined sewage collected in the combined sewer system during rainfall events will be captured for treatment. 3) For the volume of collected sewage, the mass of pollutants identified as causing water quality impairment will be eliminated or reduced.

Phase II of NPDES was implemented March 1 of 1999. Santa Barbara County and the Cities of Lompoc, Santa Maria, Santa Barbara, and Carpinteria are included in the list of counties and incorporated places automatically designated under Phase II, according to the 1990 Census of Population and Housing. Phase II permits are anticipated to be required as of May 31, 2002 (City of Monterey, *et al.*, 1998). At this point it has not been determined whether the entire County of Santa Barbara will apply for a joint permit, or if cities such as Lompoc and Santa Maria will apply for permits individually (Aston, personal communication). A natural progression of the permit application process is the establishment of a countywide urban runoff program. Such a program could be modeled after City of Monterey, *et al*. (1998), or other areas in California such as Ventura County, San Diego County, and the City of Los Angeles that have already established stormwater management programs.

The establishment of an urban runoff program for Santa Barbara County would serve to formalize stormwater management practices for the County, which currently occur on a more informal basis. The implementation of an urban runoff program involves the following six main areas that are considered mandatory for meeting NPDES requirements: 1) Public involvement and participation 2) Public education and outreach 3) Illicit connection and discharge detection/elimination 4) Municipal operations control 5) Construction site control and 6) New development/redevelopment control. Phase II of NPDES does not specifically address commercial, industrial, or residential pollutant sources that already exist. Industrial sources are considered to be addressed under existing Phase I regulations (the requirement to control all pollutants under a general permit). Commercial and residential sources of pollution can be addressed through education and outreach efforts. The Model Urban Runoff Program guidelines (City of Monterey, *et al*., 1998) do include commercial facilities control and industrial facilities control, however, as optional portions of urban runoff programs.

The installation of the bioswale at the Camino Real development can be considered an anticipation of potential future regulations governing the operation of commercial facilities under a future Santa Barbara County Stormwater Management Plan. Construction at Camino Real will be complete before Phase II is effective and the development would be considered existing (and therefore not specifically regulated under Phase II of NPDES), but the potential exists that Santa Barbara County would incorporate the "optional" commercial and industrial facilities controls as a required part of their plan. This could impact existing developments through the requirement of stormwater system retrofitting to achieve runoff quality goals.

8.0 Design Assessment

The bioswale design chosen for the Camino Real Site is one of many possible designs. Since the bioswale is not expected to be fully functional within the time frame of this report, a full analysis of the success of this specific design at this specific site will not be possible. Comparing the bioswale design with other surface runoff treatment designs, however, provides an initial prediction of the success of the bioswale.

8.1 Existing Bioswale Design Standards

Although bioswales are rare in Southern California, they have been used for many years in the Pacific Northwest. King County, Washington has recently updated its Surface Water Design Manual, giving detailed design recommendations for bioswales that reflect their long-term experience with a variety of designs. This section compares the bioswale at the Camino Real Site with King County's requirements.

The bioswale at Camino Real corresponds most closely to what the King County Surface Water Design Manual (KCSWDM) refers to as a wet biofiltration swale.

> A *wet biofiltration swale* is a variation of a basic biofiltration swale for use when the longitudinal slope is slight, water tables are high, or continuous base flow is likely to result in saturated soil conditions. Where saturation exceeds about 2 weeks, typical grasses will die. Thus, vegetation specifically adapted to saturated soil conditions is needed. (KCSWDM p. 6-50)

The bioswale at Camino Real closely matches this definition because the longitudinal slope of the site is slight, and daily low flows from irrigation and pavement washdown are likely to result in saturated soil conditions and a persistent “micropool” at the southern end of the bioswale.

The KCSWD Manual (1997) provides a series of calculations for designing a bioswale that is expected to meet the Basic Water Quality goal of 80% TSS removal. King County has not frequently used bioswales to treat runoff from commercial sites of this size, but the design calculations from the Surface Water Design Manual would still apply to a large site (Kulzer, personal communication). Table 8.1 shows the dimensions of the backbay of the bioswale at Camino Real and recommended dimensions based on the calculations outlined in the KCSWD Manual. The Manual calculations are based on a water quality design flow that is sixty- percent of the two year, 24 hour rain event. This water quality design flow is then used to estimate the size of the wet biofiltration swale that is expected to reduce TSS by 80 percent. As with the Camino Real bioswale, King County recommendations are based on the expectation that swales will deal with more frequent low intensity rains and daily low flows from irrigation and washdowns.

Table 8.1

Dimensions of the Bioswale at Camino Real and King County Recommendations

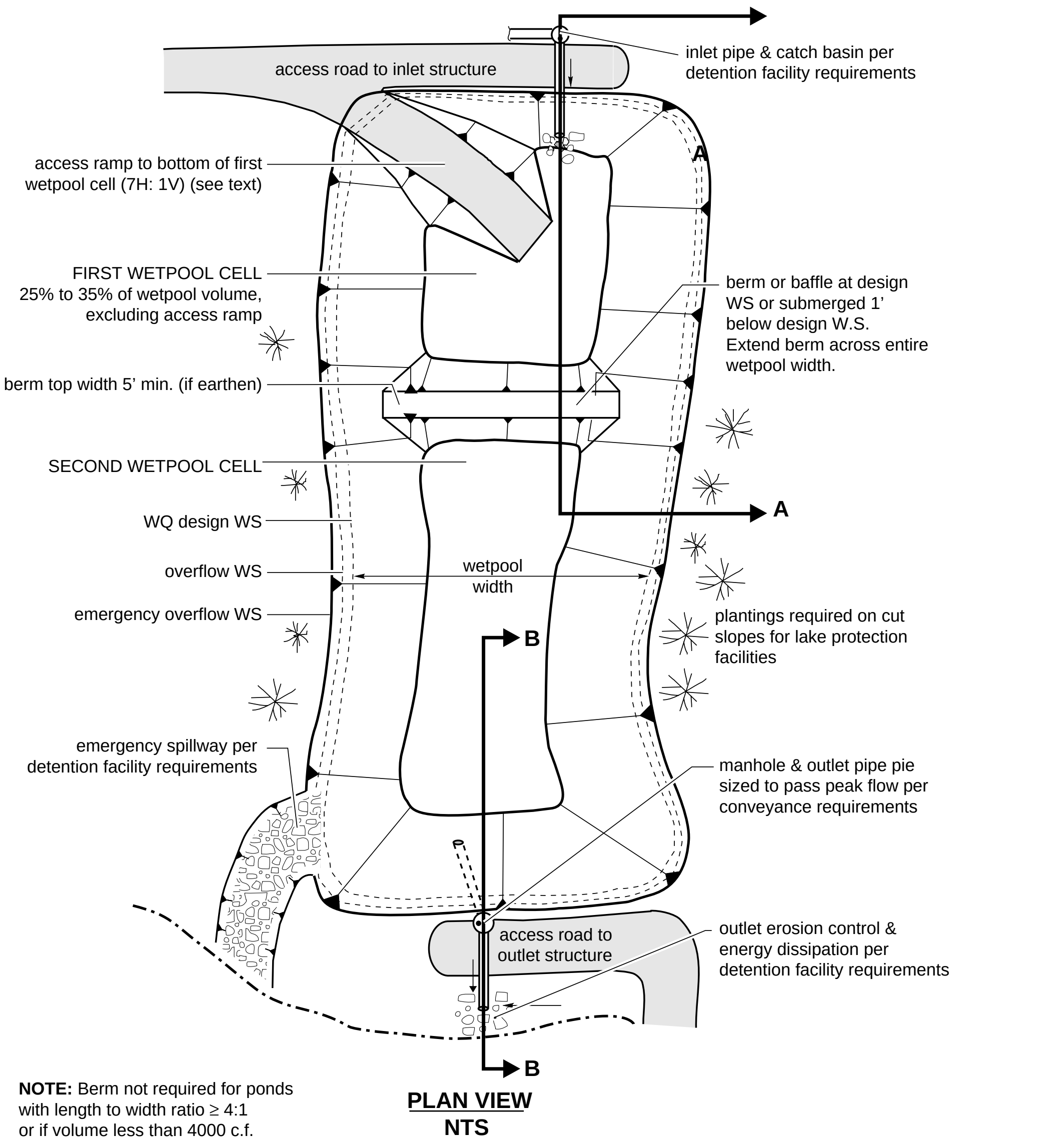
	Bioswale at Camino Real (Backbay)	KCSWDM (Calculated)
Treatment Area (sq. ft.)	21750	53150
Length (ft.)	290	516
Width (ft.)	75	103
Side Slopes (H:V)	2:1	Not steeper than 2:1
Design Flow Velocity (fps)	0.25	Less than 1.0

The King County Surface Water Design Manual specifies a variety of design parameters including: flow velocity, aspect ratio of the swale, slope stabilization, use of riprap, planting designs, bypasses, and detention times. The bioswale at Camino Real is compliant with the KCSWD Manual, excluding the treatment area. Although the bioswale is smaller than the King County recommendations, placing undersized biofiltration swales in available space is allowed (KCSWDM, 1997). The use of a forebay is known to reduce the backbay size necessary to meet treatment goals. Since the forebay is not included in the calculations, the effective treatment area of the Bioswale at Camino Real is somewhat larger than the 21750 sq. ft. calculated. The King County Surface Water Design Manual does not address the use of a forebay in calculations, but would likely require a larger backbay regardless. An example bioswale from the KCSWD Manual is included in Figure 8.1.

We conclude that though the bioswale is smaller than the ideal suggested by KCSWDM calculations, the more than doubling of area necessary to meet KCSWDM standards is not an efficient use of the area. As shown in Table 4.10, increasing the bioswale by 2.4 times it's present size (without a forebay) results in the removal of 54% of Total Suspended Solids (TSS) during a 0.15 in/hr storm, and a removal of 30% TSS during a 2-year storm. Similarly, Table 4.9 shows the effectiveness of the bioswale in TSS removal during the same two types of storm events, with no increase in area. Removal rates are 46% TSS for the 0.15 in/hr storm and 25% for the 2-year storm, based on expected settling velocities in the bioswale when vegetation is fully established.

Figure 8.1

Example Bioswale from the King County Surface Water Design Manual



(Source: King County Surface Water Design Manual, 1997)

9.0 Conclusions

In the introduction, we listed the three questions the group intended to answer:

- To what extent does the bioswale improve water quality?
- What is the total impact of the bioswale in the Devereux Creek Watershed
- Given other available options, is the bioswale a cost-effective water treatment method?

In this section, based on our research, sampling, and modeling efforts, we answer the three main questions. Since construction is not completed and vegetation is not fully established in the bioswale, many of our results are preliminary. Conclusions are based on limited field data and are necessarily cautious since only a few storm events were measured.

9.1 To what extent does the bioswale improve water quality?

Chemical sampling results indicated small decreases in concentration between the bioswale inlet and outlet for most parameters (Table 5.3). Statistical analysis revealed that the decreases are not statistically significant. We cannot conclude at this time that any observed differences in concentration are due to bioswale processes (settling of suspended sediment and plant uptake) rather than inherent spatial and temporal variability in the stormwater samples. Some concentrations increased slightly between the bioswale inlet and outlet, and are again interpreted to be due to individual sample variability. In the case of increased total suspended solids, the observation of bare soil with gullies next to the bioswale outlet sampling location leads to the hypothesis that increases in TSS at the bioswale outlet are a temporary function of the currently incomplete vegetation growth and erosion from the banks in the bioswale (Figure 5.2).

Modeling results, however, predict a strong role for the bioswale in water quality improvement. Most modeling scenarios were conducted without the orifice plate in place, since removal of the orifice plate is recommended, and its removal should be a simple operation. Comparison of model runs with and without the orifice plate in place show improved bioswale efficiency in reducing total TSS loads leaving the study site when the orifice plate is removed. Modeling conclusions are therefore based on simulations conducted with the orifice plate removed within the model.

Modeling results indicate that in its current unfinished state, the bioswale is effective in removing TSS from the water it receives for very small storms or other low flow runoff from irrigation or washdown. For a 2 hour storm with 0.03 in/hr intensity, the modeled bioswale removes 77% of the TSS it receives. This effectiveness drops sharply as storm intensity increases. For a 2 hour storm with 0.15 in/hr intensity, the modeled bioswale removes 26% of the TSS it receives. When the bioswale's soil and vegetation become established, simulations show the bioswale's effectiveness will improve for all storm events. In addition, the drop in effectiveness due to increased storm size is not expected to be as dramatic after vegetation becomes established.

The model simulations performed show that bioswales have the potential to significantly reduce TSS and pollutant loads leaving a developed site, particularly for small storm events. Developed areas could benefit from their application, especially in areas with no other means of runoff control. The effectiveness of bioswales is somewhat dependent upon their capacity to receive and retain flows, however. Bioswales are limited in the amount of water they can process. Within the frame of runoff from a large area, their impact may be relatively small, depending upon the size of the bioswale. In addition, other means for reducing TSS and pollutants in stormwater runoff may already be in place.

At the study site, modeling indicates that the natural area, because of its larger area, lower gradient, and thicker vegetation, is a more effective mechanism for the removal of TSS and other pollutants than the bioswale in its current unvegetated state. This holds true even when the model is calibrated to simulate the bioswale's future functioning. The model also indicates that the natural area is almost as effective at removing TSS and other pollutants by itself as when coupled with the bioswale. Model simulation show that the bioswale improves the overall removal of TSS by about 4-19% of the total load generated by the site. If the natural area is a habitat that needs protection from stormwater runoff, however, the bioswale will significantly reduce the loading to the natural area.

Presence of a forebay appears to have an impact on the effectiveness of a bioswale. During model simulations, the area of the forebay of the bioswale was increased, while the overall area of the bioswale was not changed. Results from these simulations indicate that a larger forebay improves bioswale effectiveness, especially for smaller storms. Further modeling showed that a bioswale without a forebay, but of a larger size, is not as effective for small storms as the bioswale design implemented at Camino Real. This is significant, since bioswales are generally designed to be effective during the low flow conditions of first flushes or small storms.

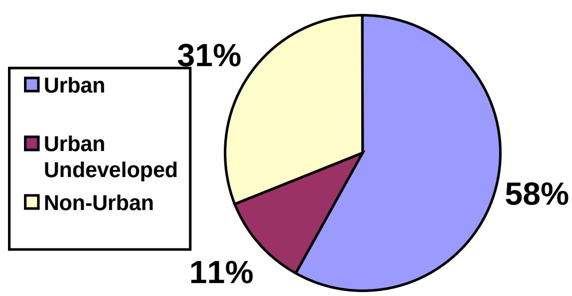
9.2 What is the total impact of the bioswale in the Devereux Creek Watershed?

The bioswale at Camino Real processes approximately 3% of the total runoff within Devereux Creek Watershed; the remainder of urban land uses--58% of the watershed--lacks this level of stormwater runoff quality protection (Figure 9.1,9.2). In order to preserve the wetland and estuarine habitats of the Devereux

Slough, action must be taken throughout the watershed to prevent the increased sedimentation and water quality problems associated with urban storm water runoff (see Section 5.1) from reaching the Slough. The bioswale at Camino Real is an important first step in addressing the preservation of the Slough. Since vegetation establishment is not yet complete, the final evaluation of the success of the bioswale is outside the scope of this report. However, the goals of the bioswale, which include keeping sediment and contaminants on site, are exactly what is required to preserve the wetland and estuarine habitats. Carey, *et al.,* (1998) noted that wetland protection requires coherent action and consistent planning on a watershed scale. Mitigation to improve stormwater runoff quality should be included for the 11% of the watershed that is zoned for future development, but the maintenance of the long-term health of the Devereux Slough ecosystem will also require stormwater pollution prevention at existing urban land uses within the watershed.

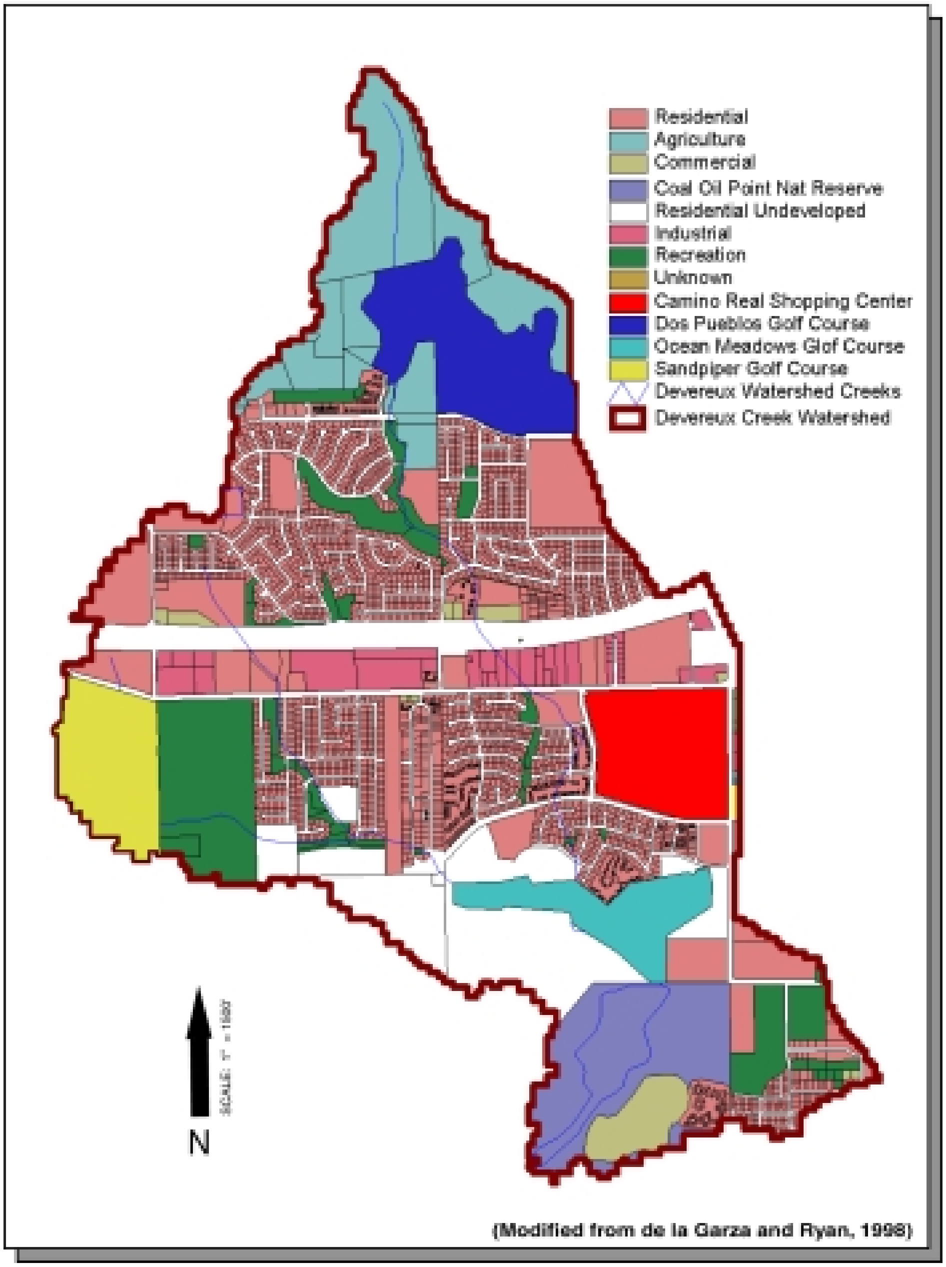
Figure 9.1

Existing Land Use in the Devereux Creek Watershed



A variety of BMPs are available to prevent or reduce stormwater pollution on existing or future urban land developments. Once the vegetation has been established and monitoring of the bioswale reveals that it achieves its goals of improving stormwater runoff quality, then bioswales should be seriously considered as a BMP for stormwater pollution prevention at future development sites in the Devereux Creek Watershed. Considerations of economic feasibility will also be a dominant factor in deciding on a BMP. Bioswales are unlikely to be deployed at existing urban development within the watershed because 1) bioswales require land which is expensive and which is frequently unavailable at existing developments and 2) there is no legal pressure for existing sites to improve their stormwater runoff quality.

Figure 9.2
Land Use in the Devereux Creek Watershed



(Modified from de la Garza and Ryan, 1998)

9.3 Given other available options, is the bioswale a cost-effective water treatment method?

If improved water quality were the only concern, there are several options to treat surface runoff. The use of Fossil Filters® or Stormceptors® would be sufficient and the additional expense of a bioswale would not be contemplated. However, the bioswale addresses the following considerations: (1) flood containment capacity, (2) wetland mitigation, and (3) reduction of pollutant loading off site. The bioswale was therefore the most cost-effective option for addressing Wynmark's concerns and obligations.

The bioswale provides flood storage capacity by acting as a detention basin, while the Stormceptor® and Fossil Filter® options provide no additional storage capacity. Maximum storage for the bioswale occurs during a 2-year flood event, however the combination of bioswale, natural area and playfields contains a 100-year flood event. The bioswale was placed to take advantage of a remnant stream channel and thus avoided costly floodwater detention construction elsewhere on the development site.

A minimum replacement ratio of 2:1 was required by the EIR for the loss of wetlands existing on the site before construction. From the beginning of the project development, the natural area was to remain and be enhanced to maintain open space, but off-site habitat restoration within the Devereux Creek watershed would still have been required. The installation of the bioswale, in conjunction with the natural area, accounted for full wetland mitigation according to the Army Corps of Engineers. An option such as the bioswale is cost-effective when compared to off-site restorations that are more expensive and more difficult to implement and monitor. Again, neither the Stormceptor® nor Fossil Filter® options provided mitigation for wetland loss.

10.0 Report Recommendations

Based on the conclusions of our report, we make the following recommendations:

- Expand Bioswale Management Plan
- Review Performance of the Bioswale
- Maintain Oil and Grease Devices
- Remove Orifice Plate
- Modify Energy Dissipator

10.1 Expand Bioswale Management Plan

The expansion of the Bioswale Management Plan will facilitate management of the bioswale and help to ensure efficiency and effectiveness of bioswale performance. This plan is necessary because of the variety and complexity of tasks associated with bioswale inspection, maintenance, testing, and performance review.

In order to achieve the stated goals as well as justify the costs associated with the bioswale, effective and efficient performance is vital. To ensure that the bioswale fulfills these goals correctly and continues to perform up to these standards, inspection, maintenance, and performance monitoring are essential post-construction activities. These activities are equal in importance to the planning, design, and construction of the bioswale. Failure to meet these responsibilities would diminish the performance of the bioswale, and could conceivably create new health and safety issues exceeding those which the bioswale was intended to prevent. Included below are brief descriptions of elements intended to supplement and reinforce the existing Bioswale Management Plan. This section provides brief descriptions of elements intended to supplement and reinforce the existing Bioswale Management Plan.

10.1.1 Identify Team Members

Identify individuals within the facility organization to be members of a Bioswale Management Team. Establish responsibility for developing the plan and assisting in its implementation, maintenance, and revision. The responsibilities of each team member must be clearly identified.

10.1.2 Assess Sources of Pollutants

Provide a description of potential sources that may be reasonably expected to add significant amounts of pollutants to storm water discharges. Additionally provide a description of pollutants which may be spilled and result in the discharge of pollutants during dry weather. Important spatial differences in contaminant loading are to be expected due to the variety of land uses within the 159 acres the bioswale serves. Additionally, equipment and areas that have the potential for failures or spills must be identified.

10.1.3 Source Reduction

The life expectancy of the bioswale, like all filters, is strongly determined by the quantity and type of pollutants that it is required to filter. Direct reduction of pollutant loading at the identified potential sources of contamination will greatly benefit water quality and bioswale longevity. Examples of contaminant source reduction include: frequent street and parking lot sweeping, avoidance of excessive fertilizer and pesticide use, and trained onsite personnel available for spill containment and cleanup.

10.1.4 Inspection

The explicit and official inclusion of regular bioswale inspection in the Bioswale Management Plan is vital. Regular inspection allows repairs to be performed promptly without the need for major remedial or emergency action. In view of the complex nature of the bioswale and the wide range of technical aspects, the need for competent inspectors is obvious. A team of inspectors may be necessary to adequately review the geotechnical, environmental performance, structural, hydraulic, and biological aspects of the bioswale. Designated personnel should conduct inspections and report to the Pollution Prevention Team member responsible for inspections. Examples of inspection tasks include:

- Creation of inspection sheets and their use by inspection personnel during inspections.
- Inspection of storm water inlets, storm sewer pipes, and other storm water control features and clearing of debris after each major storm event and at a minimum of once a month. Record current physical condition of storm water control features.
- Inspection of natural area and clearing of debris after each major storm event and at a minimum of once a month. Record and photograph physical conditions (erosion, sedimentation, and structural integrity), biotic conditions (plant health, plant abundance and animals present), and water levels.
- Conduct comprehensive site inspection semi-annually to update pollutant sources and source reduction opportunities.

10.1.5 Maintenance

The essence of any site management plan is the regular, consistent performance of the actual maintenance tasks that the Bioswale Management Plan has identified, planned, and scheduled, and for which staff, equipment, and funding have been provided. The competent and consistent performance of these routine tasks is the single greatest factor in determining the overall success of the overall Bioswale Management Plan. These routine tasks may include watering, trimming, trash and debris removal, soil fertilization, and sediment removal. Experience has shown that the regular, frequent (monthly or less) performance of these tasks often requires less overall time and effort on an annual basis than if the tasks are performed only a few times a year.

In addition, modeling results indicate that sedimentation within the forebay of the bioswale will begin to clog the forebay drainage pipes after approximately 4-5 years of average rainfall. The pipes are expected to be covered with sediment after approximately 8-10 years. We therefore recommend that sedimentation within the forebay be monitored, and a plan to excavate excess sedimentation every 4 years be implemented.

A list of management issues and response actions is presented in Table 10.1.

Table 10.1

Management Issues and Actions

Maintenance Component	Defect	Conditions When Maintenance Is Needed	Results Expected When Maintenance Is Performed
General	Trash & Debris	Any trash and debris which exceed 1 cubic foot per 1,000 square feet (this is about equal to the amount of trash it would	Trash and debris cleared from site.

		take to fill up one standard size office garbage can). In general, there should be no visual evidence of dumping.	
	Poisonous Vegetation	Any poisonous or nuisance vegetation which may constitute a hazard to Maintenance Personnel or the public.	No danger of poisonous vegetation where Maintenance personnel or the public might normally be.
	Pollution	Oil, gasoline, or other contaminants of one gallon or more or any amount found that could: 1) cause damage to plant, animal, or marine life; 2) constitute a fire hazard; or 3) be flushed downstream during rain storms.	No contaminants present other than a surface film.
	Drought	Extended drought threatens vegetation survival.	Irrigate plants to ensure survival.
	Rodent Holes	Any evidence of rodent or any evidence of water piping through dam or berm via rodent holes.	Rodents destroyed and dam or berm repaired.
	Insects	When insects such as wasps and hornets interfere with maintenance activities.	Insects destroyed or removed from site.
	Weeds	Weeds threaten establishment of native vegetation or, after establishment, grow in the Bioswale.	Weeds Removed
	Tree Growth	Tree growth does not allow maintenance access or interferes with maintenance activity (i.e., slope mowing, silt removal, or equipment movements). If trees are not interfering with access, leave trees alone.	Trees do not hinder maintenance activities.

Side Slopes of Bioswale	Erosion	Eroded damage over 2 inches deep where cause of damage is still present or where there is potential for continued erosion.	Slopes should be stabilized by using appropriate erosion control measure(s); e.g., reinforcement, wood chips.
Storage Area	Sediment	Accumulated sediment that exceeds 10% of the designed pond depth.	Sediment cleaned out to designed pond shape and depth; pond reseeded if necessary to control erosion.
Spillway	Rock Missing	Only one layer of rock exists above native soil in area five square feet or larger, or any exposure of native soil at the top of out flow path of spillway. Rip-rap on inside slopes need not be replaced.	Replace rocks to design standards.
Pipes	Sediment & Debris	Accumulated sediment that exceeds 20% of the diameter of the pipe.	Pipe cleaned of all sediment and debris.
	Vegetation	Vegetation that reduces free movement of water through pipes.	All vegetation removed so water flows freely through pipes. (After KCSWDM, 1997)

Despite the best efforts of any management program, emergency maintenance measures may be necessary at the bioswale from time to time for a variety of causes, ranging from excessive rainfall to vandalism. As a result, the successful inspection and maintenance program must be ready to respond to this need in a timely and comprehensive manner. To do so, it is best to plan ahead for emergencies by developing an emergency response plan that identifies potential emergency problems and ways to address them. This may include the preparation of a list of typical repair materials, which then can be either stockpiled in house or quickly acquired through designated suppliers. The plan may also identify individuals and organizations that can provide technical input or services on short notice to assist in the emergency repair effort. Finally, a designated number of staff personnel should be available on a 24-hour basis to respond to maintenance emergencies.

10.2 Review Performance of the Bioswale

Rainfall-runoff processes are inherently complex and it can be difficult to determine how well water quality goals are being met, regardless of the proficiency of BMP design, construction, and maintenance efforts. For this reason, performance monitoring of the bioswale is essential. Evaluation of bioswale performance through field monitoring, sampling, and careful analysis of field data will provide the information necessary to address several concerns. One major concern is the potential impact of polluted runoff on Devereux Slough. Even though the total amount of runoff the bioswale will treat is small relative to the total amount generated within the Devereux Creek watershed, the bioswale filters the most contaminated portion and contributes positively to the incremental reduction of pollutants that reach the Slough.

Formal performance review of the bioswale will facilitate the evaluation of the bioswale as an cost-effective solution to stormwater detention, water quality improvement, and wetland habitat replacement. This information will allow developers and regulators to assess the applicability of bioswales in future developments. Furthermore, the chemical sampling recommended for performance review will help to characterize the gradual accumulation of contaminated sediment in the bioswale and provide an early warning of possible ecological or disposal hazards associated with contaminated sediments.

In addition, bioswale performance monitoring can also be seen as a way to help ensure overall program credibility and achieve stronger community acceptance. In recent years, much attention has focused on the need to expand traditional stormwater management programs beyond structural measures, such as a dry detention pond, to also include nonstructural measures in order to achieve more comprehensive results. With the real data obtained through bioswale performance monitoring, it will be easier to convince the community of both the need for and the promise of stormwater management. Finally, bioswale performance monitoring will help to more closely monitor progress and more quickly identify program problems and shortcomings. This will help to develop and implement program modifications and improvements that enhance community acceptance. Specific recommendations for water and sediment sampling are outlined in the following section.

10.2.1 Minimum Chemical Analysis Recommendations for Both Sediment and Water

Table 10.2 presents minimum recommendations for sample analysis. The primary source of this information was the Guidance for Monitoring the Effectiveness of Stormwater Treatment BMPs (EOA, 1996), and is reinforced in other documents such as Monterey, *et al.,* (1998). The list includes the four main areas of pollutant concern (sediment, nutrients, metals, and hydrocarbons) that were analyzed during the group project. Addition of particle size distribution and total dissolved solids is recommended to improve understanding about pollutant partitioning and the fate of pollutants in the bioswale. Field measurements are recommended because they are an inexpensive source of information about changes in water quality between the bioswale inlet and outlet, and about water quality exiting the site at the natural area outlet.

Table 10.2

Recommended Parameters for Assessing the Effectiveness of BMPs

Parameter	Media	Practical Quantitation Limit
General, Physical, and Inorganic Non-Metals		
TSS	Water	5.0 ppm
TDS	"	5.0 ppm
Hardness	"	5.0 ppm
Particle Size Distribution	Water and Sediment	NA
Nutrients		
NO_3 + NO_2 (as N)	Water	0.1 ppm
NH_3 (as N)	"	1 ppm
Total Phosphorus (as P)	"	0.5 ppm
Orthophosphate (as P)	"	0.5 ppm
Total and Dissolved Metals		
Copper	Water and Sediment	0.5 ppm
Lead	"	1.0 ppm
Zinc	"	1.0 ppm
Antimony	*Sediment*	*5.0 ppm*
Arsenic	"	*5.0 ppm*
Barium	"	*0.5 ppm*
Beryllium	"	*0.5 ppm*
Cadmium	"	*1.0 ppm*
Chromium	"	*1.0 ppm*
Cobalt	"	*1.0 ppm*
Mercury	"	*0.1 ppm*
Molybdenum	"	*1.0 ppm*
Nickel	"	*1.0 ppm*
Selenium	"	*5.0 ppm*
Silver	"	*1.0 ppm*
Thallium	"	*5.0 ppm*
Vanadium	"	*1.0 ppm*
Organic Constituents		
Total Petroleum Hydrocarbons	Water and Sediment	1.0 ppm
Field Measurements		
pH	Water	NA
Temperature	"	NA
Conductivity	"	NA

NA = Not Applicable
Italicized metals are not required, but along with Copper, Lead, and Zinc comprise the CAM-17 list of metals regulated by the State of California.
Source: Modified from EOA, (1996).

10.2.2 Chemical Sampling Considerations

The purpose of performing chemical sampling and data analysis is to aid in the review of the performance of the bioswale. The minimum analysis recommendations for sediment and water described above will allow bioswale managers to track and evaluate known and existing bioswale performance concerns. Unfortunately, not all possible bioswale performance issues or the relative importance of these performance issues can be known at this time. If new performance issues arise, chemical sampling and data analysis should be tailored to address these new performance issues. This section provides a general background in chemical sampling and analysis, as well as information on how the minimum analysis recommendations were selected.

10.2.2.1 Assessment of Sediment Contamination

The bioswale is designed to filter sediment, nutrients, and contaminants found in urban stormwater runoff. Although some pollutants are expected to degrade, many will accumulate over time, leading to contaminated sediments within the bioswale. Many contaminants the bioswale is expected to filter can be hazardous at high concentrations. In King County, Washington, sediments excavated from biofiltration swales are frequently hazardous and require treatment before disposal (Kulzer, personal communication). Accurate prediction of contaminant loading rates to the bioswale is limited by several factors, including the spatial and temporal variability of both the types and quantity of pollutants that will loaded on the site, the stochastic nature of the storms that transport pollutants, and uncertainty regarding the fates of contaminants within the bioswale (U.S. EPA ,1992). Given these factors, the long term monitoring of sediments is important to performance analysis of the bioswale, and provides information useful for avoiding hazards associated with contaminated sediments. This section addresses sample design and collection and chemical and physical analyses. We emphasize that a broad range of information regarding sampling and analysis is presented in the following section, and represents a comprehensive ideal for a monitoring program.

10.2.2.2 Sediment Sampling Design

The goals of sediment sampling in the bioswale are to determine current levels of sediment contamination, and to track long-term changes in sediment contamination. Continued sampling is necessary because 1) characterization of contaminant loading from the fully built out site cannot be accurately predicted from existing site conditions 2) if excavated sediment is contaminated, the nature of the contamination will have to be characterized for proper disposal and 3) site use and subsequent pollutant loading may change over time. For example, changes in fuel and oil use may alter contaminant loading to parking lots. Preliminary modeling results suggest that sediment loading could begin to clog the pipes that convey flow to the backbay in as soon as four years. At minimum, sediments should be analyzed in the forebay and backbay of the bioswale, as well within the natural area, before any excavation of sediments.

As part of this project, pre-pollutant loading sediment samples were collected in the forebay. Results of this sampling are available in Table 5.4. These data provide the initial conditions necessary to track changes in sediment contamination. Based on the results of this testing, we have made specific recommendations for future sampling that is intended for reconnaissance and simple tracking of sediment condition. More extensive sampling not outlined in this document should be undertaken if hazardous concentrations of contaminants are found in the sediments.

10.2.2.3 Sediment Chemistry and Physical Analyses

The bioswale group did not perform extensive sampling and analysis of sediment. The main focus of the project was hydrology and water quality, but a logical extension of water quality sampling is investigation of sediment contaminant loading over time. Included below is a comprehensive list of parameters that are of general concern for sediments. This list does not necessarily represent the actual list of parameters that would be routinely tested at the Camino Real bioswale. The need for trained sampling personnel and the high expense of certain analyses will eliminate certain tests from routine analysis.

- Particle or grain size of sediment is a physical parameter that determines the distribution of particles. Size is important because finer grained sediments tend to bind contaminants more than coarse sediments do.
- Total organic carbon (TOC) is an important indicator of bioavailability for nonionic hydrophobic organic pollutants.
- Acid volatile sulfides (AVS) can indicate the presence of toxic sediment-related metals.
- Polyaromatic hydrocarbons (PAHs) are semivolatile organic pollutants, several of which are potential carcinogens and are linked to tumors in fish.
- Polychlorinated biphenyls (PCBs) are highly toxic, chlorinated organic compounds once used for numerous purposes, including as a dielectric fluid in electrical transformers.
- Pesticides are synthetic compounds predominantly used in agriculture to control crop-damaging insects. Pesticides are known to have acute and chronic ecosystem impacts.
- Other semivolatiles, including acid/base neutral compounds (ABNs) such as phenols, naphthenes, and toluenes.

- Heavy metals are naturally occurring in the environment, but an excess of metals can be an indication of anthropogenic contamination; heavy metals can be toxic to benthic organisms.
  (Source: Dennis-Flagler, 1995)

10.2.2.4 Water Quality Assessment

A major purpose in the establishment of a long term water quality monitoring program for the Camino Real bioswale is to establish a local water quality data set that can be used to evaluate the overall effectiveness of the bioswale in improving stormwater runoff quality. Another contribution of the bioswale is expected to be the absorption of concentrated pollutants in small volume irrigation and pavement washdown events, which aids in the prevention of contaminated runoff reaching Devereux Slough. Evaluation of water quality data can lead to an overall assessment of the bioswale as a Management Practice, and whether other bioswales would be a recommended management measure for other development projects in the area. Information about water quality must be combined with information about runoff volumes generated for a variety of storm intensities, to evaluate the relative amount of stormwater runoff that the bioswale is able to treat. The bioswale may not be able to handle large volumes of runoff generated during large storm events, but is expected to be effective in treating small rain events and small volumes of runoff generated during irrigation and cleaning operations such as pavement washing.

10.2.2.5 Water Quality Sampling Design and Collection

Recommendations for water sampling design are the same as those outlined in the description of chemical sampling performed for the group project. Refer to Sections 5.1 and 5.2 for a review of information on pollutants that are of concern in stormwater and sampling design recommendations. We emphasize the importance of collecting a series of samples and flow measurements at each sample location for adequate establishment of Estimated Mean Concentration (EMC) values. Attempting to sample the runoff generated at the very beginning of each rain event is also emphasized. Information about first flush concentrations is essential for long term evaluation of whether the bioswale is treating the majority of this water, or whether a large proportion of polluted runoff is being routed around the bioswale through the bypass pipe. The sampling recommendations are a reflection of the efforts of a group of five people with a yearlong focus on attempting to answer specific questions about the functioning of the bioswale at Camino Real. Even with highly specific goals and close monitoring of incoming storm events, it was difficult in practice to arrive at the bioswale in time to capture first flush samples. We had five people locally available for sample collection and this proved helpful, but in practice sample collection is more likely to be the job of one or two people.

10.3 Maintain Oil and Grease Devices

Urban stormwater runoff carrying high concentrations of petroleum hydrocarbons can significantly impact the filtration capacity of the bioswale. Careful maintenance of the Fossil Filters® that have been installed will be necessary for optimal bioswale performance, since the bioswale at Camino Real is receiving petroleum hydrocarbon loading from two service stations, several high use roads, intersections, and parking lots. A recommended goal of treatment is to have no visible sheen for runoff leaving the facility, or to have less than 10 mg/L total petroleum hydrocarbons (KCSWDM, 1997).

10.4 Remove Orifice Plate

As mentioned previously in the hydrologic section, the orifice plate on the inlet to the bioswale is diminishing the potential role of the bioswale. For a relatively small design storm of 0.15 in/hr over two hours, the model indicated that the bioswale's effectiveness in reducing the TSS loads leaving the site increased with the removal of the orifice plate. This was due to the increase in the amount of flow routed to the bioswale with the orifice plate removed. The percent of flow from the site treated by the bioswale increased dramatically and the overall removal of TSS by the bioswale and natural area was also increased without the orifice plate in place.

10.5 Modify Energy Dissipator

The main impetus for placing an energy dissipator at the exit of a culvert pipe is to reduce water velocity, thereby mitigating the effects of erosion. As mentioned in the hydrologic section, when water exits the culvert pipe it is slowed down as it enters the energy dissipator, but when it leaves the flow contracts through three 0.5-foot openings and the velocity leaving the energy dissipator increases significantly. Some erosion has already been observed in the area where water is discharged from the energy dissipator into the natural area. If the effects of erosion become severe, the energy dissipator could be modified to slow down the velocity at which water exits this device and thereby slow down the erosion processes. To decrease its exiting velocity the three 0.5-foot openings could be enlarged. The amount of flow leaving the energy dissipator would still be the same, but the velocity at which this flow leaves could be decreased.

The energy dissipator may need to be cleaned out periodically because large clumps of sediment have already been observed to be accumulating in it. The main reason the energy dissipator is accumulating sediment is due to the fact it decreases the velocity of water as flow enters this device. This is further enhanced by the energy dissipator’s ability to pond water as flow is only allowed to leave through three 0.5-foot openings. In the future, the energy dissipator should be monitored for sediment accumulation and possible erosion effects at the entrance of the natural area.

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Appendix A

A-1 Hydrology Calculations

A-2 Flow into the Bioswale through the Orifice Plate when under a Pressure Head

$Q = K*A_0*(2*g*\Delta H)^{1/2}$

$R = D_1*V_1*\rho/\mu$

Where: R = Reynolds Number dimensionless
D_1 = the diameter of the pipe (ft)
V_1 = the velocity of the approach (ft/s)
ρ = the density of water (slug/ft^3)
μ = the viscosity of water (lb*s/ft^2)
D_0 = the diameter of the orifice plate (ft)
V_0 = the velocity of the discharge (ft/s)

Assuming the temperature of the water is approximately 50°F
ρ = 1.94 slugs/ft^3
μ = 2.735 * 10^{-5} lb*s/ft^2
1 slug = lb*s^2/ft
From Table A.1a (Daugherty, 1985)

D_0 = 1.0 ft
D_1 = 1.5 ft
D_0/D_1 = 0.67 ft
$V_0 = (2*g*\Delta H)^{1/2}$

Sample calculation with ΔH = 0.25 ft

Using $D_0/D_1 = 0.7$
Assume K = 0.7 (this is where the curve flattens out)
From Figure 12.23 (Daugherty, 1985)

$Q = 0.7*(3.14*1^2/4)*(2*32.2*0.25)^{1/2}$

Q = 2.21 cfs

Checking assumption

$V_1 = Q/A = 2.21/(3.14*1.5^2)/4)$
$V_1 = 1.25$ ft/s
$R = (1.5ft)*(1.25 ft/s)*(1.94 lb*s^2/ft^4) / (2.735 * 10^{-5} lb*s/ft^2)$
$R=1.3*10^5$
K = 0.7 (checks)

Sample calculation for the flow to the bioswale, under a pressure head, but without the orifice plate

For a change in elevation of 0.5 feet

L = 25.44 ft
D = 1.5 ft
f = 0.024

$0.5 = 0.024*25.44*V^2/1.5*2*g$
V = 8.89 ft/s
$Q = 8.89 ft/s * 3.14*(1.5^2)/4$
Q = 15.73 cfs

Assuming temperature of the water is approximately 50°F
$\mathit{V} = 1.410 * 10^{-5} ft^2/s$
$R = 1.5 ft * 8.89 ft/s / 1.410*10^{-5} ft^2/s$
$R = 9.5 * 10^5$

Consulting the Moody diagram f = 0.024 checks

A-3 Flow Exiting the Bioswale

Sample Calculation for flow leaving the bioswale as an open channel

Using a height of 0.5 ft in the exit pipe.

$R = 0.29$
$s = 0.005$
$n = 0.013$
$V = 1.49*(.29)^{2/3}*(0.005)^{1/2}/0.013$
$V = 3.57$ ft/s

$Q = (3.57 \text{ ft/s})*(0.62\text{ft}^2)$
$Q = 2.21$ cfs

Sample Calculation for flow leaving the bioswale under a pressure head

Using a change in height of 0.3

$f = 0.022$
$L = 63$ ft
$D = 2$ ft

$0.3 = 0.022*63*V^2/2*2g$
$V = 5.28$ ft/s
$Q = 5.28 \text{ ft/s} * 3.14529*2^2/4$
$Q = 16.61$ cfs

Assuming temperature of the water is approximately 50°F
$\mathit{V} = 1.410 * 10^{-5}\ \text{ft}^2/\text{s}$
$R = 2\text{ft}*5.28\text{ft/s}/1.410*10^{-5}\text{ft}^2/\text{s}$
$R = 1.9 * 10^6$

Consulting the Moody diagram f = 0.022 checks

A-4 Flow Leaving the Bypass Pipe

When flow was leaving the bypass pipe without a pressure head, Manning Equation was used.

Sample Calculation

Using a height of 0.83 ft

R = 0.51
S = 0.002
n = 0.013

$V = 1.49*(0.51)^{2/3}*(0.002)^{1/2}/0.013$
V = 3.28 ft/s

$Q = (3.28\ ft/s)*(2.24\ ft^2)$
Q = 7.36 cfs

A-5 Flow Leaving the Energy Dissipator

Sample Calculation

Observed while sampling.
Flow from bypass pipe Q = 0.73 cfs
Flow from the bioswale Q = 2.93 cfs
Total flow to energy dissipator Q = 3.66 cfs
Flow depth 0.63 ft

Velocity of Approach:

$1 = V/(32.2*0.63)^{1/2}$
V = 4.5 ft/s
$h = (4.5)^2/(2*32.2)$
h = 0.31 ft

With three weirs all having a length of 0.5 feet

$Q = 3*3.33*0.5*[(0.63 + 0.31)^{3/2} – 0.31^{3/2}]$
$Q = 3.62$ cfs

Sample calculation for flow leaving the energy dissipator in a high flow event.

Ht = 3.4 feet

Velocity of Approach

$1 = V/(32.2*3.4)^{1/2}$
$V = 10.46$ ft/s
$h = (10.46)^2/(2*32.2)$
$h = 1.70$

With three weirs all having a length of 0.5 feet

$Q = 3.33*0.5*[(3.4+1.7)^{3/2} – 1.7^{3/2}] *3$
$Q = 46.50$ cfs

For flow over the broad crested weir

$Q = 16*(32.2)^{1/2}*(2/3)^{3/2}*(3.4-2.75)^{3/2}$
$Q = 25.90$ cfs
$Q_{total} = 72.40$ cfs

Table A.1

Flow From the Site and Flows into the Bioswale and Bypass Pipe With the Orifice Plate.

Q in (cfs)	Q splitter (cfs)	Q bypass (cfs)	Height change from the culvert chart (inches)	
2.9	3.7	0.7	2.0	estimated
3.7	6.9	3.1	2.0	estimated
4.4	11.8	7.4	2.0	estimated
4.6	17.9	13.2	2.0	estimated
5.2	25.7	20.6	2.0	estimated
5.6	30.6	25.0	2.0	estimated
5.9	35.3	29.4	4.2	
6.3	46.1	39.7	4.5	
6.9	57.6	50.6	6.0	
7.3	70.0	62.7	6.3	
7.8	82.8	75.0	7.8	
8.2	96.2	88.0	8.1	
8.5	109.4	100.9	8.4	
8.8	122.9	114.1	8.7	
9.1	135.0	125.9	9.0	
9.4	146.6	137.2	9.3	
9.7	157.0	147.3	9.6	

Table A.2

Flows Exiting the Energy Dissipator

Energy dissipator Observed Height H (ft)	Velocity of approach V (ft/s)	Flow Exiting (cfs)	Field H (ft)	FlowExiting (cfs)
0.12	2.0	0.3	0.13 (1.5")*	0.3
0.21	2.6	0.7		
0.30	3.1	1.2	0.46 (5.5")	2.3
0.55	4.2	3.0	0.63 (7.5")	3.6
0.81	5.1	5.2		
1.04	5.8	7.9		
1.31	6.5	10.9		
1.57	7.1	14.2		
1.79	7.6	17.8	1.83 (22")	18.4
2.04	8.1	21.6	2.0 (24")	21.0
2.30	8.6	25.7		
2.57	9.1	30.1		
2.80	9.5	35.0		
3.04	9.9	47.1		
3.29	10.3	64.0		
3.56	10.7	84.3		
3.83	11.1	107.3		
4.32	11.8	132.8		

*Field Measurements were taken in inches and rounded to the nearest ½ inch.

Table A.3
Storage-Outflow Relationship for the Bioswale

Water Above The exit pipe (ft)	Storage Above the bottom of the exit pipe (ft^3)	Rate of Outflow (cfs)	S/Δt (cfs)	(s(t)-o/2) (cfs)	(s(t)+o/2) (cfs)
0.10	857	0.08	0.95	0.91	0.99
0.20	1291	0.33	1.43	1.27	1.60
0.30	1849	0.78	2.05	1.66	2.44
0.40	2558	1.41	2.84	2.14	3.55
0.50	3419	2.21	3.80	2.69	4.90
0.60	4315	3.12	4.79	3.23	6.35
0.67	5168	3.90	5.74	3.79	7.69
0.72	5790	4.50	6.43	4.18	8.68
0.77	6434	5.00	7.15	4.65	9.65
0.81	6964	5.50	7.74	4.99	10.49
0.88	7974	5.90	8.86	5.91	11.81
1.42	16784	10.9	18.65	13.20	24.10
2.00	26291	14.9	29.21	21.76	36.66

Table A.4
Hydrograph Routing Through the Bioswale

Time (minutes)	Inflow (cfs)	Average Inflow (cfs)	(S_1/Δt –O_1/2) At beginning of time interval (cfs)	(S_2/Δt –O_2/2) At end of time interval (cfs)	Outflow (cfs)
0	0	-	-	-	0.0
15	1.0	0.5		0.5	0.0
30	1.5	1.3	0.0	1.3	0.2
45	4.5	3.0	1.1	4.1	1.7
60	6.0	5.3	2.0	7.3	3.4
75	7.0	6.5	3.5	10.0	5.2
90	8.5	7.8	4.8	12.6	6.2
105	9.0	8.8	6.3	15.1	7.2
120	9.0	9.0	7.8	16.8	7.9
135	7.5	8.3	8.8	17.1	8.1
150	4.0	5.8	9.1	14.9	7.2
165	2.2	3.1	7.8	10.9	5.7
180	1.4	1.8	5.4	7.2	3.6
195	1.0	1.2	3.6	4.8	2.1
210	0.7	0.9	2.7	3.6	1.5

Table A.5

Flow From the Site into Bioswale and Bypass Pipe Without the Orifice Plate

Q in (cfs)	Q bypass (cfs)	Q splitter (cfs)
2.3	0.0	2.3
5.5	0.0	5.5
5.9	0.7	6.6
10.9	3.1	14.0
14.9	7.4	22.3
18.4	13.2	31.6
21.4	20.5	41.9
24.1	25.0	49.1
25.8	29.4	55.2
28.2	39.7	67.9
31.1	50.6	81.7
33.2	62.7	95.9
35.7	75.0	110.7
36.4	88.0	124.4
37.1	100.9	138.0
37.9	114.1	152.0
38.7	125.9	164.6
39.5	137.2	176.7
40.3	147.3	187.6

Table A.6
Depth-Volume-Outflow Relationships for Bioswale Forebay, Bioswale Backbay and Natural Area

Unit	**Depth (ft.)**	**Surf. Area (sq. ft.)**	**Volume (cu. ft.)**	**Treated Outflow (cfs)**
Bioswale Forebay	0.00	0.00	0.00	0.00
	0.50	2860	1430	0.11
	1.00	2860	2860	0.47
	1.50	2860	4290	0.71
	2.15	2860	6149	1.51
	2.20	2860	6292	2.47
	2.22	2860	6349	2.92
	2.25	2860	6435	3.69
	2.27	2860	6492	4.25
	2.30	2860	6578	5.14
	2.35	2860	6721	6.79
	2.40	2860	6864	8.61
	2.45	2860	7007	10.59
	2.50	2860	7150	12.72
	2.60	2860	7436	17.38
	2.70	2860	7722	22.53
Bioswale Backbay	0.00	0.00	0.00	0.00
	0.25	2851	537	0.00
	0.75	9280	3419	2.21
	1.00	12865	6155	4.70
	1.05	15639	6820	5.40
Natural Area	0.00	11484	0.00	0.0
	1.00	29387	19747	12.4
	2.00	41831	55174	32.3
	3.00	50439	107140	43.3
	4.00	60191	176897	52.1
	6.00	86480	362639	98.5
	7.00	163954	510937	137.3
	8.00	230492	735449	186.4

Appendix B

Table B.1
Bioswale Plant List

Planting Area	Scientific name	Common Name
Forebay	*Eleocharis palustris*	Spike Rush
	Anemopsis californica	Yerba Manza
	Lilium pardolinum	Water Lilly
Backbay	*Scirpus maritimus*	Bull Rush
	Scirpus californica	Bull Rush
	Distichlis spicata	Salt Grass
	Juncus patens	Common Rush
	Cyperus eragrostis	Common Cyprus
	Juncus phaeocephalus	Brown Headed Creeping Rush
Dam	*Artemesia californica*	California Sagebrush
	Baccaris pilularis	
	Diplacus duranliucus	Monkeyflower
	Elymus condensatus	Giant Ryegrass
Bank	*Plantanus racemosa*	Western Sycamore
	Populus fremonti	Fremont Cottonwood
	Acer negundo	Boxelder
	Quercus agrifolia	Live Oak
	Prunus lyonii	Catalina Cherry
	Geteromeles arbutifolia	
	Rhus integrifolia	Lemonade Berry
	Nassella pulchra	Purple Needlegrass
	Berberis nevinii	Barkberry
	Rubus ursinus	California Blackberry
	Artemesia douglasii	Mugwort
	Rosa californica	California Wild Rose

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Appendix D

Chemical Sampling Data

Table D.1. Water Sampling Data from 11/7/98 Sampling Event at K-Mart.

Date	**11/7/98**						
Sample I.D.			K-Mart 1	K-Mart 2	K-Mart 3	K-Mart 4	
Time			4:20 p.m.	5:24 p.m.	5:40 p.m.	6:00 p.m.	
Avg. Flow (cfs)			0.005	0.029	0.058	0.032	
Constituent	Test Method	Detection Limit					K-Mart EMC
TPH (mg/L)	EPA 418.1	10	3	7.6	7.1	2.1	6
Lead (mg/L)	EPA 200.8	0.005	0.01	0.013	0.014	0.008	0
Total P as Phosphorous (mg/L)	SM 4500-P	0.2	4	5.7	14	8	10
Total P as Phosphate (mg/L)	SM 4500-P	0.6	12	17	42	24	30
Total Alkalinity (mg/L) CaCO3	EPA 310.1	5.0	66	110	74	82	84
Calcium (mg/L)	EPA 200.8	0.5	86	51	50	35	48
Chloride (mg/L)	EPA 300.0	0.5	320	740	260	84	329
Hardness (mg/L) CaCO3	Calculation	5.0	320	220	190	130	187
Magnesium (mg/L)	EPA 200.8	0.1	26	25	16	8.8	17
Nitrate (NO3-N) (mg/L)	EPA 300.0	0.5	6.2	2.4	2.4	2	2
Nitrite (NO2-N) (mg/L)	EPA 300.0	0.5	0	0	1.1	0.5	1
pH	EPA 9040	-	7.1	7.3	7.2	7.2	7
Potassium (mg/L)	EPA 200.8	0.5	27	26	43	27	34
Sodium (mg/L)	EPA 200.8	0.5	220	180	110	46	114
Conductance (umhos/cm)	EPA 120.1	1.0	1500	2800	1200	620	1437
Sulfate (mg/L)	EPA 300.0	0.5	130	140	99	49	97
Total Dissolved Solids (mg/L)	EPA 160.1	5.0	1400	1900	1200	570	1209
Total Suspended Solids (mg/L)	EPA 160.2	5.0	20	18	18	41	24

Table D.2. Soil Sampling Results for Composite Forebay Soil Collected on 1/19/99.

Constituent	Ontario Ministry of Environment and Wisconsin Dept. of Natural Resources Sediment Quality Critera mg/kg (ppm)	Forebay Composite Results mg/kg (ppm)
TPH	100	230
Total P as Phosphorous	600	700
Total P as Phosphate		2100
Antimony		nd
Arsenic	10	nd
Barium		61
Beryllium		nd
Cadmium	1	nd
Chromium	100	16
Cobalt	25	6.9
Copper	100	7.8
Lead	50	5.7
Mercury	0.1	nd
Molybdenum	4	nd
Nickel	100	95
Selenium	2	nd
Silver	0.5	nd
Thallium		nd
Vanadium		16
Zinc	100	44

nd = not detected

Source: Baudo, *et al.,* 1990

Table D-3. Water Sampling Data from 1/24/99 Sampling Event at Camino Real Bioswale and Natural Area.

Date	**1/24/99**		Bioswale	Bioswale	Bioswale	
Sample I.D.			Inlet 1	Inlet 2	Inlet 3	
Time			3:33 p.m.	4:05 p.m.	4:33 p.m.	
Avg. Flow (cfs)			3.12	3.37	2.85	
Constituent	Test Method	Detection Limit				Inlet EMC
TPH (mg/L)	EPA 418.1	10	nd	nd	nd	nd
Total Alkalinity (mg/L) CaCO3	EPA 310.1	5.0	27	26	28	27
Calcium (mg/L)	EPA 200.8	0.5	8.7	8	9.4	9
Chloride (mg/L)	EPA 300.0	0.5	6.5	4	5.7	5
Copper (mg/L)	EPA 200.8	0.01	nd	nd	nd	nd
Hardness (mg/L) CaCO3	Calculation	5.0	31	27	32	30
Magnesium (mg/L)	EPA 200.8	0.05	2.3	1.7	2	2
Nitrate (NO3-N) (mg/L)	EPA 300.0	0.5	nd	nd	nd	nd
pH	EPA 9040	-	8.5	8.6	8.8	9
Potassium (mg/L)	EPA 200.8	0.5	4	3.6	4.4	4
Sodium (mg/L)	EPA 200.8	0.5	9.7	7.3	9.7	9
Conductance (umhos/cm)	EPA 120.1	1.0	110	82	96	96
Sulfate (mg/L)	EPA 300.0	0.5	15	9.4	12	12
Total Dissolved Solids (mg/L)	EPA 160.1	5.0	110	80	99	96
Total Suspended Solids (mg/L)	EPA 160.2	5.0	32	29	21	28
Zinc	EPA 200.8	0.01	nd	nd	nd	nd

Date	**1/24/99**		Bioswale	Bioswale	Bioswale		Natural	Natural	Natural	
Sample I.D.			Outlet 1	Outlet 2	Outlet 3		Area 1	Area 2	Area 3	
Time			4:23 p.m.	4:53 p.m.	5:23 p.m.		5:13 p.m.	5:43 p.m.	6:13 p.m.	
Avg. Flow (cfs)			2.6	2.2	1.9		4.6	3.1	3.1	
Constituent	Test Method	Detection Limit				Outlet EMC				Nat. Area EMC
TPH (mg/L)	EPA 418.1	10	nd	nd	nd	nd	nd	nd	nd	nd
Total Alkalinity (mg/L) CaCO3	EPA 310.1	5.0	42	39	37	40	41	46	40	42
Calcium (mg/L)	EPA 200.8	0.5	12	13	11	12	13	15	14	14
Chloride (mg/L)	EPA 300.0	0.5	13	12	9.7	12	11	14	10	12
Copper (mg/L)	EPA 200.8	0.01	nd	nd	nd	nd	nd	nd	nd	nd
Hardness (mg/L) CaCO3	Calculation	5.0	54	52	43	50	49	59	51	52
Magnesium (mg/L)	EPA 200.8	0.05	5.7	5	3.4	5	4.4	5.1	4.2	5
Nitrate (NO3-N) (mg/L)	EPA 300.0	0.5	nd	nd	nd	nd	nd	nd	nd	nd
pH	EPA 9040	-	8.1	8.2	8.3	8	8.1	7.8	8.1	8
Potassium (mg/L)	EPA 200.8	0.5	5.2	5.3	4.7	5	6	5.5	6.1	6
Sodium (mg/L)	EPA 200.8	0.5	21	19	15	19	17	20	18	18
Conductance (umhos/cm)	EPA 120.1	1.0	180	160	140	162	160	190	150	166
Sulfate (mg/L)	EPA 300.0	0.5	33	29	23	29	26	31	22	26
Total Dissolved Solids (mg/L)	EPA 160.1	5.0	160	140	120	142	130	160	130	139
Total Suspended Solids (mg/L)	EPA 160.2	5.0	62	41	34	47	23	19	23	22
Zinc	EPA 200.8	0.01	nd	nd	nd	nd	nd	nd	nd	nd

Table D.4. Water Sampling Data from 1/31/99 Sampling Event at Camino Real Bioswale.

Date	1/31/99		Bioswale	Bioswale	Bioswale	Bioswale	Bioswale	Bioswale
Sample I.D.			Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5	Inlet 6
Time			12:31 a.m.	12:46 a.m.	1:01 a.m.	1:16 a.m.	1:31 a.m.	1:45 a.m.
Avg. Flow (cfs)			1.66	1.15	1.15	0.87	0.61	0.33
Constituent	Test Method	Detection Limit						
Total P as Phosphate (mg/L)	Flow Inj. Analysis	0.1 uM	19.6	9.7	8.3	9.3	8.2	10.2
Nitrate (NO3-N) (mg/L)	Flow Inj. Analysis	0.5 uM	69.3	66.9	47.7	74.5	50.5	76.7
Nitrite (NO2-N) (mg/L)	Flow Inj. Analysis	0.1 uM	7.7	6.2	4.6	7.4	5.4	7.7
Ammonia (NH3-N) (mg/L)	Flow Inj. Analysis	0.1 uM	194	137	152	167	107	123
Copper (mg/L)	flame AAS	0.01 mg/L	0.02	0.01	0.01	0.01	0.01	0.01
Lead (mg/L)	flame AAS	0.03 mg/L	0.16	0.15	0.06	0.06	0.04	0.04
Zinc (mg/L)	flame AAS	0.005 mg/L	0.018	0.037	0.042	0.071	0.058	0.081
Total Suspended Solids (mg/L)	EPA 160.2	5.0	641	290	187	250	154	213

Date	1/31/99			Bioswale	Bioswale	Bioswale	Bioswale	
Sample I.D.				Outlet 1	Outlet 2	Outlet 3	Outlet 4	
Time				1:07 a.m.	1:28 a.m.	1:43 a.m.	1:58 a.m.	
Avg. Flow (cfs)				0.14	0.25	0.25	0.36	
Constituent	Test Method	Detection Limit	Inlet EMC					Outlet EMC
Total P as Phosphate (mg/L)	Flow Inj. Analysis	0.1 uM	12	5.7	6.8	6.4	7.3	7
Nitrate (NO3-N) (mg/L)	Flow Inj. Analysis	0.5 uM	64	42.9	39	45	51.8	46
Nitrite (NO2-N) (mg/L)	Flow Inj. Analysis	0.1 uM	6	4.2	3.9	5	5.5	5
Ammonia (NH3-N) (mg/L)	Flow Inj. Analysis	0.1 uM	157	157	146	129	116	132
Copper (mg/L)	flame AAS	0.01 mg/L	0.01	0.01	0.01	0.01	0.01	0.01
Lead (mg/L)	flame AAS	0.03 mg/L	0.10	0.06	0.04	0.03	0.01	0.03
Zinc (mg/L)	flame AAS	0.005 mg/L	0.04	0.037	0.03	0.028	0.032	0.03
Total Suspended Solids (mg/L)	EPA 160.2	5.0	346	347	411	252	781	495

Table D.5. Water Sampling Data from 2/9/99 Sampling Event at Camino Real Bioswale and Natural Area.

Date	**2/9/99**		Bioswale	Bioswale	Bioswale		Bioswale	Bioswale
Sample I.D.			Inlet 1	Inlet 2	Inlet 3		Outlet 1	Outlet 2
Time			6:08 a.m.	6:38 a.m.	7:08 a.m.		7:05 a.m.	7:38 a.m.
Avg. Flow (cfs)			3.5	3.3	3		2.6	1.9
Constituent	Test Method	Detection Limit				Inlet EMC		
TPH (mg/L)	EPA 418.1	10	nd	nd	nd	nd	nd	nd
Total P as Phosphate (mg/L)	Flow Inj. Analysis	0.1 uM	4.9	4.3	4.9	5	6	5.6
Nitrate (NO3-N) (mg/L)	Flow Inj. Analysis	0.5 uM	17.9	12.9	15.8	16	20.8	24.7
Nitrite (NO2-N) (mg/L)	Flow Inj. Analysis	0.1 uM	1.7	1.4	1.6	2	2	2.4
Ammonia (NH3-N) (mg/L)	Flow Inj. Analysis	0.1 uM	149	89	152	130	162	92
Copper (mg/L)	flame AAS	0.01 mg/L	0.04	0.01	0	0.02	0.01	0
Lead (mg/L)	flame AAS	0.03 mg/L	0.01	0	0	0.00	0	0
Zinc (mg/L)	flame AAS	0.005 mg/L	0.028	0.018	0.01	0.02	0.028	0.018
Total Suspended Solids (mg/L)	EPA 160.2	5.0	289	245	271	269	243	235
Date	**2/9/99**		Bioswale		Natural	Natural	Natural	
Sample I.D.			Outlet 3		Area 1	Area 2	Area 3	
Time			8:16 a.m.		8:05 a.m.	8:38 a.m.	9:24 a.m.	
Avg. Flow (cfs)			1		5.2	4.6	5.2	
Constituent	Test Method	Detection Limit		Outlet EMC				Nat. Area EMC
TPH (mg/L)	EPA 418.1	10	nd	nd	nd	nd	nd	nd
Total P as Phosphate (mg/L)	Flow Inj. Analysis	0.1 uM	5.6	6	5.7	4.8	5.3	5
Nitrate (NO3-N) (mg/L)	Flow Inj. Analysis	0.5 uM	20.9	22	16.7	12.1	19.9	16
Nitrite (NO2-N) (mg/L)	Flow Inj. Analysis	0.1 uM	2.1	2	1.7	1.3	2	2
Ammonia (NH3-N) (mg/L)	Flow Inj. Analysis	0.1 uM	88	124	165	97	129	132
Copper (mg/L)	flame AAS	0.01 mg/L	0	0.01	0	0	0	0.00
Lead (mg/L)	flame AAS	0.03 mg/L	0	0.00	0.01	0	0	0.00
Zinc (mg/L)	flame AAS	0.005 mg/L	0.018	0.02	0.013	0.008	0.01	0.01
Total Suspended Solids (mg/L)	EPA 160.2	5.0	201	233	218	225	215	219

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