COUNTY OF SAN DIEGO
MODEL MUNICIPAL OPERATIONS CENTER

Final Report
Phase II Porous Paving and Treatment Train
Water Quality Monitoring Program

Oblique view of County Operations Center –Google Earth Pro

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SEPTEMBER 2008

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INTRODUCTION

In 2003, the County of San Diego Department of General Services developed the concept of using the County Operations Center (COC) as a model site for demonstrating the use of enhanced source control and treatment control best management practices (BMPs) in the San Diego River Watershed Management Area (WMA). The intent of this project was to demonstrate how municipalities could provide leadership in improving water quality by making changes at existing facilities and improving the design and construction of future facilities. The project was also intended to demonstrate to the municipalities, the development community, and the design community the potential for using porous paving to reduce urban runoff and limit modification of stream hydrology in future new development and significant redevelopment projects. Implementation of this project was designed to help towards addressing three goals of the San Diego River Watershed Urban Runoff Management Plan and provide information to assist in meeting the surface water quality and flood control goals of the San Diego River Watershed Management Plan.

BACKGROUND AND OVERVIEW

As is common in both commercial and industrial districts, vehicle parking areas represent the largest amount of impervious surface at the COC. Parking lots associated with the COC comprise roughly 66 percent of the 35.45 acres of the COC. Another 25 percent of the COC consists of other impervious areas, mostly rooftops and sidewalks. Overall, 91 percent of the COC consists of impervious surfaces. The high percentage of impervious surfaces at the COC leads to increased stormwater runoff and pollutant loading. This demonstration project was designed to examine BMPs to both reduce runoff and increase the quality of water discharged from the site and serve as an regional example as to how these goals can be accomplished at similar sites throughout the County.

This project was comprised of two major elements. The first element was designed to examine the effects of reducing overall discharges by incorporation of infiltration BMPs. The second element was designed to assess the ability of a treatment train to remove contaminants of concern that tend to be associated with the particulate fraction before they leave the site. The general locations of the porous paving and treatment train demonstration sites are shown in Figure 1.

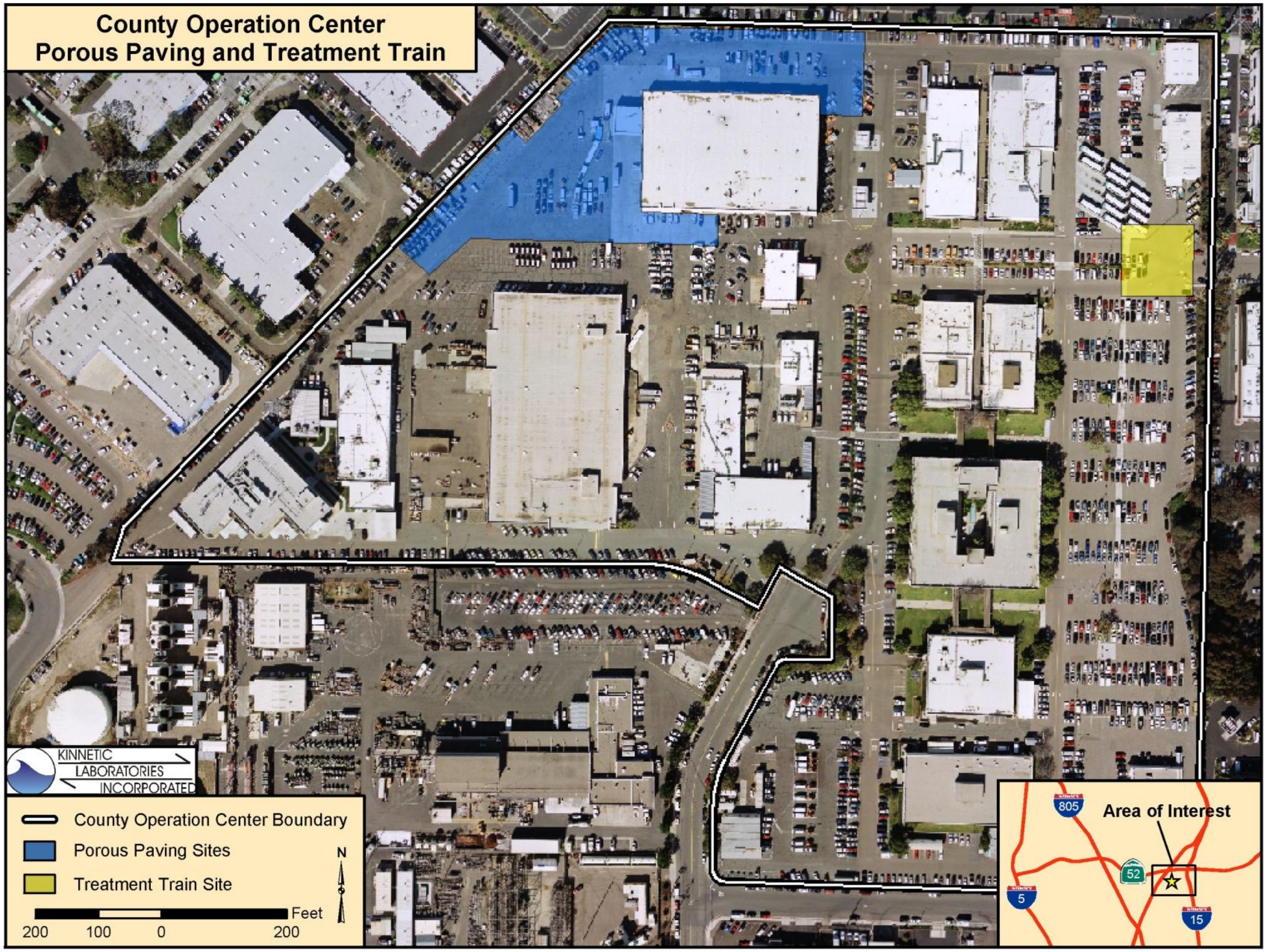

Figure 1. General Location of the Porous Paving and Treatment Train Demonstration Sites at the County Operations Center.

Stormwater runoff from impervious pavements is one of the primary sources of pollutant loading to surface waters in the San Diego River watershed and other watersheds in the County. This is especially true for pavements utilized by automotive vehicles for transportation or parking, where residual hydrocarbons and metals combine with sediment particles and organic detritus to produce a significant pollutant load which is scoured from the land surface with any significant rainfall. The best solution is to eliminate any direct runoff from impervious surfaces and infiltrate the rainfall, recharging the aquifer system. The Center for Watershed Protection[1] and others have clearly demonstrated the importance of imperviousness and the functional relationships between impervious surface areas and stream quality. As a general rule, indicators of stream quality indicators start to shift to a poor condition as the effective impervious area of the watershed reaches 25 to 30%.

The DGS has been conducting a pilot program to evaluate performance of various types of porous pavement as a method to control runoff quantity and quality at the source and thus start to address the environmental damage caused by increasing quantities of stormwater runoff and pollutants associated with that runoff. During the first phase of this program, the County replaced approximately 64,000 square feet of traditional imperious pavement with three different types of porous paving materials at the COC. The three types of porous paving materials included roughly 7,896 square feet of EcoStone concrete pavers, 14,936 square feet of porous concrete, and 41,092 square feet of porous asphalt. An adjacent area consisting of 36,209 square feet of older traditional asphalt was initially isolated to serve as a reference site.

During the second phase, an additional 54,000 square feet of existing pavement at the COC was removed and replaced with three combinations of porous pavement types, reinforcement materials and reservoir configurations. The porous pavement was installed over an aggregate reservoir base to store water in order to reduce runoff and promote infiltration. A portion of the reservoir under the second phase, porous asphalt was designed with added capacity necessary to accept roof runoff from an adjacent building and runoff from an adjacent section of impervious parking lot. The initial reference area was maintained and monitored separately during the 2006/2007 rainy season in order to measure runoff reduction and estimate reductions in pollutant concentrations and loads. Most of the reference area used in the initial stages of this program was disrupted due to construction of the new Medical Examiners (ME) building that started in 2007. The reference area was reconfigured for the 2007/2008 rainy season to isolate water from an adjacent area yet still discharge at the same location to facilitate use of the previously installed flume used to allow accurate measurement of runoff.

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[1] Schueler, T.R. and H.K Holland, Editors (2000) The Practice of Watershed Protection: Article 1, WatershedProtection Techniques 1(3):100-111

Runoff quality and quantity from portions of the roof were expected to differ substantially from runoff derived from the impervious asphalt in the parking lot. The site selected to monitor roof runoff was therefore considered as a second reference site to be used to estimate flow and load reductions that can be achieved by directing roof runoff into the infiltration beds. Due to the increasing amounts of runoff being directed to the infiltration beds, lysimeters were installed at porous asphalt and concrete sites developed during the second phase of the program. The lysimeters were used to sample water as it infiltrated through the soils.

The initial pilot treatment train was installed near the eastern edge of the COC property to provide treatment of the stormwater prior to discharge to the City of San Diego's municipal storm drain system. The first portion of the treatment train consisted of a Continuous Deflective Separation (CDS) unit designed to remove up to 80% of the suspended solids and 100% of the floatables. During the initial phase, this was followed by a single Media Filtration System (MFS) that provided filtration through perlite media filters to remove remaining suspended solids. During this period, the MFS unit was equipped with an internal bypass that allowed untreated water to flow over a weir and out the effluent side whenever flow exceeded the capacity of the filters. Both systems were manufactured by CDS Technologies which since was acquired by CONTECH Stormwater Solutions.

Under the second phase of this program, three more filtration treatment units (one additional MFS unit and two StormFilter systems were added to the treatment train. As a result of the increased infiltration capacity added by the expanded porous paving installations and the addition of these three new filtration units, 100 percent of the runoff passing through the CDS unit passed through the treatment train. The internal bypass incorporated in the original MFS unit was eliminated as part of the final modifications. Each of the four filtration systems was fitted with a variety of media and filter configurations. This was intended to enable direct comparisons of the performance of different types of media in removing constituents of concern. Dissolved metals were of primary concern but removal of other constituents such as TSS/SSC and nutrients were also to be assessed.

This report presents the results of the second phase (Phase II) of the program but also incorporate results from the initial phase for discussion and interpretation.

GOALS AND OBJECTIVES

Goals and objectives for continuation of monitoring at the existing sites and for monitoring of the new sites were generally consistent with those established during Phase I of this program. The only differences involved 1) the addition of a roof runoff site to examine contaminants associated with both atmospheric deposition and roof top sources and 2) the inclusion of lysimeters to examine water quality as stormwater is infiltrated.

Porous Paving

This element of the study was designed to monitor and evaluate the effectiveness of the five configurations of porous pavement systems in reducing runoff and removing constituents of concern including solids, nutrients, and trace metals. Testing the performance of each type of porous pavement was intended to involve comparisons of both the quantity and quality of stormwater discharges from each type of pavement with stormwater runoff from the adjacent reference site.

The program was designed to address the following questions:

- ✓ How do normalized[2] stormwater discharges from each treatment type compare to normalized runoff from the reference area by both individual storm events and for the entire storm season?
- ✓ How does water quality of stormwater discharges from each treatment type, measured in terms of flow-rated event mean concentrations, compare to the quality of runoff from the reference area?
- ✓ How do the infiltration basins associated with each of the porous surface treatments impact stormwater discharge hydrographs?
- ✓ How do normalized pollutant loading rates[3] associated with each porous surface treatment compare to those of the adjacent impervious reference area?
- ✓ At what rates do water levels in the infiltration basins of each treatment type change during and between storm events?
- ✓ How does water quality and pollutant loading from building roofs compare to runoff from the reference area?
- ✓ Is water infiltrating through soils underlying the infiltration basin and how does water quality change during the process of infiltration?

Treatment Train

The objective of this element of the program is to evaluate the pollutant removal efficiencies of the treatment technologies. The two different treatment technologies were assessed individually and as a treatment train. The first treatment control device is a CDS unit. After gross solids are removed by the CDS unit the system was designed to provide filtration through one of four different configurations. The filtration units include two MFS units and two StormFilter units to make up filtration component of the treatment train. Each of the filtration

[2] All data will be normalized to a standard area to allow comparisons of data from widely differing areas for each of the three porous treatment type.

[3] The normalized loading rate will be defined as the mass of each constituent per unit area per inch of rain.

units has equivalent treatment capacity. Construction of the expanded system was not completed until the 2007/2008 wet season. Prior to that time, the configuration remained the same as during the Phase I studies. This included a single MFS unit preceded by a CDS unit. Since not all water could be treated by the MFS unit, a portion of the flow was redirected back into the main storm drain. At that time, flow entering the MFS unit could also go through an internal bypass when the filters could not handle the full volume.

The Mass Balance Approach was utilized to characterize the removal effectiveness of the CDS unit. The CDS unit was designed to remove trash and litter, vegetative material, and sediments.

The program is designed to address the following questions:

- ✓ What is the total volume of stormwater processed by the CDS unit for the monitoring event and for the season?
- ✓ What are the mass and general characteristics of solids removed by the CDS unit at the end of the monitoring period?
- ✓ What is the mass of each target pollutant in the sediment portion of the solids removed by the CDS unit?
- ✓ What are the volume and pollutant loads entering each filtration unit and the volume and pollutant loads after treatment?
- ✓ Does the treated stormwater meet receiving water quality standards?

SEASONAL RAINFALL AT THE COUNTY OPERATIONS CENTER

The San Diego County Operations Center (COC) is located within Hydrologic Sub-Area 907.11 at an elevation of approximately 415 feet. This region, also known as the Mission San Diego Sub-Area, discharges to the Lower San Diego River. According to the CSU Sacramento, Office of Water Program, Water Quality Planning Tool (http://www.water-programs.com/), this region receives average annual rainfall of 12.7 inches. This is slightly greater than the 10.29 average annual rainfall reported at Lindbergh Field (http://www.sdcwa.org/manage/rainfall-lindbergh.phtml) near the northern end of San Diego Bay.

The San Diego Water Authority maintains an ALERT precipitation gauge near their offices in the COC. Data from this site, known as KEA, are available in near real-time through the California Data Exchange Center (http://cdec.water.ca.gov/). This site also maintains historical records.

Rainfall has fallen below normal levels for the last three years with the 2006/2007 being the driest. Rainfall during the 2006/2007 wet season was 42% of normal at the COC and 35% of normal precipitation at Lindbergh Field (Table 1, Figure 2 through Figure 4). The 2007/2008 season was the wettest of the three but nearly half the precipitation occurred in the month of January. March, April and May of 2008 yielded a cumulative rainfall of only 0.07 inches at the COC.

Table 1. Summary of Wet Season (October 2005 through May 2008) Rainfall Measured at the Kearny Mesa and Lindbergh Field Precipitation Gauges.

Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
Kearny Mesa (KEA)									
2005/2006	0.90	0.04	0.24	0.79	1.34	2.48	1.61	0.75	**8.15**
2006/2007	0.55	0.27	0.79	0.59	2.24	0.32	0.59	0.00	**5.35**
2007/2008	0.16	1.93	1.54	4.55	2.33	0.07	0.00	0.00	**10.58**
Lindbergh Field (SDG)									
2005/2006	0.46	0.12	0.25	0.36	1.11	1.36	0.88	1.41	**5.95**
2006/2007	0.76	0.15	0.53	0.51	1.12	0.09	0.46	0.00	**3.62**
2007/2008	0.37	0.97	0.80	3.34	1.21	0.26	0.00	0.23	**7.18**

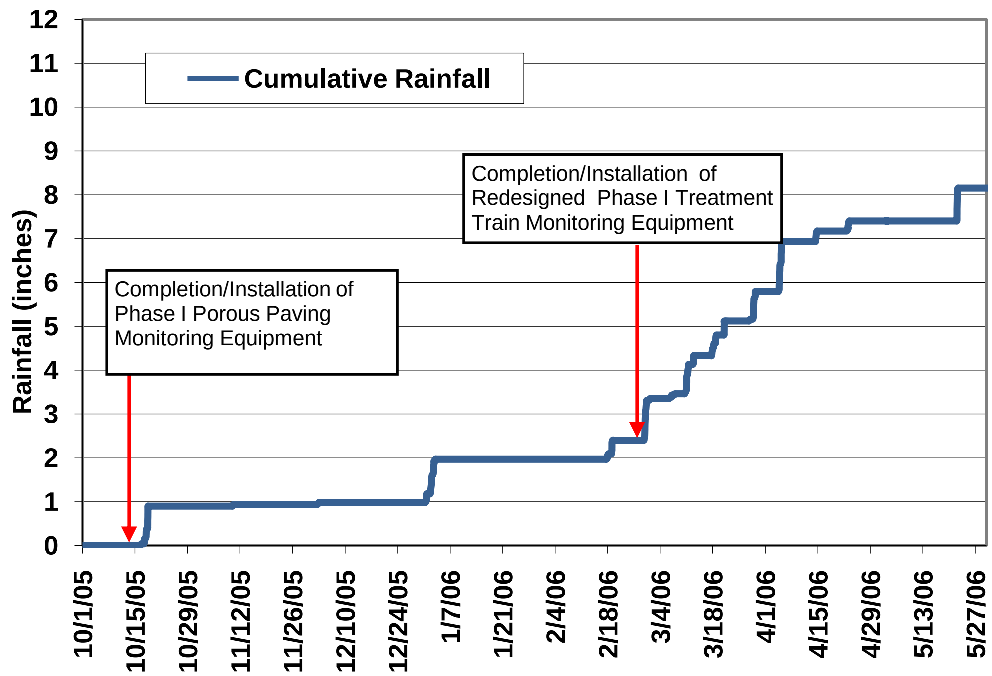

Figure 2. Cumulative Rainfall and Key Milestones at the COC during the 2005/2006 Wet Season (data from KEA Rain Gauge)

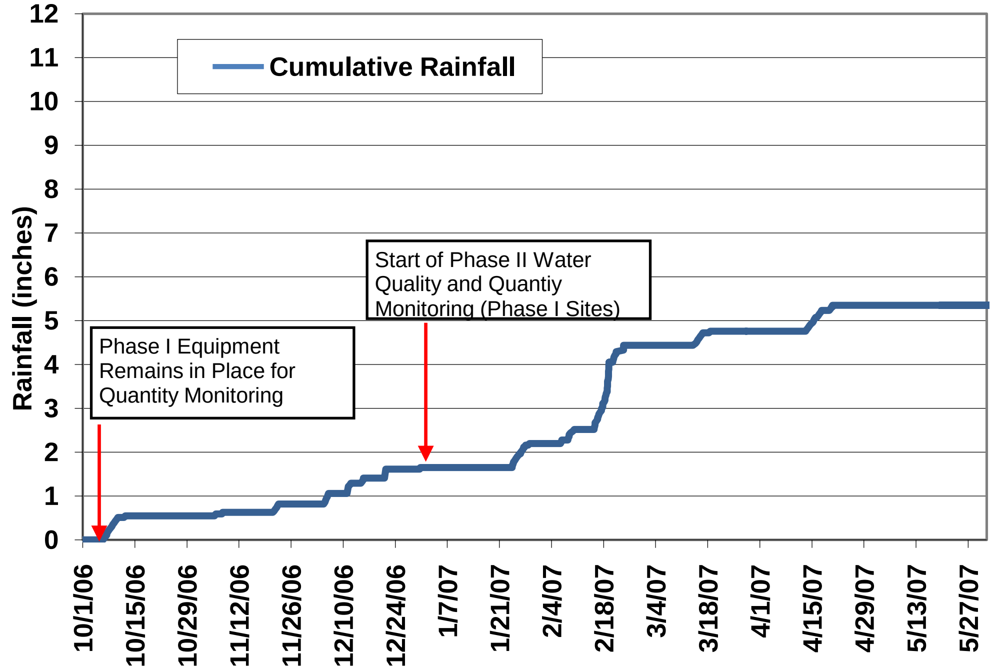

Figure 3. Cumulative Rainfall and Key Milestones at the COC during the 2006/2007 Wet Season (data from KEA Rain Gauge)

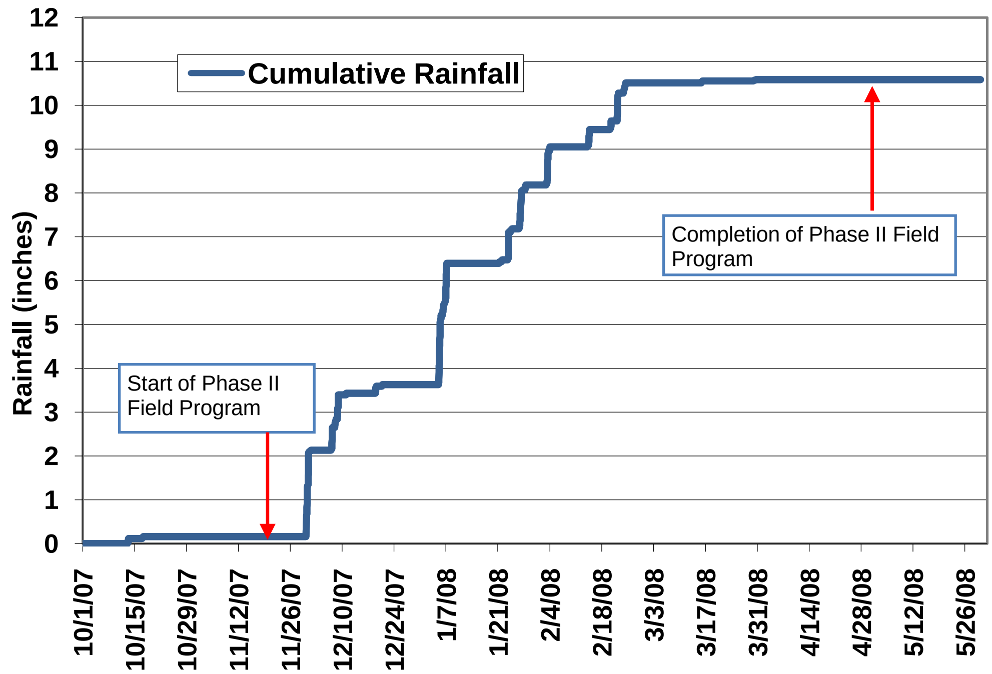

Figure 4. Cumulative Rainfall and Key Milestones at the COC during the 2007/2008 Wet Season (data from KEA Rain Gauge)

Figure 2 through Figure 4 provide a summary of rainfall and key milestones during both Phase I and II of the project. Initiation of sampling efforts at the Phase I porous paving and treatment sites during the 2005/2006 storm season is noted on Figure 2. Phase I equipment installations at the porous paving sites were fully operational in time for the first event of the season in 2005. Some delays were experienced in implementing monitoring at the Treatment Train site due to a need to redesign the monitoring system to facilitate improvements in measuring stormwater flow entering the MFS unit, treated stormwater exiting the system and flow over the internal bypass weir. In addition, the system needed to be altered to assure that the effluent monitoring system collected only treated water. All required Phase I monitoring was completed during the 2005/2006 season but equipment was reinstalled at the start of the 2006/2007 season to assure that rainfall and runoff data was recorded. Phase II sampling started in January 2007 at the reference site, three porous paving sites and treatment train facilities that were previously developed during Phase I of the project. Construction of the two Phase II porous paving sites and the expanded treatment train began in the summer of 2007. Construction was complete and monitoring equipment installed at all the new sites by mid-November 2007. Phase II monitoring then continued through April 30, 2008.

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POROUS PAVING

The following sections provide a thorough discussion of monitoring methods at each of the porous paving sites, the parking lot reference sites and the roof reference site. Results are presented for the Phase II monitoring program. The discussion incorporates results of both Phase I and II of the Model Municipal Operations Center program.

METHODS

Information on site locations, sampling frequencies, sampling handling and collection, and quality control procedures were detailed in two separate documents. The Sampling and Analysis Plan (Kinnetic Laboratories, Inc., 2005a) and Quality Assurance Project Plan (Kinnetic Laboratories, Inc., 2005b) detailed the approach and methods used to conduct the Phase I studies. These documents also served as the basis for initial Phase II monitoring performed during the 2006/2007 monitoring season prior to completion of the new Phase II porous paving sites and expanded treatment train. A new Quality Assurance Project Plan and Monitoring Plan (QAPP/MP) (Kinnetic Laboratories, Inc., 2007) was developed for the expanded Phase II program. This plan was approved by the Regional Board on October 2, 2007. Monitoring methods in the new QAPP/MP remained consistent with the Phase I program but incorporated additional information to address the new sites and the addition of lysimeters.

Site Locations and Descriptions

During Phase I the County replaced approximately 64,000 square feet of traditional imperious pavement with three different types of porous paving materials at the COC; EcoStone concrete pavers, porous asphalt and porous concrete. Another 54,000 square feet of impervious asphalt was replaced with porous asphalt and porous concrete during construction of the Phase II improvements (Figure 7).

EcoStone Pavers – Phase I

EcoStone concrete pavers were installed as part of the Phase I work. The pavers were laid in a rectangular form along the northwestern edge of the property line (Figure 5 and Figure 7). As with all sites, including the reference site, the EcoStone pavers were isolated by berms to assure that the test sites were not subject to runon or runoff. Since some runoff was expected from the pavers, a catch basin was installed at the southwestern end to redirect any runoff from intense events back into the infiltration bed. A filtration system was installed in the catch basin to prevent introduction of coarser sediment and trash into the infiltration bed. The monitoring site was established at the southwestern edge of the EcoStone pavers (Figure 6).

Figure 5. EcoStone Paver Installation

Figure 6. EcoStone Paver Stormwater Monitoring Site

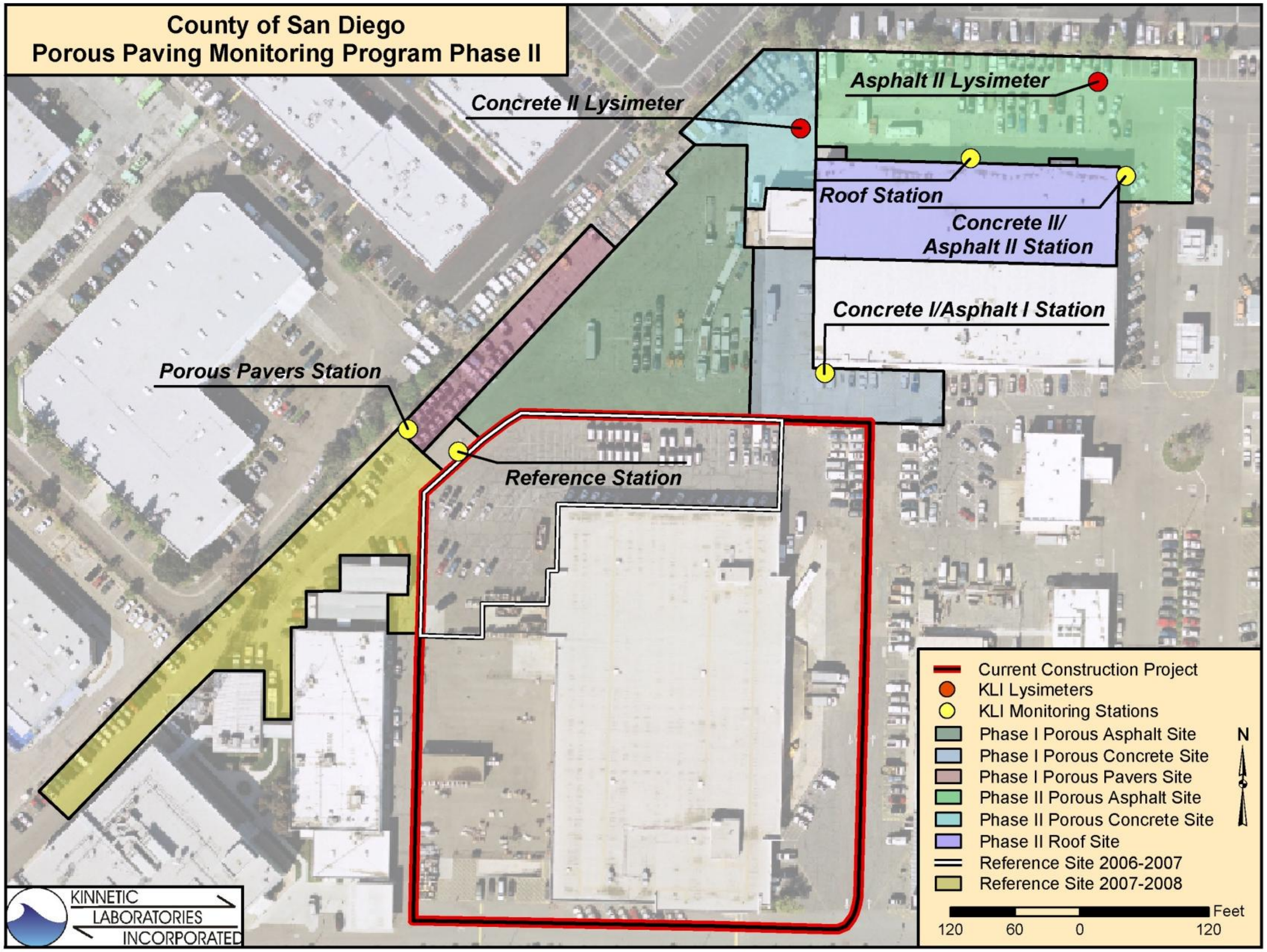


Figure 7. Porous Pavement/Infiltration System Layout

Table 2. Summary of Reference and Porous Treatment Areas

	Area	
Site	Square Feet	Square Meters
Reference Sites		
Phase I Reference	36,209	3,364
Phase II Reference	37,000	3,438
Roof Reference	26,150	2,430
Porous Treatments		
Phase I Pavers	7,896	734
Phase I Concrete	14,936	1,388
Phase I Asphalt	41,092	3,818
Phase II Concrete	12,100	1,124
Phase II Asphalt	41,900	3,894
+ Roof Reference	25,000	2,323
TOTAL TREATMENT AREA	**142,942**	**13,280**

Porous Concrete – Phase I

Porous concrete (14,936 square feet) was installed adjacent to Building 7 as part of the Phase I construction effort (Figure 7 through Figure 9, Table 2). The test site largely replaced an existing impervious concrete apron in this region. Figure 8 is a view looking north showing the transition from porous concrete to porous asphalt. The canopy of the Building 7 washdown area is visible in the upper right portion of the photograph. Figure 9 is a view looking to the west with the porous asphalt in the background. A portion of the Phase 1 reference area can be seem in the upper left portion of the photograph inside the yellow berm that was installed to assure isolation of the reference area and to prevent runoff from entering the porous concrete and porous asphalt sites.

The Phase 1 porous concrete and asphalt sites shared a common monitoring location situated at the corner of Building 7 (Figure 10 and Figure 11). A rain gauge was located on top of the building. A phone line was connected at this site and provided the link to all other sites. Radio modems allowed remote communication with the EcoStone concrete paver site, reference site as well as all treatment train monitoring sites located on the east side of the facility at Hazard Way.

Figure 8. Transition between Phase I Porous Concrete and Asphalt.

Figure 9. Southern Edge of Phase 1 Porous Concrete looking West.

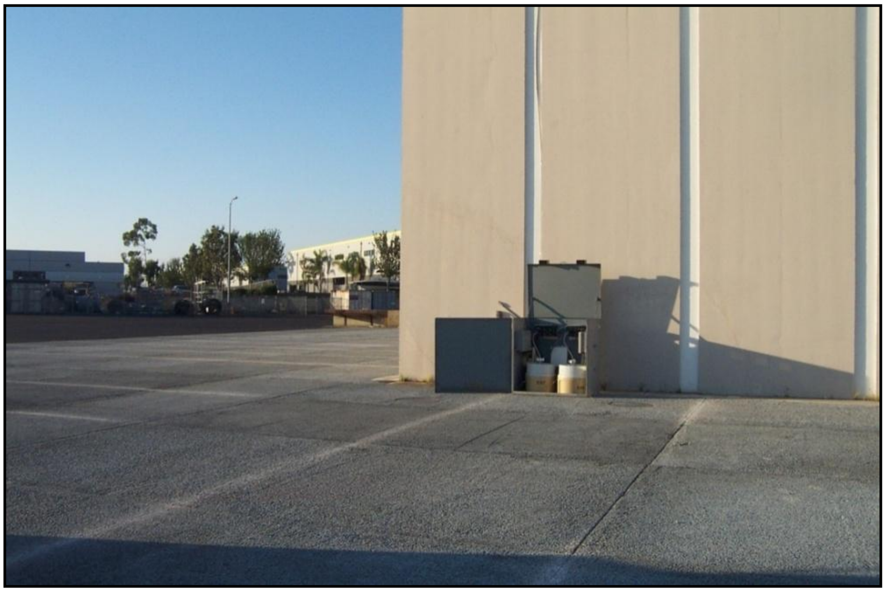


Figure 10. View of Porous Asphalt I/Concrete I Monitoring Site at Corner of Building 7.

Figure 11. Closeup of Phase I Porous Asphalt /Concrete Monitoring Site.

Porous Asphalt – Phase I

Porous asphalt formed the largest Phase I test site with over an area of 41,092 square feet (Figure 7). As previously noted, the Phase I porous asphalt and concrete sites shared a common monitoring location (Figure 10, Figure 11). Figure 12 provides a view towards the west during a storm event showing the Phase I parking lot reference site to the left of the yellow berm and the porous asphalt to the right.

Figure 12. View of Phase I Porous Asphalt and Reference Areas during a Storm Event in 2005.

Porous Concrete – Phase II

The Phase II Porous Concrete is located in the northwestern corner of the COC (Figure 7). The process of installing the porous concrete is shown in Figure 13. Black plastic necessary to maintain moisture is visible on alternating swaths of poured concrete in the background. The overflow structure (control basin) for the Phase II concrete (Figure 14) can be seen closest to the antiseep collar that was installed to prevent flow between the Phase II asphalt and concrete infiltration basins. The 8-foot inlet pipe that provides a conduit to the infiltration basin can be seen coming out of the concrete box on the left side of the photograph. This was later wrapped in geotextiles to prevent large particles from passing into the overflow system. Similar to all other porous paving sites, holes were drilled along the inlet pipe to allow water from the infiltration basin to enter. The inlet pipe was located at the bottom of the scarified layer which was about six inches deep.

Figure 13. Installaton of Phase II Concrete

Figure 14. Phase II Concrete Water Level Control Structure and Anti-Seep Collar

Figure 15. Phase II Concrete Control Basin showing the Weir.

Figure 15 shows the Phase II porous concrete weir used to control water levels in the infiltration basin. When water levels in the infiltration basin exceed the height of the weir, water is discharged through a pipe which goes to the sampling point located at the northeast corner of Building 7. The sampling points for both the Phase II concrete and asphalt were located at this site. The Phase II concrete discharge pipe ran to the east under the Phase II asphalt to a catchbasin located near the corner of the building. Flows entering the catchbasin were measured with a compound weir installed within the pipe just before it entered the monitoring catchbasin.

Discharge pipes from both the Phase II concrete and asphalt are shown in Figure 16. The sampling basins are visible in the background near Building 7. The Phase II concrete sampling basin is seen on the right. The drain pipe from the Phase II asphalt is visible in the foreground going to the sampling basin on the left near the building.

Figure 16. Phase II Concrete and Asphalt Drain Pipes Leading to Sampling Basins at the Corner of Building 7.

Porous Asphalt – Phase II

The Phase II porous asphalt was largest test site covering 41,900 square feet of the parking lot (Figure 7, Table 2). Runoff from 25,000 square feet of the roof at Building 7 was also directed into the underlying infiltration bed. Although a single infiltration bed was used for the asphalt, two different asphalt formulations were used and a geogrid was used with half of each type of formulation to assess how the formulations and geogrid impact durability. That evaluation was separate from the water quality testing and will require a longer period of time to fully assess performance of the different surfaces.

As noted in the previous section, the Phase II concrete and asphalt monitoring sites were located together at the northeastern corner of Building 7 (Figure 17). A hard-wire telephone line was installed to provide remote control and communication with this site. This site also provided communications with the roof reference site using a spread-spectrum radio link.

Figure 17. Phase II Porous Concrete and Asphalt Monitoring Enclosure and Equipment.

Lysimeter Sites

Suction lysimeters were installed at both of the Phase II porous paving sites (Figure 7) for use in collection of infiltrating water for water quality testing. Lysimeters were installed near each of the basin control structures, at a depth of 1.7' to 2.3' below the bottom of the scarified layer of the infiltration basins. Sampling ports for the lysimeters were located inside a utility box and were accessible by removal of a square cover.

Parking Lot Reference Sites

Both the Phase I and II reference areas consisted of an older, impervious asphalt surface. The cracked asphalt typical of the reference areas can be seen in the foreground of Figure 18. The Phase I Reference Area monitoring site collected runoff from 36,209 square feet of surface area (Figure 7, Table 2). The Phase I Reference Area Runoff was collected in a series of area drains that were connected to a one-foot H-flume (Figure 19). Construction of the new Medical Examiner Building starting in summer of 2007 required the reference area to be reconfigured for the 2007/2008 wet season since large portions of the Phase I reference area was being torn up and/or used for construction activities. An adjacent portion of the parking lot located along the western boundary of the COC was isolated to serve as a parking lot reference area during Phase II monitoring (Figure 7). Fortunately the location of the monitoring site used for Phase I (Figure 18) was able to be used for the Phase II testing. In both cases, runoff was directed through a 1-foot H-Flume (Figure 19) which then discharged to the existing storm drain.

Flow was monitored by a bubbler associated with a stilling adjacent to the flume. Stormwater was sampled from the bottom of the last area drain at the head of the flume where turbulence was sufficient to keep most solids well-mixed. This site also had a rain gauge and a solar panel (Figure 18) to maintain battery power for the water sampler, data logger, and communications.

Figure 18. Reference Area Monitoring Site looking towards the Phase I Porous Pavers and Asphalt Test Sites

Figure 19. One-foot H-Flume at Reference Monitoring Site.

Roof Runoff Reference Sites

The roof runoff reference site was located on the north side of Building 7 (Figure 7). This system drained roughly half of the roof or 25,000 square feet. This site used a manifold system to aggregate all downspouts from the north side of the Building into a single pipe. Runoff from the roof was directed through the manifold and down the side of the building (Figure 21). Approximately 18 inches before reaching ground level the pipe made a 90 degree angle and ran 45 feet along the wall at a 1% slope before turning down and being directed into the infiltration bed (Figure 20). An access port was cut in the top of the pipe at a distance of 30 feet past the downspout and 15 feet before entering the infiltration basin. This location was considered the optimal spot to measure flow. A Doppler flow meter was installed in the pipe to monitor flow. The autosampler intake hose was installed downstream of the flow sensor using a special low flow, intake strainer to allow effective sampling with relatively low water levels.

The roof runoff reference site served two purposes. First it allowed for the evaluation of contaminant concentrations and loads from roof tops. Secondly it allowed quantification of additional stormwater runoff volumes and pollutant loads to the Phase II asphalt infiltration basin. In addition, it also provided some insight as to atmospheric deposition of contaminants of concern.

Figure 20. Roof Reference Monitoring Site and Discharge Point into the Phase II Porous Asphalt Infiltration Basin.

Figure 21. Roof Reference Monitoring Site Showing Approach Section and Manifold Downspout.

Sampling Frequency

The program called for continuous monitoring of flow at all reference and porous paving sites throughout each wet season (October 1 through April 30). Monitoring of water quality was to be conducted in association with up to six storm events during each wet season. Storm events were considered viable for monitoring activities if they were predicted to achieve greater than 0.25 inches of rainfall with a 50% or higher probability of measureable precipitation.

Sample Collection and Handling

Monitoring stations were established at locations where subsurface drains exited each of the five porous paving test sites, the adjacent parking lot reference areas that drained parking areas with standard impervious paving and similar use characteristics. The roof reference site was located in the discharge pipe just prior to water entering the Phase II asphalt infiltration bed. For each of the porous paving test sites, catch basins provided access to the discharge pipes before water mixed with other runoff. The sampling catch basins also provided enhanced mixing of the stormwater to assure that samples were representative. All sites were provided with remote control, monitoring and data-downloading capability. Equipment at each test site consisted of a peristaltic autosampler, a bubbler to measure water depth, a primary control device (e.g. a compound rectangular weir with a V-notch for low flow), a datalogger and controller, a CDMA cellular modem, and enclosures. Rain gauges were incorporated into monitoring stations at two of the sites to provide accurate measure of stormwater volumes associated with each site. A San Diego County Flood Control District ALERT rain gauge located just east of Building 2 served as additional backup confirmation.

During construction, a monitoring well was installed by the construction contractor at each of the porous pavement test sites for the purpose of monitoring water levels within the infiltration basins and measuring infiltration rates. Pressure sensors were installed in each monitoring well and connected to the datalogger to provide continuous water level records throughout the storm season. Pressure sensors in each monitoring well were referenced to the invert of the pipe entering the monitoring well from the infiltration beds. The monitoring station at the reference site was similar with the exception that a manhole and compound weir were not required. Instead, a 1-foot H-flume was used to measure surface runoff.

Monitoring locations were located at positions where the equipment was able to measure all potential discharges from each type of porous pavement and the reference site. KLI coordinated with the design engineers to assure that each site was designed to allow for accurate measurement of flow from an underlying drain system and suitable configuration for collection of water samples for chemistry. Major design considerations included the size of the discharge pipe, the slope and length of pipe prior to the sampling location, and appropriate access to the pipe.

The automated samplers collected sample aliquots in direct proportion to flow via a peristaltic pumping mechanism. Water samples were pumped through a Teflon/stainless steel intake strainer and Teflon tubing into pre-cleaned and blanked 20-liter borosilicate glass sample bottles. Bottles were kept on ice during the storm event.

Composite sample bottles were subsampled at KLI's Carlsbad facility. Prior to subsampling the composite bottles were placed on a magnetic stir-plate. A pre-cleaned Teflon stir bar was inserted into the bottle and the sample was stirred to ensure homogeneity. The subsample bottles were then delivered to the analytical laboratory for chemistry analyses under appropriate chain of custody procedures.

Flow-weighted composite samples were analyzed for the following constituents: hardness, suspended sediment concentration (SSC), total suspended solids (TSS), chemical oxygen demand (COD), dissolved organic carbon (DOC), total phosphorus, orthophosphate-P, ammonia-N, total Kjeldahl nitrogen (TKN), nitrate-N, and total and dissolved cadmium, copper, lead, and zinc (Table 3).

Additional water was collected from the vadose zone at a depth interval of 1.7 to 2.3 feet below the scarified layer at the bottom of the porous pavement infiltration basins by applying pressure to the suction lysimeters. Immediately following each storm event, a vacuum of 65 centibars was applied to each lysimeters, which caused water to pass through the ceramic walls of the lysimeters and collect in the reservoir. Water was then extracted by applying pressure to the lysimeters which causes water to be extruded into a pre-cleaned borosilicate sample container. Depending upon soil moisture conditions at each site, the vacuum would be maintained for a period of several hours to several days. Exact duration depended upon the amount of rainfall, hydraulic conductivity of the soil and the time it took to obtain 1.7 to 2 liters of water. The lysimeters had a glazed reservoir capable of retaining just over ½ liter. Regardless of the total volume of water sampled, the vacuum was maintained for no more than 48 hours due to both the potential for alteration of sample characteristics for any longer period and the unlikelihood of obtaining significantly more sample volume past this time limit. Vacuum pressures were reapplied as necessary and additional sample volumes collected during this time period using the same borosilicate sample container.

Water collected by the lysimeters passed through a high-fired, alumina ceramic material. The lysimeters were specifically designed for collection of water samples for low-level analysis of metal and nutrients. Most constituents were expected to be largely in the dissolved phase since most solids could not pass through the ceramic material. Nevertheless, samples were analyzed for the same set of constituents used for the reference site, with the exception of suspended sediments and suspended solids, which would be largely unable to pass through the ceramic of the lysimeters. Furthermore, volumes necessary to measure low levels of solids would be prohibitive.

Table 3. Water Quality Analytical Parameters for the Porous Pavement Water Quality Monitoring Project

Analytical Parameter	Analytical Method	Sample Volume	Containers, type	Preservation (chemical, temperature, light protected)	Maximum Holding Time: Preparation/ analysis
Total Hardness	EPA 130.2	100mL	Plastic or Glass	pH <2, HNO_3, 4ºC	6 Months
SSC	ASTM 2000 D3977-97C	500 mL	Plastic or Glass	4ºC	7 Days
TSS	EPA 160.2	1000 mL	Plastic or Glass	4ºC	7 Days
COD	EPA 410.4	25 mL	Glass	pH <2, H_2S0_4, 4ºC	28 Days
DOC	EPA 415.1	250 mL	Glass	pH <2, H_2S0_4, 4ºC	28 Days
Total Phosphorus	EPA 365.2	300 mL	Plastic or Glass	pH <2, H_2S0_4, 4ºC	28 Days
Orthophosphate-P	EPA 300.0	150 mL	Plastic or Glass	4ºC	48 Hours
Ammonia - N	SM 4500-NH_3-F /EPA 350.3	500 mL	Plastic or Glass	pH <2, H_2S0_4, 4ºC	28 Days
TKN	EPA 351.3	600 mL	Amber Glass	pH <2, H_2S0_4, 4ºC	28 Days
Nitrate - N	EPA 300.0	100mL	Plastic or Glass	4ºC	48 Hours
Total & Diss. Cadmium	EPA 200.8	250 mL	Plastic	pH <2, HNO_3, 4ºC	6 Months
Total & Diss.Copper	EPA 200.8	250 mL	Plastic	pH <2, HNO_3, 4ºC	6 Months
Total & Diss. Lead	EPA 200.8	250 mL	Plastic	pH <2, HNO_3, 4ºC	6 Months
Total & Diss. Zinc	EPA 200.8	250 mL	Plastic	pH <2, HNO_3, 4ºC	6 Months

Sample bottles were stored and transported on ice, maintaining 4 degrees Celsius (°C) until processed. Sample bottles collected during the storm event were thoroughly homogenized at the KLI Carlsbad facility. The flow-weighted composite samples were then sub-sampled for the project constituents. Chemistry samples were analyzed by Soil Control Lab. (SCL) in Watsonville, California.

Chemistry samples were labeled with the project name, sample identification number, site location, date and time collected, analyses to be performed, and sample preservatives (if any). Samples were then stored and transported on ice (4 °C) to the analytical laboratory.

RESULTS AND DISCUSSION

The following sections summarize the results of 1) monitoring rainfall, runoff and the representativeness of water quality samples, 2) water levels in the infiltration basins in response to each event and 3) characterization of water quality associated with runoff.

Rainfall, Runoff and Sampling Characteristics

The general characteristics of each event (based upon measurements at the parking lot reference site) are summarized in Table 4 and Table 5. Table 4 provides a summary of rainfall during each event. The primary rainfall characteristics described in this table are the duration, total rainfall and maximum rainfall intensity measured during each event. Rainfall intensity is based upon a running evaluation of total rainfall during the previous 15-minute time period expressed in terms of inches per hour. Higher intensity events have more capacity to suspend and transport particulates with the discharges. Information on antecedent conditions identifies the number of days since a rainfall event totaling greater than 0.1 inches as well as the total amount of rainfall associated with that event. Table 5 provides a description of stormwater discharge characteristics for each event such as the duration of flow and total flow volume as well as peak flow rates measured during the event. In addition, information is provided that is useful in assessing the overall quality of the flow-rated composite sample. Sample characteristics of major interest are the number of aliquots taken over the period of the storm, what percentage of the event was included in the flow-rated composite sample and whether the period of peak discharge was effectively represented in the stormwater composite. In both tables, events monitored for water quality are shaded in gray.

Hydrographs are presented for each monitored event (Figure 22 through Figure 25) at the parking lot reference site. Hydrographs from all measured events are included in Appendix A. These plots provide a graphic illustration of the stormwater discharges in relationship to rainfall during each event. These are limited to the seven events at the Reference Area since no discharges occurred at any of the porous treatment sites. These clearly show the strong link between rainfall and runoff at this site as well as the sensitivity of this small, impervious area in responding to very small amounts of rain. The responsiveness of this small, impervious area to rainfall is of significance. Rainfall as low as 0.04 inches is sufficient to produce measurable runoff.

Table 4. Rainfall Statistics and Antecedent Conditions for each Monitored Storm Event at the Parking Lot Reference Site.

	Start Rain		End Rain					Antecedent Event	
Event	Date	Time	Date	Time	Duration Rain (hrs:min)	Total Rain (inches)	Max Intensity (inches/hr)	Days since last rainfall	Total Rainfall (inches)
2006/2007									
1	01/04/2007	20:00	01/04/2007	22:00	2:00	0.04	0.02	9	
2	01/29/2007	20:10	01/31/2007	13:00	16:50	0.50	0.16	25	0.04
3	02/11/2007	10:20	02/13/2007	18:00	56:40	0.29	0.28	11	0.50
4	02/18/2007	23:00	02/20/2007	14:30	39:30	1.31	0.60	5	0.29
5	02/22/2007	19:50	02/23/2007	05:20	9:30	0.16	0.16	2	1.31
6	02/27/2007	07:00	02/28/2007	11:00	28:00	0.40	0.04	4	0.16
7	03/20/2007	21:00	03/22/2007	18:00	46:00	0.28	0.24	20	0.40
8	04/20/2007	12:45	04/20/2007	21:50	8:55	0.44	0.36	29	0.28
2007/2008									
1	11/30/2007	6:00	12/01/2007	1:00	19:00	1.67	0.52	>60	
2	12/07/2007	4:35	12/07/2007	9:05	4:30	0.36	0.16	6	1.67
3	12/08/2007	1:00	12/09/2007	0:00	23:00	0.67	0.28	0.6	0.36
4	12/11/2007	03:00	12/11/2007	04:00	1:00	0.05	0.04	2.2	0.67
5	12/19/2007	0:20	12/19/2007	6:50	6:30	0.11	0.12	10	0.74
6	12/20/2007	21:40	12/20/2007	22:00	0:20	0.02	0.04	1.6	0.11
7	01/04/2008	23:35	01/7/2008	18:00	66:25	1.90	0.28	16.7	0.11
8	01/21/2008	10:00	01/22/2008	7:00	21:00	0.12	0.04	13.7	1.90
9	01/23/2008	18:25	01/24/2008	7:00	12:35	0.56	0.52	1.5	0.12
10	01/26/2008	18:00	01/29/2008	0:00	54:00	0.63	0.12	2.5	0.56
11	02/03/2008	6:00	02/04/2008	16:00	34:00	0.61	0.12	5.3	0.63
12	02/14/2008	9:00	02/15/2008	13:00	28:00:	0.34	0.20	9.7	0.61
13	02/20/2008	6:00	02/20/2008	17:00	11:00	0.11	0.08	4.7	0.34
14	02/22/2008	3:00	02/22/2008	17:00	14:00	0.45	0.08	1.4	0.11
15	02/23/2008	21:00	02/24/2008	16:00	19:00	0.16	0.04	1.2	0.45
16	03/16/2008	02:25	03/16/2008	02:40	0:15	0.06	0.24	19.4	0.16
17	03/30/2008	00:05	03/30/2008	06:35	6:30	0.03	0.04	13.9	0.06

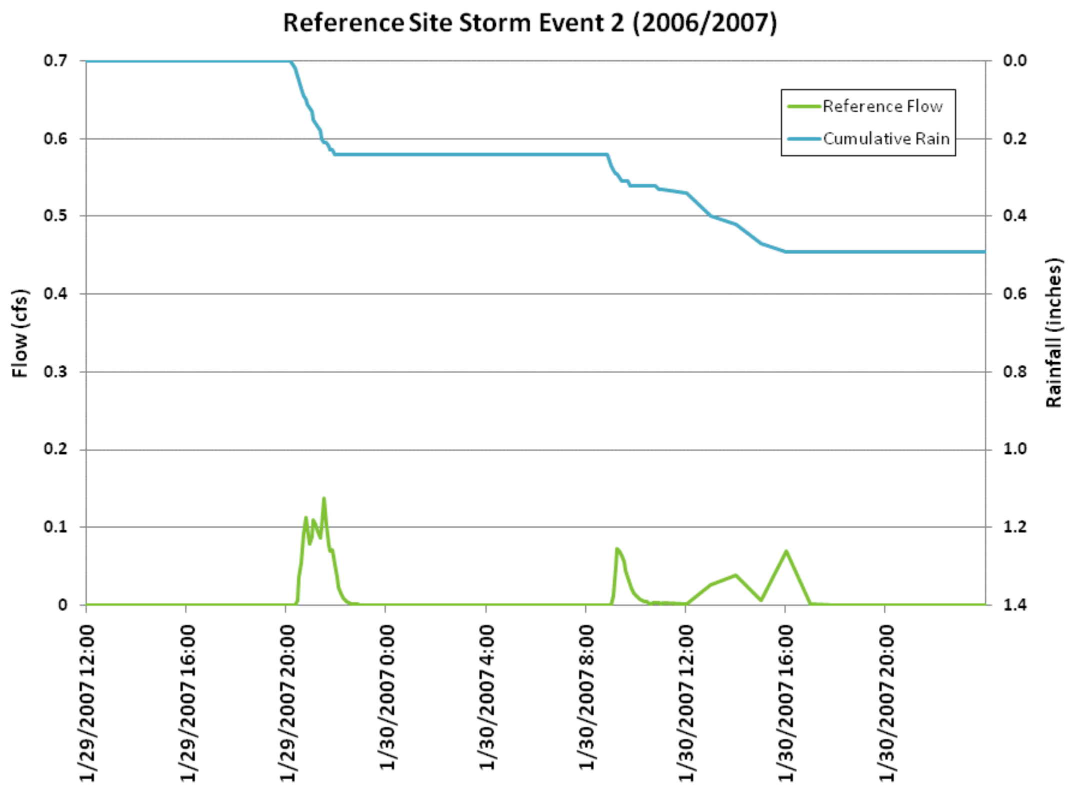
Notes: Shading indicates events monitored for water quality.
All rainfall data based upon rain gauge located at the reference site.

Table 5. Stormwater Discharge and Sample Quality Assessment for the Parking Lot Reference Site.

	Start Flow		End Flow					Sample Characteristics		
Event	Date	Time	Date	Time	Flow or Discharge Duration (hrs:mins)	Total Flow (kilo- cubic feet)	Peak Flow (cfs)	No. of Sample Aliquots Collected	% Storm Capture	Peak Capture
2006/2007										
1	01/04/2007	22:00	01/04/2007	23:00	1:00	18.0	0.003	-	-	-
2[1]	01/29/2007	20:25	01/30/2007	17:00	20:35	1190	0.137	-	-	-
3	02/11/2007	12:20	02/13/2007	08:00	43:40	314	0.058	-	-	-
4	02/19/2007	00:00	02/20/2007	01:05	25:05	4087	0.678	98	80	Yes
5	02/22/2007	20:15	02/23/2007	06:15	10:00	377	0.158	14	100	Yes
6	02/27/2007	09:00	02/28/2007	11:00	26:00	817	0.890	-	-	-
7	03/21/2007	04:00	03/22/2007	18:00	38:00	918	0.139	-	-	-
8	04/20/2007	13:10	04/20/2007	23:15	10:05	946	0.271	37	100	Yes
2007/2008										
1	11/30/2007	7:00	12/01/2007	7:00	24:00	6430	0.419	-	-	-
2	12/07/2007	4:55	12/07/2007	17:00	12:05	1566	0.176	78	100	Yes
3	12/08/2007	2:00	12/09/2007	12:00	34:00	2848	0.186	-	-	-
4	12/11/2007	04:00	12/11/2007	06:00	2:00	65	0.014			
5	12/19/2007	1:10	12/19/2007	08:25	7:15	122	0.005	-	-	-
6	12/20/2007	23:00	12/20/2007	0:00	1:00	4	0.001			
7	01/05/2008	0:15	01/07/2008	18:00	65:45	8122	0.226	74	100	Yes
8	01/21/2008	12:00	01/22/2008	7:00	19:00	76	0.011	-	-	-
9	01/23/2008	18:50	01/24/2008	7:00	12:10	1755	0.446	79	100	Yes
10	01/26/2008	21:00	01/29/2008	0:00	51:00	3424	0.102	-	-	-
11	02/03/2008	8:00	02/04/2008	16:00	32:00	5890	0.155	-	-	-
12	02/14/2008	14:00	02/15/2008	13:00	23:00	5839	0.187	-	-	-
13	02/20/2008	13:00	02/20/2008	17:00	4:00	2491	0.358	-	-	-
14	02/22/2008	6:00	02/22/2008	17:00	11:00	4691	0.242	-	-	-
15	02/24/2008	0:00	02/24/2008	16:00	16:00	3830	0.178	-	-	-
16[2]	03/16/2008	-	03/16/2008	-	-	-	-	-	-	-
17	03/29/2008	23:00	03/30/2008	11:00	12:00	35	0.004			

Shaded events are those that were monitored for water quality.

1. Equipment failure precluded successful sampling during the 1/29-30/2007 event.
2. Mud from the dewatering of the adjacent construction site clogged the stilling well making measurements inaccurate during the minor 3/16/2008 event.



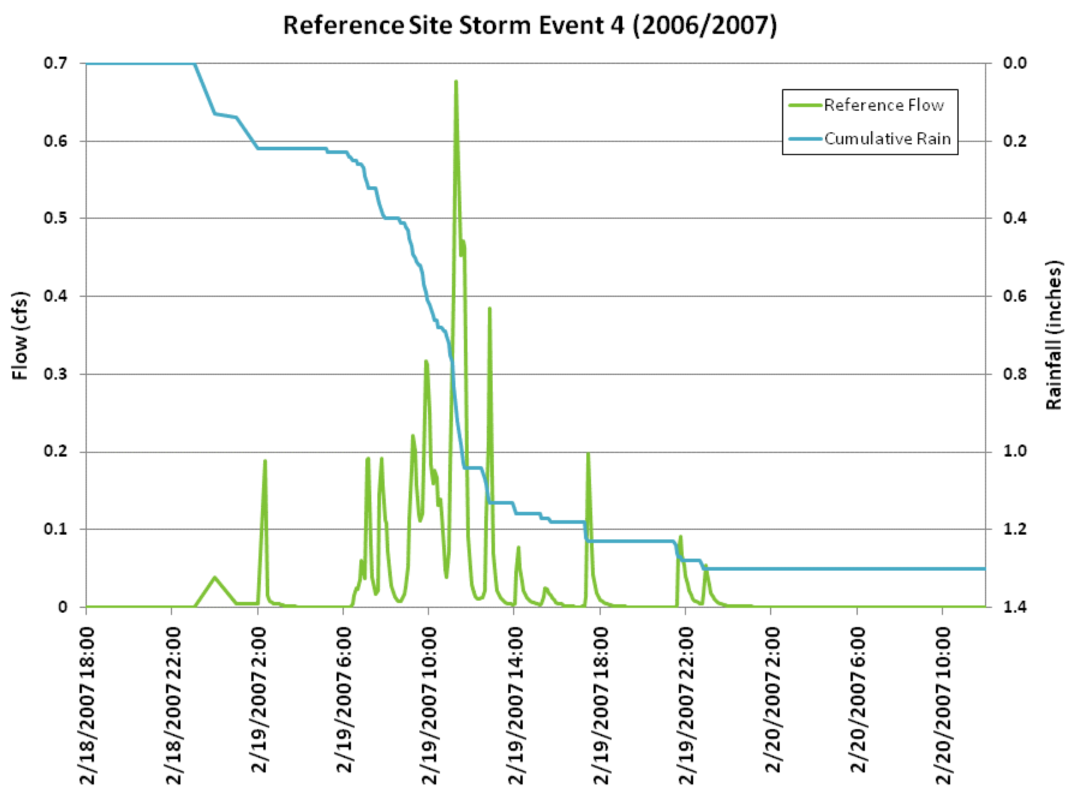
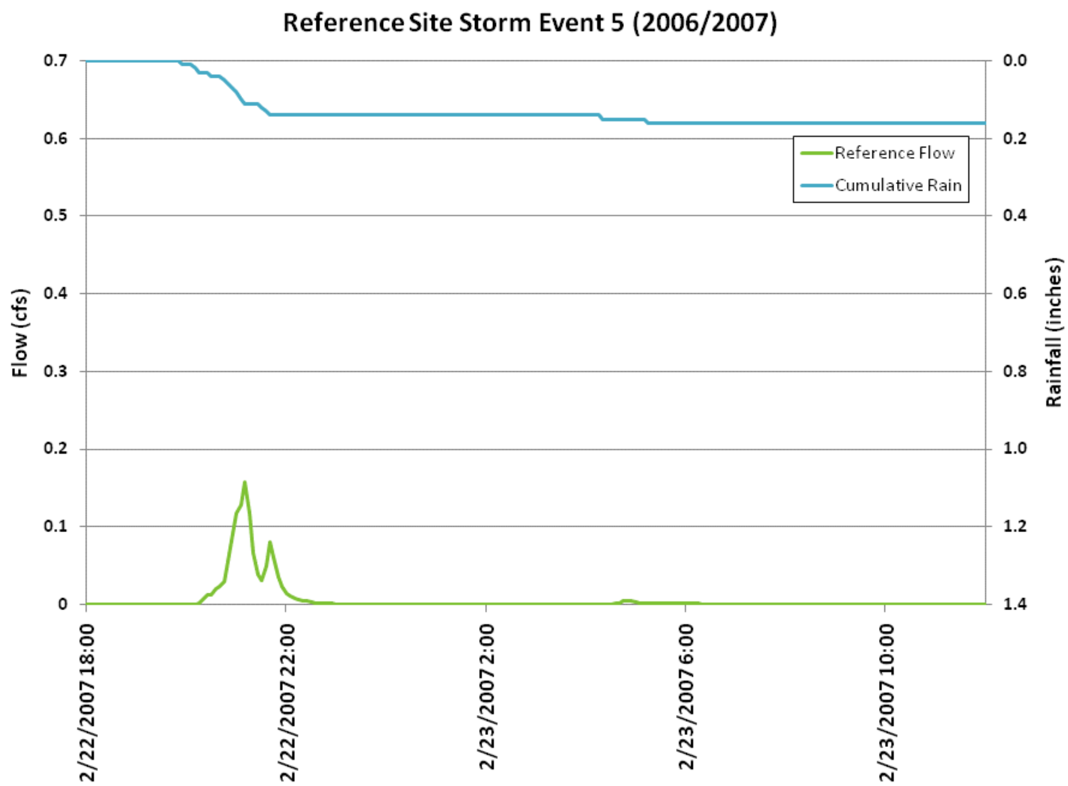


Figure 22. Hydrographs for Events 2 and 4 at the Parking Lot Reference Site, 2006/2007.



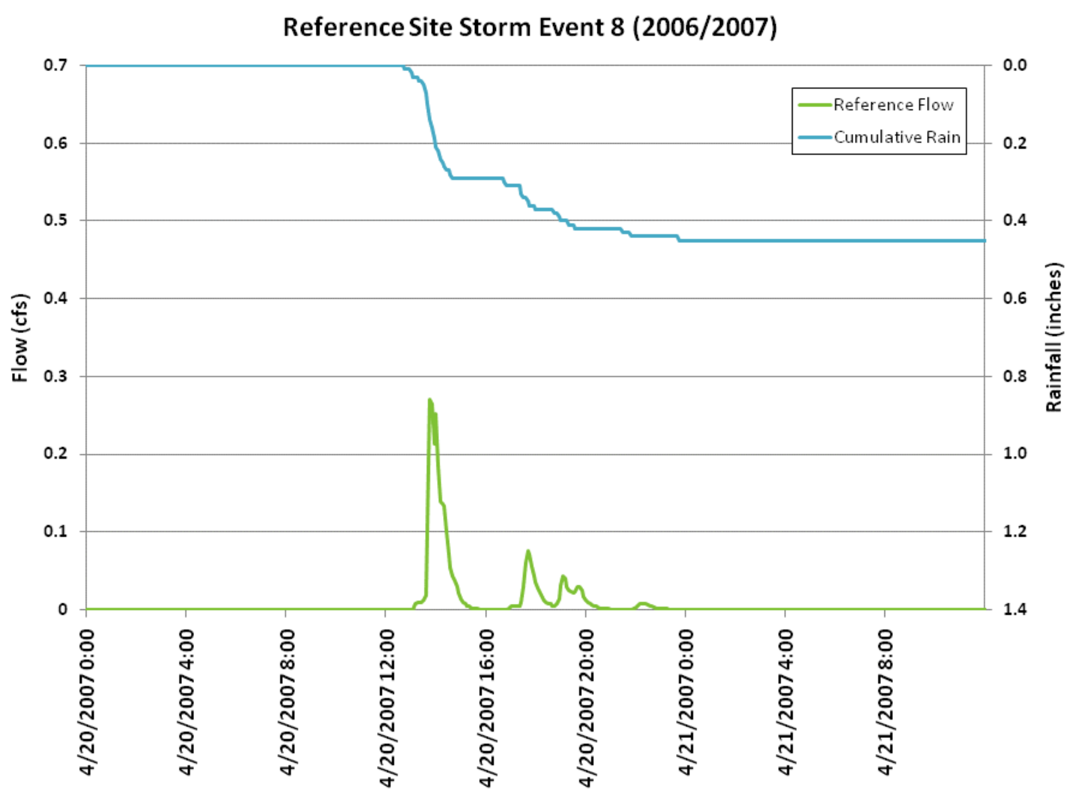
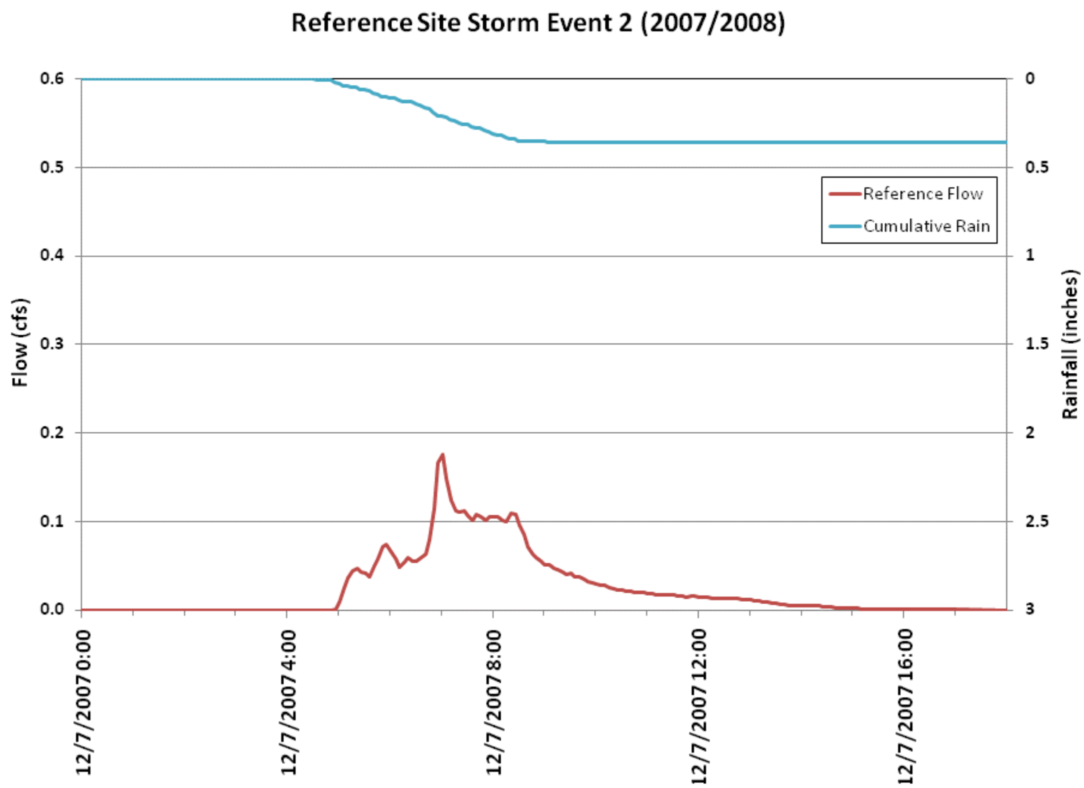


Figure 23. Hydrographs for Events 5 and 8 at the Parking Lot Reference Site, 2006/2007.



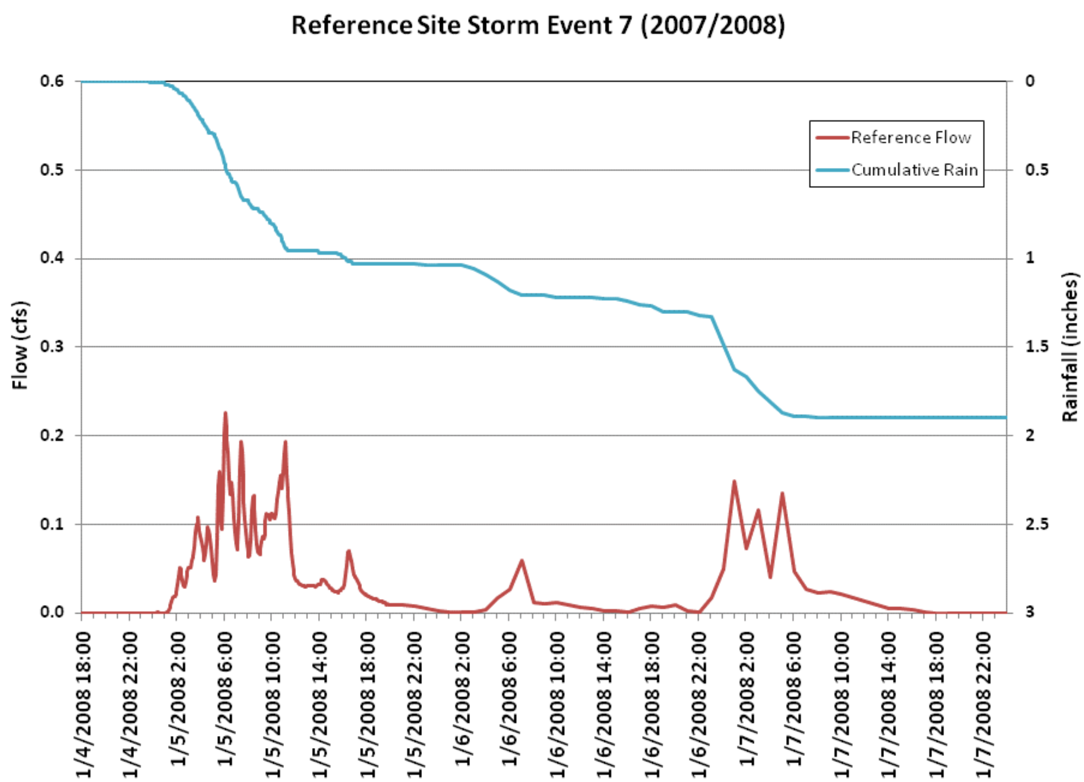


Figure 24. Hydrographs for Events 2and 7 at the Parking Lot Reference Site, 2007/2008.

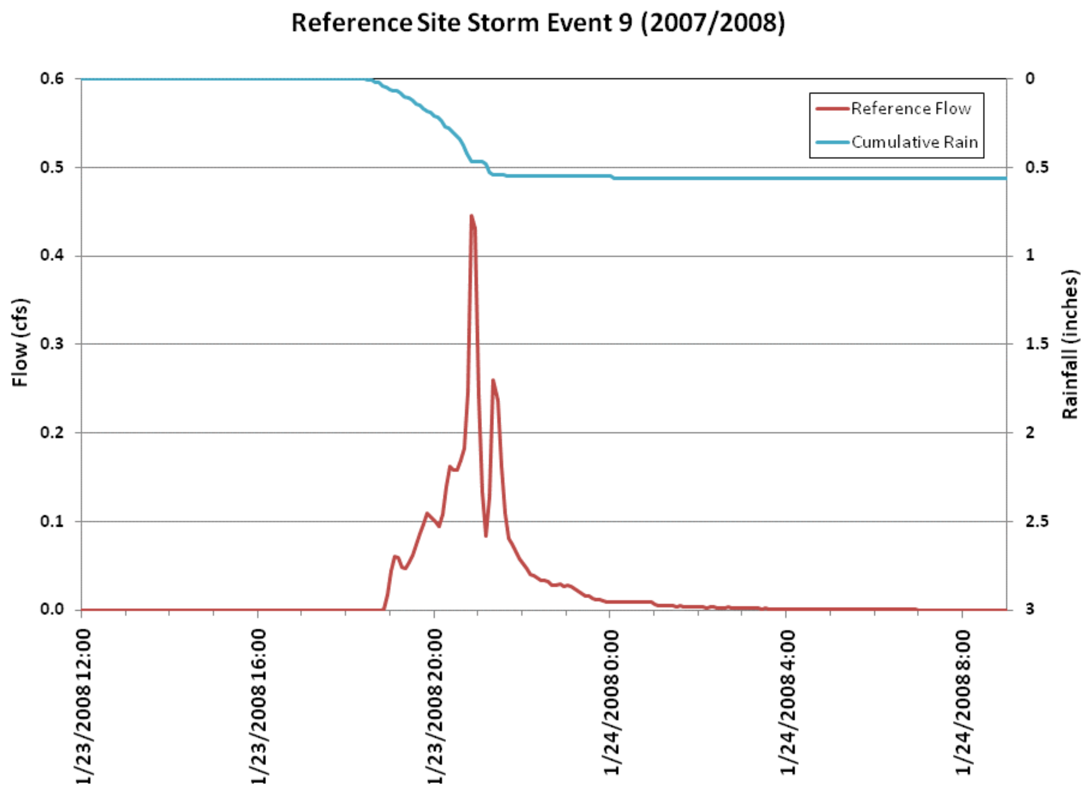


Figure 25. Hydrographs for Event 9 at the Parking Lot Reference Site, 2007/2008.

Monitoring at the roof runoff reference site was limited to the 2007/2008 season. Table 6 provides a description of stormwater discharge characteristics for each event at this highly responsive site. Due to the 100 percent impervious nature of this site, as little as 0.04 inches of rain was observed to cause measureable runoff. Hydrographs for the four monitored events (Figure 24 and Figure 25). As with the reference site, hydrographs for all roof reference storm events are presented in Appendix A.

Table 6. Stormwater Discharge and Sample Quality Assessment for the Roof Reference Site.

	Start Flow		End Flow					Sample Characteristics		
Event	Date	Time	Date	Time	Flow or Discharge Duration (hrs:mins)	Total Flow (cubic feet)	Peak Flow (cfs)	No. of Sample Aliquots Collected	% Storm Capture	Peak Capture
2007/2008										
1	11/30/2007	7:00	12/01/2007	17:00	34:00	4903	0.224	-	-	-
2	12/07/2007	5:15	12/07/2007	12:25	7:05	1298	0.196	77	100	Yes
3	12/08/2007	2:00	12/09/2007	3:00	25:00	1386	0.198	-	-	-
4	12/11/2007	04:00	12/11/2007	05:00	1:00	54	0.013	-	-	-
5	12/19/2007	0:20	12/19/2007	09:10	8:50	287	0.081	14	100	Yes
6	12/20/2007	23:00	12/20/2007	0:00	1:00	25	0.005	-	-	-
7	01/04/2008	23:25	01/05/2008	19:00	19:25	4317	0.327	54	100	Yes
7a[2]	01/06/2008	3:00	01/07/2008	11:00	32:00	3200	0.228	-	-	-
8	01/21/2008	10:00	01/22/2008	8:00	22:00	194	0.027	-	-	-
9	01/23/2008	18:40	01/23/2008	23:45	5:05	1703	0.526	56	100	Yes
9a	01/24/2008	11:00	01/24/2008	23:00	12:00	118	0.010	-	-	-
10	01/26/2008	20:00	01/28/2008	17:00	45:00	2362	0.078	-	-	-
11	02/03/2008	7:00	02/04/2008	5:00	22:00	2084	0.116	-	-	-
12	02/14/2008	11:00	02/14/2008	22:00	11:00	821	0.090	-	-	-
13	02/20/2008	6:00	02/20/2008	16:00	10:00	439	0.063	-	-	-
14	02/22/2008	4:00	02/22/2008	15:00	11:00	1541	0.133	-	-	-
15	02/24/2008	5:00	02/24/2008	15:00	10:00	468	0.031	-	-	-
16	03/16/2008	3:00	03/16/2008	6:00-	3:00	72	0.010	-	-	-
17	03/30/2008	1:00	03/30/2008	9:00	9:00	72	0.006	-	-	-

Shaded events are those that were monitored for water quality.

1. The 9th storm event for the roof runoff was terminated on 1/23/2008. Minor rainfall (Event 9a) started again just over 11 hours after this event. Total rainfall at the Porous Paving Reference site during Event 9a at the Roof Reference site was only 0.05 inches.
2. Event 7 consisted of two pulses of rain. The roof reference site was terminated after the first pulse. The second pulse followed 8 hours later. The parking lot reference event and treatment train sites included both pulses since the response of the other systems can be much slower.

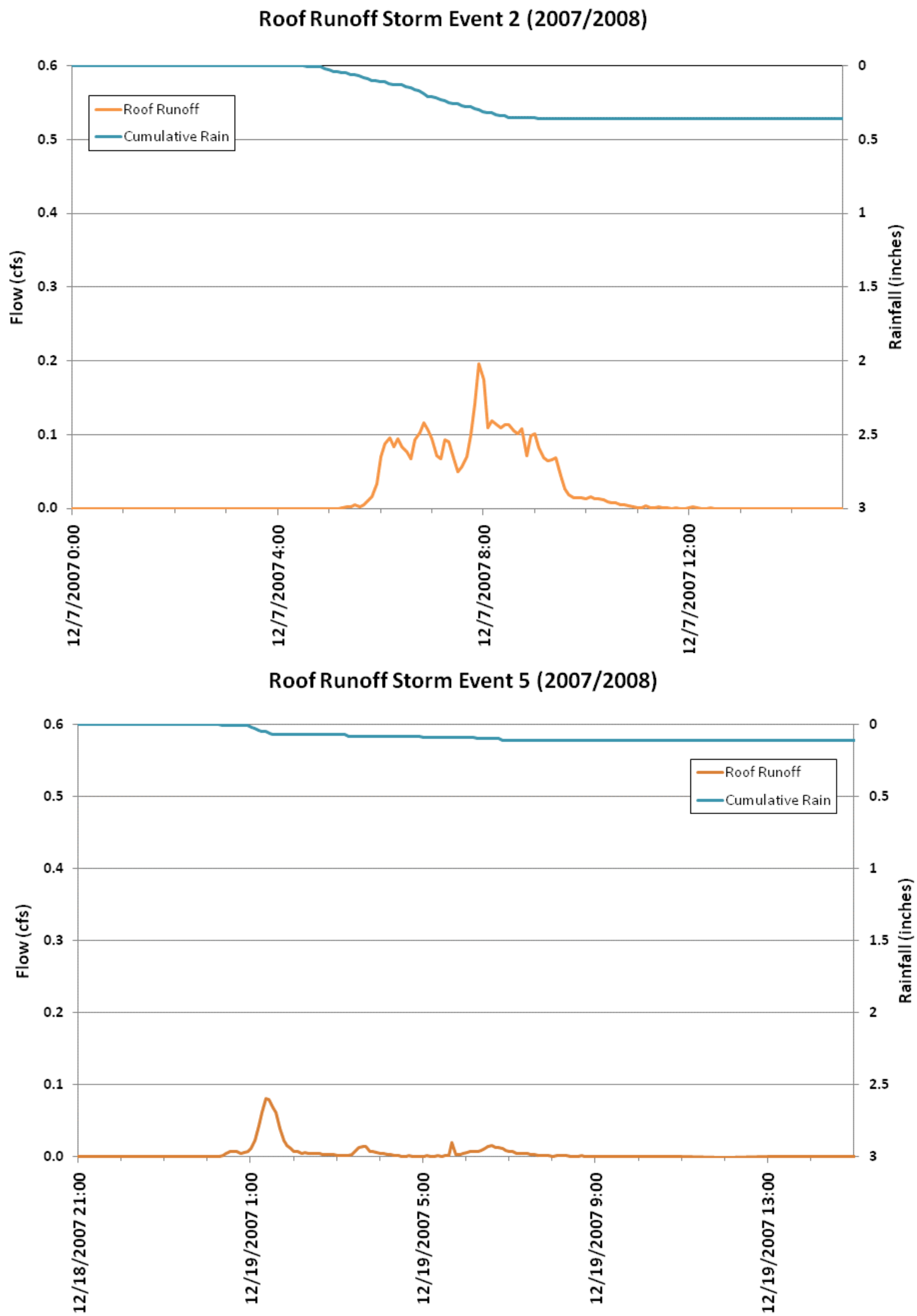
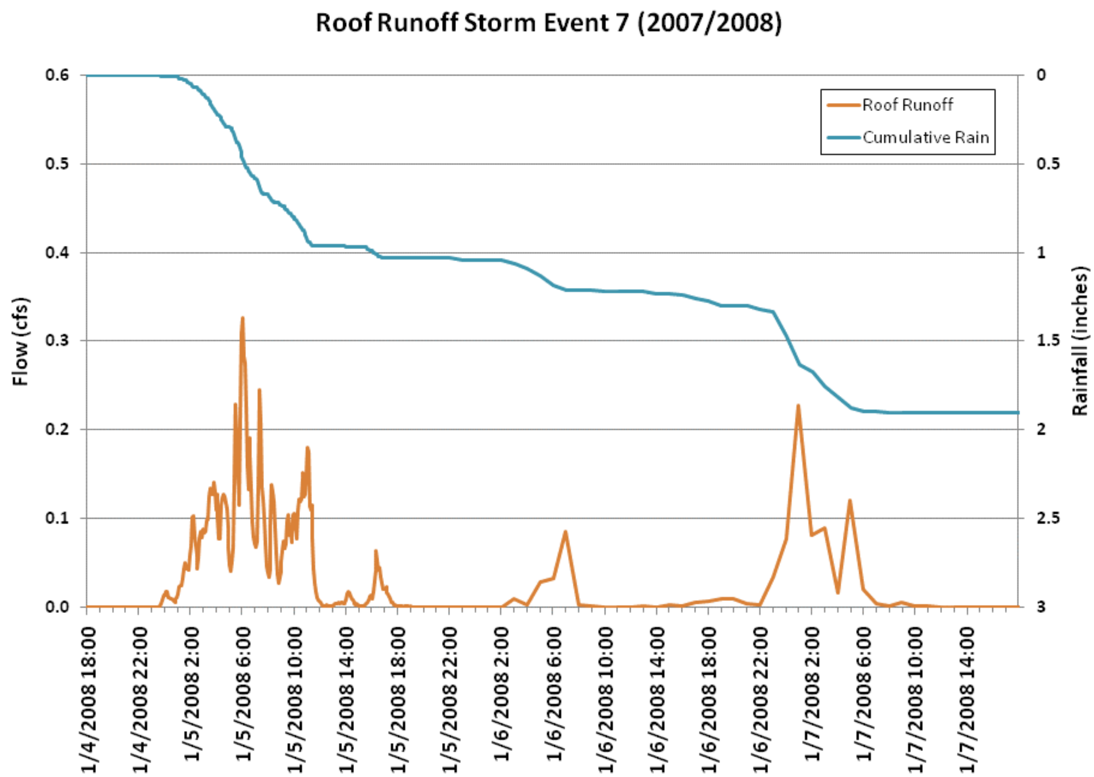


Figure 26. Hydrographs for Events 2 and 5 at the Roof Reference Site, 2007/2008.



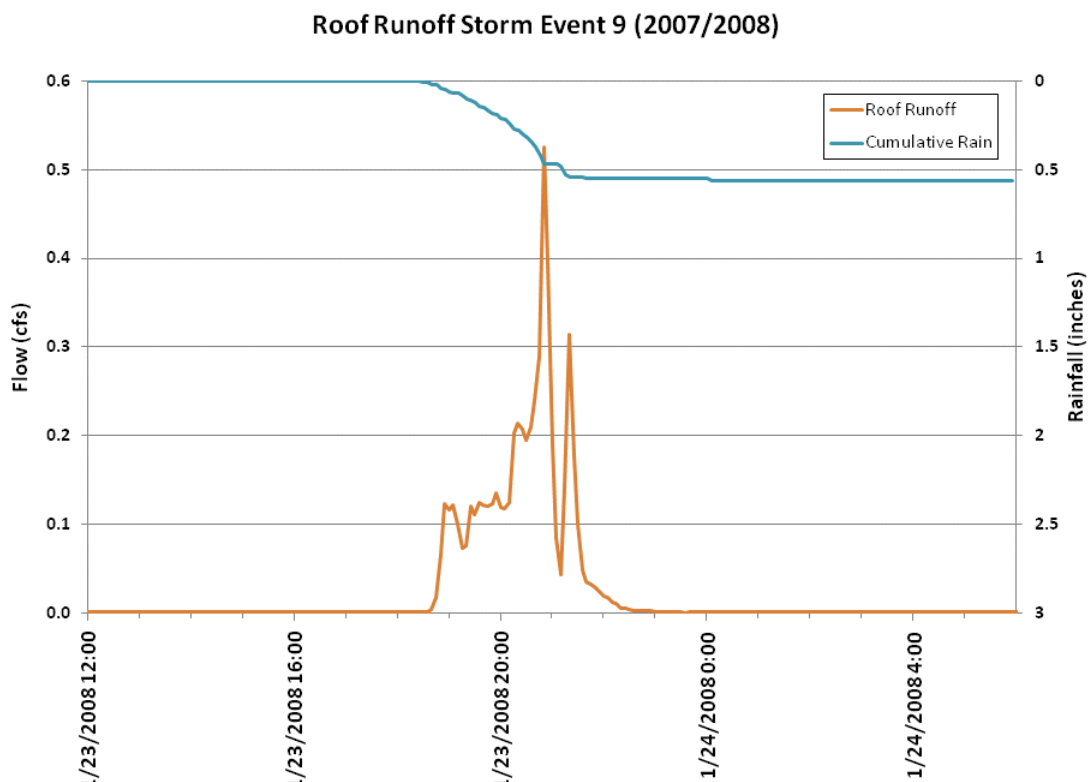


Figure 27. Hydrographs for Events 7 and 9 at the Roof Reference Site, 2007/2008.

Infiltration Basin Monitoring Wells

Water levels in the infiltration beds of all porous pavement treatment sites were continuously monitored throughout the project to determine how the infiltration basins responded to both individual events and the effects of multiple events throughout the season. Given initial measurements taken with a double-ring infiltrometer during the early design stages, it was expected that water levels within the basins might gradually increase due to a series of events due to minimal infiltration rates.

Seasonal changes in water levels within the infiltration basins for all sites are illustrated in Figure 28 through Figure 32. These figures provide a long-term comparison of water levels within the infiltration bed monitoring wells compared to the discharge level. The discharge levels at each site correspond to height of the weir relative to the invert of the pipe that connects the control basin to the bottom of the infiltration bed.

Substantial differences are evident among the five infiltration beds (Figure 28 through Figure 32). Examination of the declines in water levels within each infiltration beds requires some discussion of potential pathways out of the infiltration beds that might cause water levels to drop but could not be attributed to infiltration directly below the porous paving. Some of the differences among sites were clearly attributed to leakage out of the infiltration beds. The three Phase I sites are all suspected to have had some water escaping the infiltration beds rather than actually infiltrating. Some of these pathways were identified early and corrected while others were identified after closer review of the construction process.

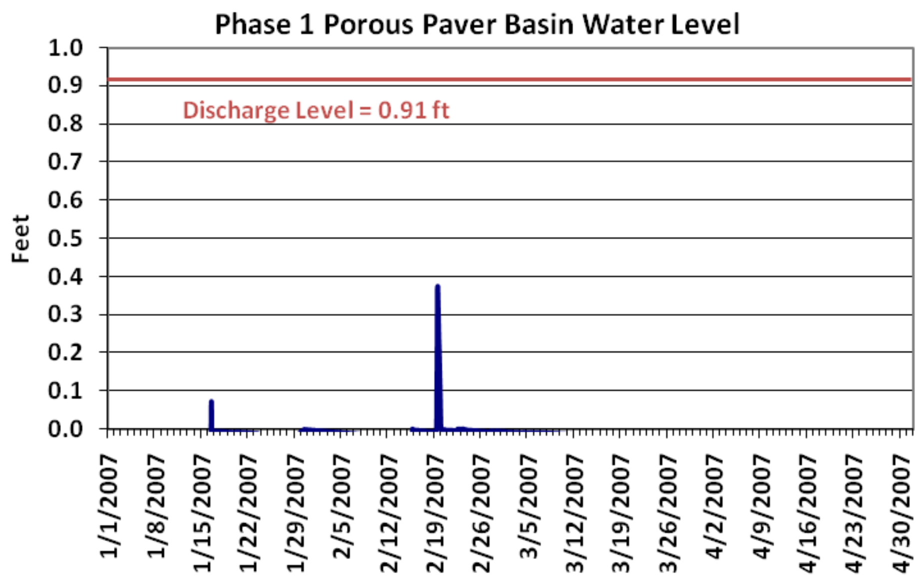
Leakage was first discovered at the Phase I Pavers site. Water was leaking under pressure through the joint between the effluent pipe and the catch basin used for sampling overflow from the system. Being downstream of the monitoring point, this discharge was not quantified. The leak was repaired in late 2007 in conjunction with installation of the Phase II sites. The presence of water at that point in system indicates that the rock bedding used for the drainage pipe is likely providing a pathway for water that collects in the infiltration bed at this site.

Review of construction photographs also indicated a likely connection between the Phase I asphalt and concrete infiltration beds. The Phase I asphalt discharge pipe passed through the berm between the two beds and over to the monitoring point at the southwest corner of Building 7. Rock bedding placed around the drainage pipe is believed to have provided a conduit between the two beds. The rock bedding used for drainage pipe going from the monitoring station to the main storm drain is thought to be another potential route for water to leave the Phase I concrete infiltration bed. At this time, it is unknown whether this provides a significant pathway for water from the Phase I concrete site and whether water can migrate along the bedding of the main storm drain.

There is evidence that drops in water level are not solely due to migration between and outside the boundaries of the infiltration basins. Figure 33 illustrates rainfall intensity and water level changes in the Phase I asphalt and concrete infiltration basins during a storm event in early 2007. Water levels in the Phase I asphalt basin came within ¾ of a inch of topping the weir and discharging to the storm drain. The rates of rise in water levels within each basin were identical. The infiltration rates (as measured by the decline in water level over time) were substantially different. From the time of the peak water level was reached in each basin, it took 14 hours for the water level to drop 6 inches in the asphalt basin compared to 19 hours in the concrete basin. The more rapid decline in water levels in the Phase I asphalt basin indicates that water was not simply passing into the Phase I concrete basin and down the bedding of the existing storm drain system.

The Phase II porous paving installations were designed to eliminate potential pathways between infiltration basins and through the rock bedding used for the drainage systems. Antiseep collars were installed between the Phase II concrete and asphalt infiltration basins at the point where pipes went through the berms and at a point just past the junction of the drain pipes from the two infiltration basins joined to the main storm drain. Despite these improvements, leaks into the drainage pipes were identified during early events at both the Phase II asphalt and concrete sites. The leaks were initially identified during storm events in December 2007 at the monitoring stations as continuous low flows occurring before water levels in the infiltration basins had reached levels necessary to overflow. The Phase II concrete site had a leak downstream of the control weir at the junction of the pipe with the concrete utility box. The Phase II asphalt site had a leak in the joint between the pipe and the sampling catch basin. Repairs at both sites were delayed to allow water levels to drop low enough to repair the pipes in a dry environment. The first attempt at repairing the leak occurred on 14 January 2008 but this initial attempt failed causing further delays. Final repairs were conducted on 23 January 2008.

Once repaired in mid January 2008, water levels progressively increased in the Phase II concrete (Figure 31) nearly reaching the top of the weir during two storm events. After the last rainfall, water levels slowly dropped and stabilized at a depth of 0.86 feet. In early May, water in the basin was crystal clear. By June, the visual appearance of water in the basin had changed substantially. Water samples were taken and analyzed to evaluate both the general water quality for reuse or disposal. The results of the analysis are summarized in the following section.



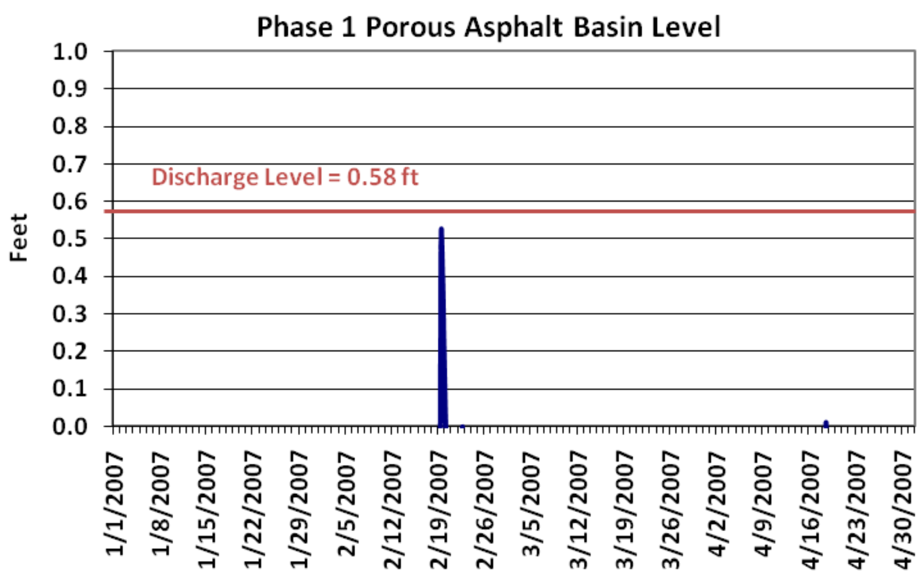


Figure 28. Water Levels in the Phase I Porous Paver and Asphalt Infiltration Basins, 2006/2007 Season.

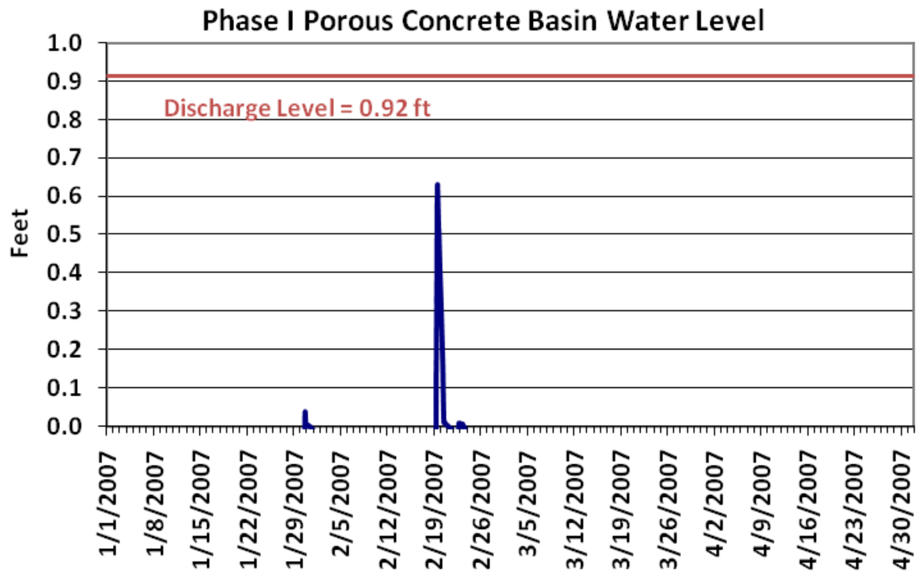
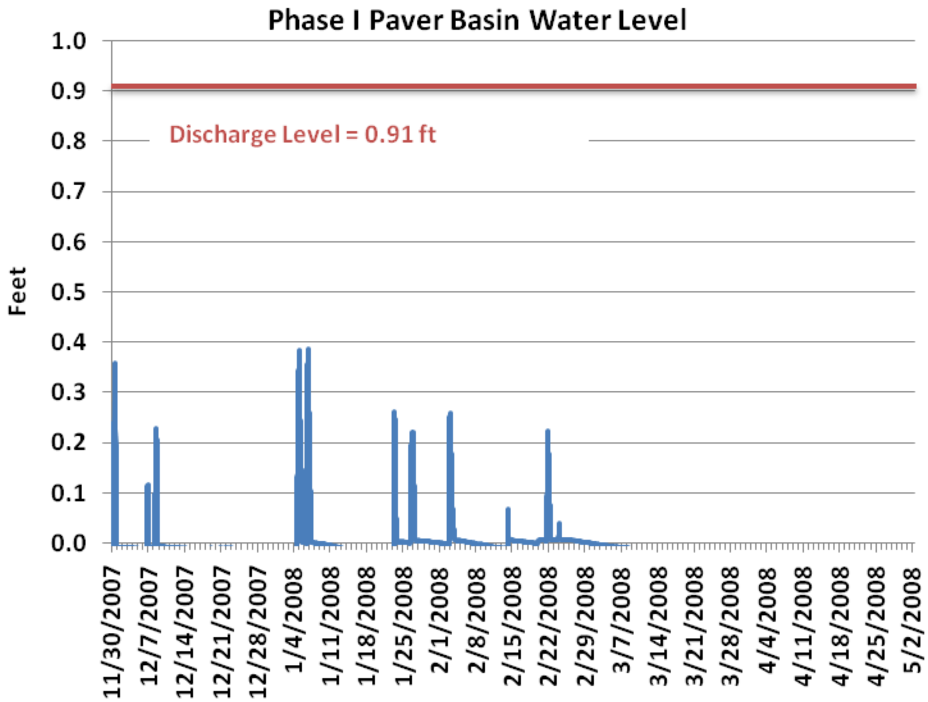


Figure 29. Water Levels in the Phase I Porous Concrete Infiltration Basins, 2006/2007 Season.



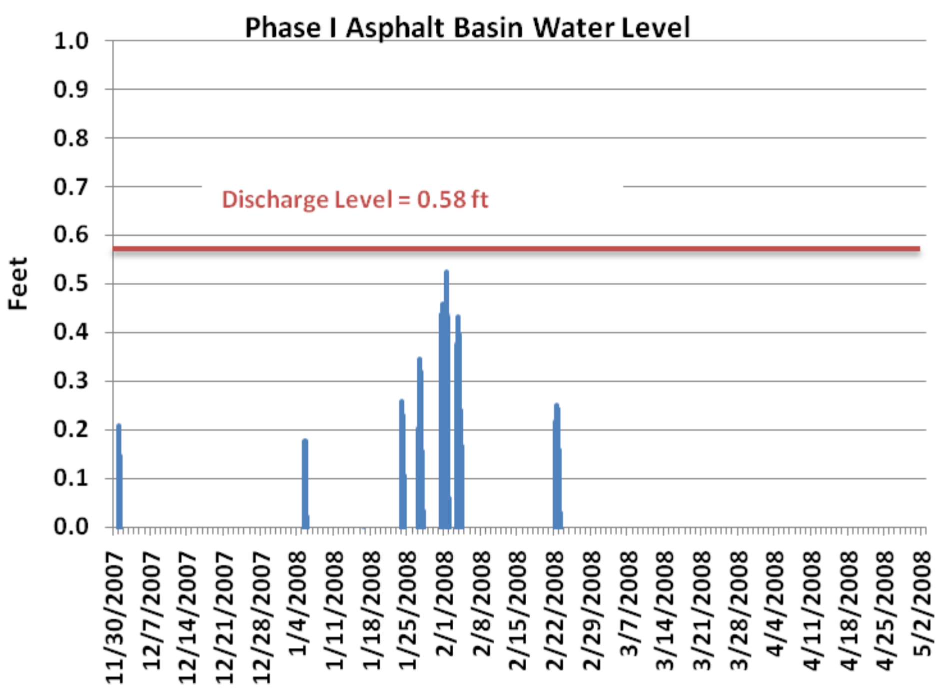


Figure 30. Water Levels in the Phase I Porous Paver and Asphalt Infiltration Basins, 2007/2008 Season.

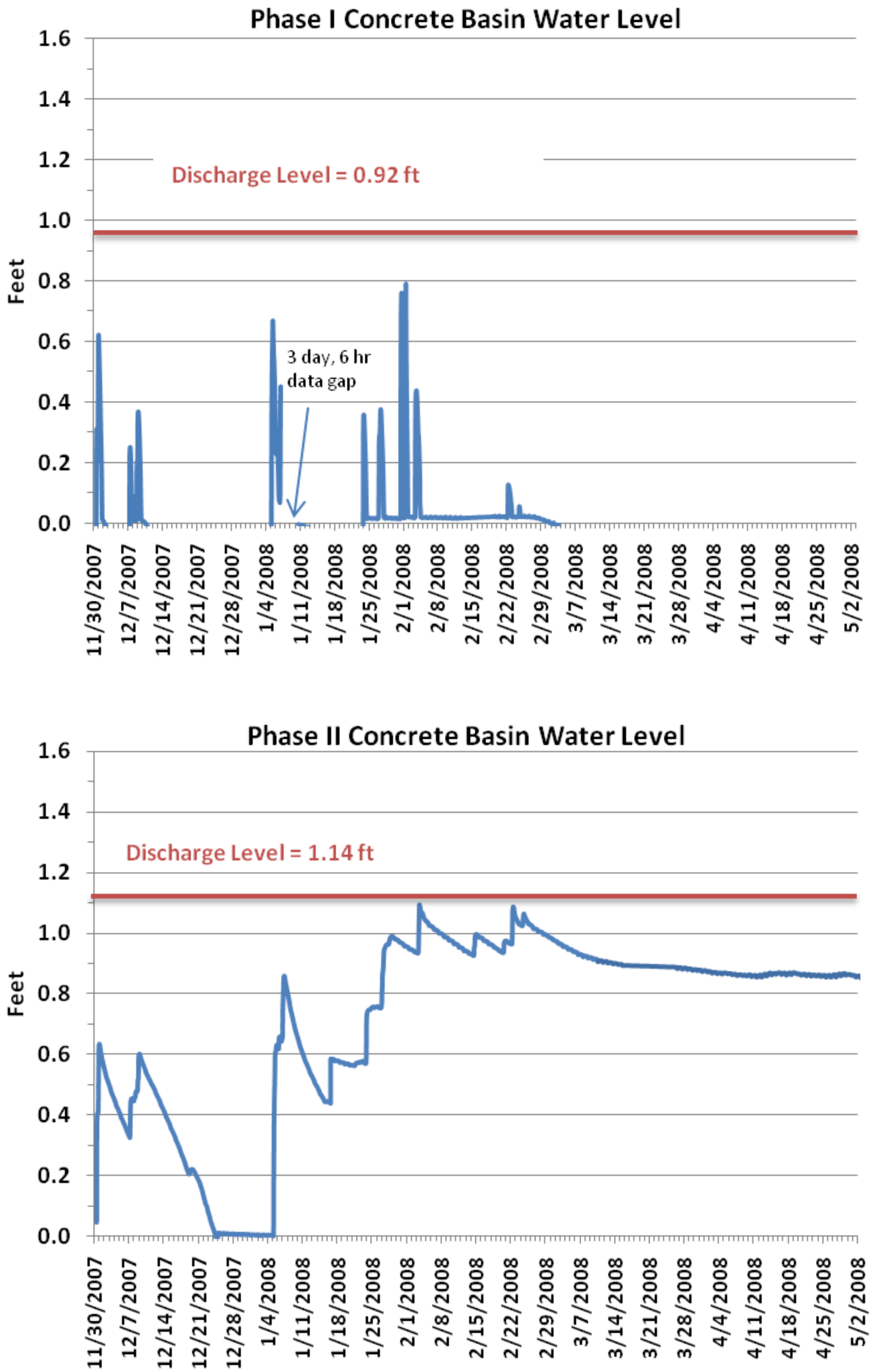


Figure 31. Water Levels in the Phase I and Phase II Porous Concrete Infiltration Basins, 2007/2008 Season.

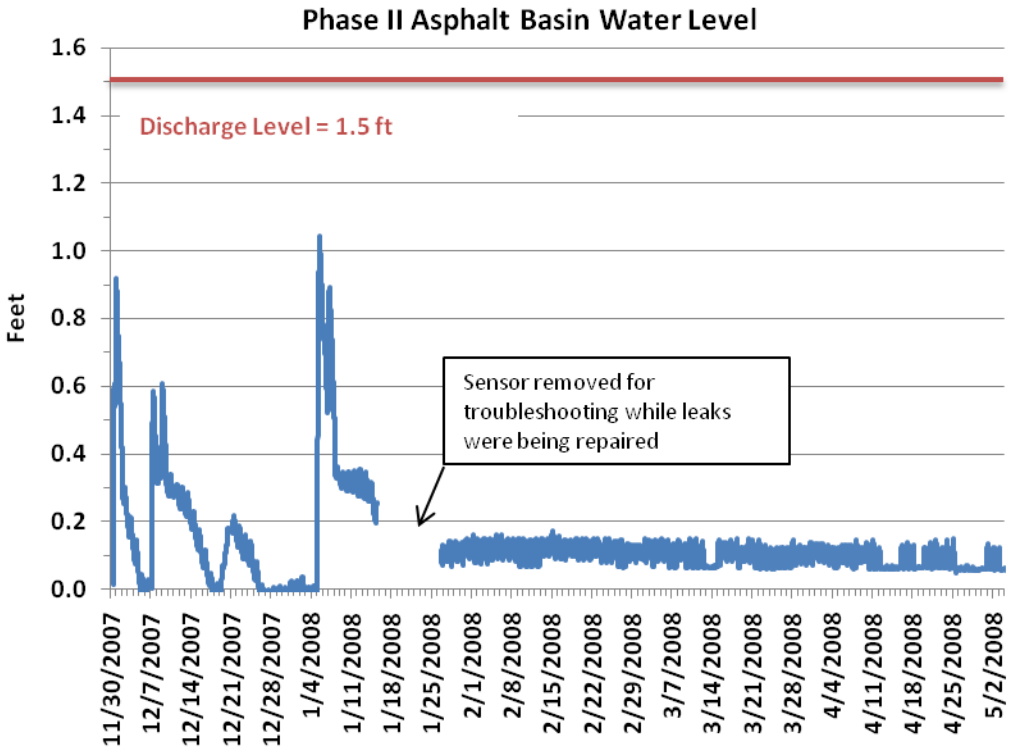
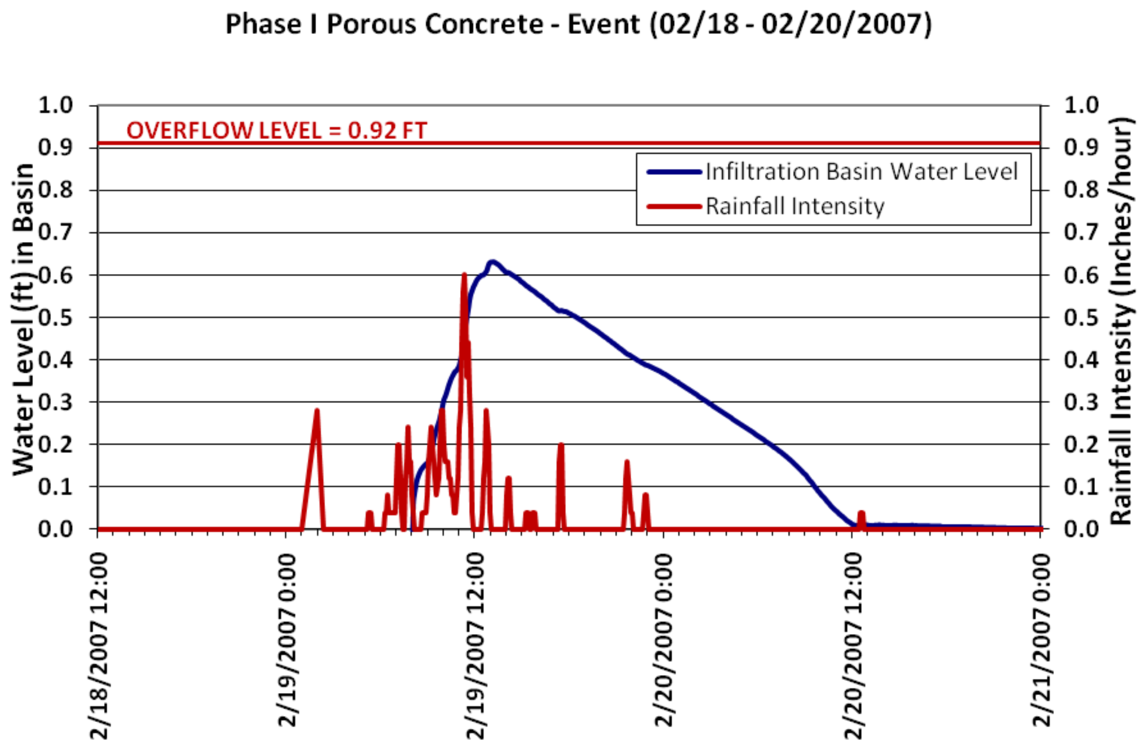


Figure 32. Water Levels in the Phase II Asphalt Infiltration Basin, 2007/2008 Season.



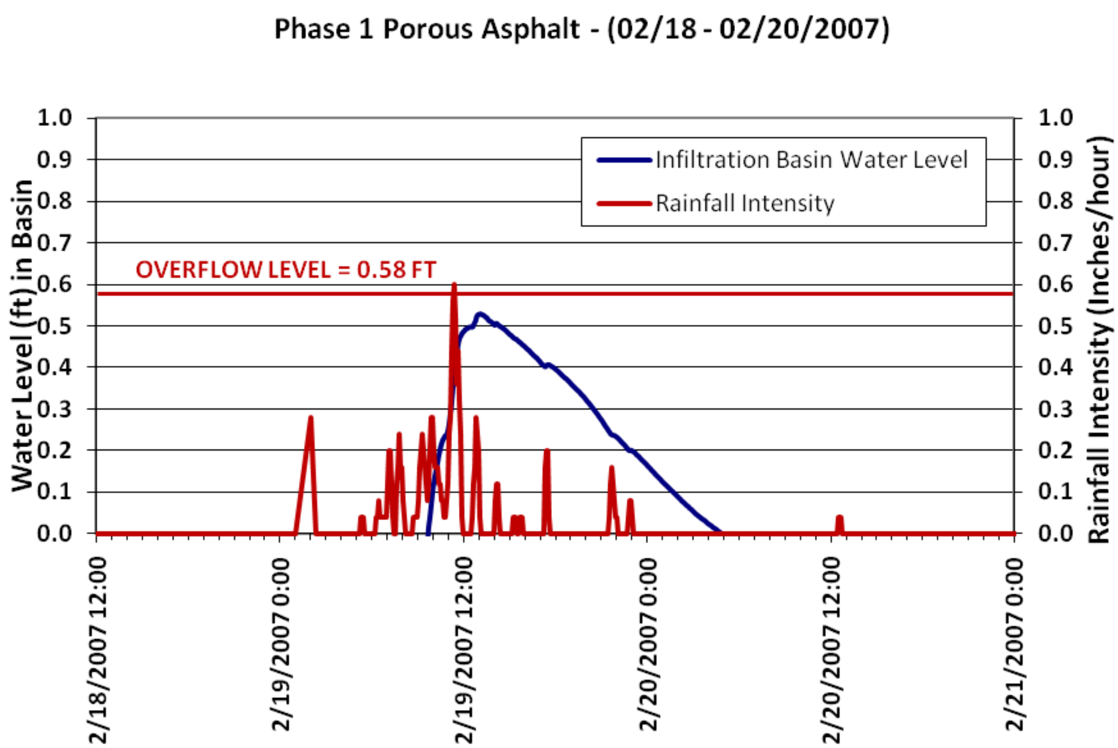


Figure 33. Comparison of Infiltration Rates at Phase I Asphalt and Concrete during a February 2007 Event.

Stormwater Quality and Pollutant Loads

Stormwater quality was measured during four events at the roof reference site, three events at the Phase 1 references site and three events at the Phase I reference site during the past two years. Event Mean Concentrations (EMCs) for each event are summarized in Table 7. Basic descriptive statistical summaries of data from the roof reference, Phase I parking lot reference and Phase II parking lot reference sites are presented in Table 8. Phase I and II parking lot reference data were separated due to potential biases caused by the overflow and dewatering of the adjacent ME construction site. The statistical summary also incorporates six events sampled during previous Phase I studies. The median value for hardness, sediment, nutrients and metals in runoff from each of three reference sites were graphically compared (Figure 34 - Figure 39). Estimates of the volume of stormwater eliminated at each porous paving site during both the 2006/2007 and 2007/2008 seasons are provided in Table 9. These volumes and the mean EMCs were then used to develop estimates of pollutant loads from the parking lot reference sites and estimates of pollutant load reductions achieved at each porous paving test site for each storm season (Table 10 and Table 11). All calculations were based upon each porous paving test site effectively retaining and infiltrating 100 percent of rainfall for each season. Table 12 then compares mean runoff quality from the reference site to other studies and to available California Toxics Rule (CTR; USEPA, 2000) acute water quality criteria.

Runoff from the roof reference site (Figure 34 through Figure 39; Table 7 and Table 8) was characterized by very low concentrations of all contaminants of concern except for dissolved zinc. Concentrations of dissolved lead were an order of magnitude lower than measured in runoff from the Phase I and II parking lot reference sites. In comparison to the two parking lot reference areas, mean concentrations of both total and dissolved copper where 50 to 80 percent lower in stormwater runoff from the roof reference site. Total zinc in roof runoff was 20 to 50 percent of concentrations measured at the parking lot reference sites. Zinc measured in the roof runoff was largely in the dissolved form. Seventy to 75 percent of the total zinc found in roof runoff was dissolved. Dissolved zinc in roof runoff was about 50% of concentrations measured at the Phase I parking lot reference area and equivalent to concentrations measured at the Phase II parking lot reference area.

In addition, the average hardness (8 mg/L as $CaCO_3$) of roof runoff was the lowest of the three reference areas (Figure 34). Rainwater is typically low in hardness. Hardness increases when the runoff is exposed to soils where calcium and magnesium compounds become dissolved. Low hardness values tend to decrease any of the hardness-dependent water quality criteria. Hardness values were two to three times higher in runoff from the two parking lot reference areas due to some exposure to sediment. The introduction of soils to the Phase II parking lot reference site from the adjacent ME construction site was evident in higher hardness, SSC and

TSS concentrations (Figure 35). The SSC data also indicated that the sediment measured in runoff from the Phase II parking lot reference site consisted of 90% or greater fine material (<63 microns).

All porous paving BMPs examined were considered successful in preventing nearly 100 percent of the metals and other contaminants from discharging to the San Diego River through the municipal storm drains over the course of the two-year study. As noted earlier, some water was lost from the Phase I porous pavers and Phase II porous concrete and asphalt infiltration basins as the result of leaks in the drainage pipes but the exact amount of these losses could not be quantified. During the 2006/2007 season, 4.5 inches of rain at the Phase I porous paving sites prevented over 686,000 liters (0.56 acre feet) of runoff from discharging to the storm drain system (Table 10). With the Phase II improvements and increase in annual rainfall, the combined Phase I/II porous paving sites prevented over 2,593,000 liters (2.1 acre feet) from discharging to the storm drain.

The seasonal mean Event Mean Concentrations (EMC) for runoff from the reference area, the areal coverage of each porous treatment, and annual rainfall were used to estimate load reductions achieved by each type of porous pavement for each year (Table 9 through Table 11). The Phase I reference area data were used to estimate load reductions associated with the 2006/2007 season (Table 8) while the Phase II reference area data were used to estimate load reductions for the 2007/2008 wet season.

The following equations were used to calculate estimated load reductions for the project. The calculation for total phosphorus during the 2007/2008 season is provided as an example. The first equation illustrates the calculation of the total volume of stormwater directly impinging on the five porous paving areas.

$$V_{PP} = (C1_A + C2_A + PP_A + A1_A + A2_A) * R * 28.32$$

$$V_{PP} = (14{,}936\ ft^2 + 12{,}100\ ft^2 + 7{,}896\ ft^2 + 41{,}092\ ft^2 + 41{,}900\ ft^2) * 0.6408\ ft * 28.32\ L/ft^3 = 2{,}140{,}020\ liters$$

where:

V_{PP} = volume of annual rainfall directly on Porous Paving Surfaces (liters)

$C1_A$ = Area of Phase I porous concrete (ft^2)

$C2_A$ = Area of Phase II porous concrete (ft^2)

$A1_A$ = Area of Phase I porous asphalt (ft^2)

$A2_A$ = Area of Phase II porous asphalt (ft^2)

PP_A = Area of Phase I porous pavers (ft^2)

R = average annual rainfall (inches)

28.32 = conversion constant from ft^3 to liters

The annual volume of water impinging on the roof reference area was then calculated separately using the same basic equation:

$$V_{RR} = RR_A * R * 28.32$$

$$V_{RR} = 25{,}000\ ft^2 * 0.6408 * 28.32 = 453{,}686\ liters$$

where:

V_{RR} = volume of annual rainfall directly on the roof reference area (liters)

RR_A = Area of roof reference site (ft2)

The next equation illustrates the calculation of the total loads that are expected to be eliminated in an average rainfall year as a result of the completed parking lot improvements. The median EMC for the parking lot reference area was used for all porous paving surfaces and the median EMC for the roof reference area was used for runoff from the roof.

$$L_x = (mPLR\_EMC_X * V_{PP}) + (mRR\_EMC_X * V_{RR})$$

$$L_{TP} = (0.00014g/L * 2{,}140{,}020\ liters) + (0.000057g/L * 453{,}686\ liters) = 325g\ P$$

where:

$mPLR\_EMC_X$ = Median EMC of constituent of concern X at the Parking Lot Reference Site converted to g/L.

mRR_EMC_X = Median EMC of constituent of concern X at the Roof Reference Site converted to g/L.

L_x = Estimated pollutant load reduction in (g) for constituent of concern X.

TP = Total Phosphorus

Mean EMCs from the Phase I and II reference sites (Table 12) were compared against the results of studies conducted in similar environments. A total of nine events have been monitored using the Phase I parking lot reference area since Phase 1 of this study was initiated in 2005. Data from the Phase II parking lot reference are far more limited with only three replicates and, in addition, sediment from the adjoining construction site is known to have had some impact on the results. Despite these differences, the quality of stormwater runoff from the COC Reference Area was very comparable to results from Caltrans Maintenance Yards, Caltrans Park and Ride facilities and a small, highly impervious urban drainage in Long Beach, California. There were no dramatic differences apparent for any constituents although slightly higher mean concentrations of total and dissolved cadmium were evident in runoff from the

Phase I parking lot reference and concentrations of phosphorous, both total P and orthophosphate were slightly lower.

The mean EMCs for three of the four trace metals monitored at the Phase I parking lot reference site exceeded the CTR acute receiving water quality objectives based upon an average hardness of 15 mg/L. Mean concentrations of both dissolved copper and zinc were greater than 5 times the CTR acute criterion. Dissolved cadmium only slightly exceeded the criteria. Although the mean EMC for dissolved lead at the Phase I parking lot reference area was high (4.2 µg/L) compared to stormwater runoff from other sites, concentrations did not exceed the CTR acute criterion.

Mean EMCs for all four dissolved metals at the Phase II parking lot reference site were lower than the Phase I values but CTR acute criteria were still exceeded for both dissolved copper and zinc. Overall, exceedances of the CTR acute criteria were largely driven by the extremely low hardness of runoff from the COC Reference Area. With parking lots, roof tops and sidewalks covering 91% of the area, runoff does not interact with soils to increase hardness and mitigate potential downstream toxicity.

Table 7. Summary of Results of Chemical Analysis of Stormwater Runoff from the Roof, Phase I Parking Lot, and Phase I Parking Lot Reference Sites.

CONSTITUENT	ROOF				PHASE I REFERENCE				PHASE II REFERENCE		
	7-Dec-07	19-Dec-07	5-Jan-08	23-Jan-08	30-Jan-07	20-Feb-07	23-Feb-07	20-Apr-07	7-Dec-07	5-Jan-08	23-Jan-08
Hardness (mg/L)	5	9.4	2.4	15	-[1]	6.2	11	20	46	17	13
pH (units)	6.0	6.9	6.9	7.0	-	-	-	-	7.5	9.8	10.2
SSC (mg/L)	9.78	43.6	6.63	25.5	-	23.3	22.5	84.3	170	46	183
>63 microns	4.09	13	3.03	10.2	-	2.18	6.06	10.3	29.9J	6.15	18.3
<63 microns	5.69	30.6	3.6	15.2	-	21.1	16.4	74.0	140	39.8	164
TSS (mg/L)	7.3	18	18	22	-	25	20	81	200	48	180
COD (mg/L)	4.1	14	7	17	-	28	49	130	46	37	79
DOC (mg/L)	2.1	3.8	1.5	1.1	-	5.4	14	22	8.4	5.4	4.2
Total P	0.029	0.089	0.032	0.078	-	0.11	0.15	0.26	0.16	0.13	0.13
Ortho-P (mg/L)	0.013	0.015	0.0074J	0.018	-	0.042	0.084	0.11	0.082	0.054	0.051
Ammonia-N (mg/L)	0.23	0.067J	0.071J	0.16	-	0.32	0.35	0.57	0.26	0.16	0.2
TKN (mg/L)	0.48	0.95	0.32	0.84	-	1.3	1.2	2.1	1.2	0.62	0.56
Nitrate-N (mg/L)	0.29	0.37	0.049J	0.082J	-	0.27	0.38	0.77	0.6	0.18	0.18
Total Cadmium (ug/L)	0.49	0.33	0.079J	0.26	-	0.65	0.68	2.4	0.36	0.075J	0.2
Diss. Cadmium (ug/L)	0.38	0.35	0.076J	0.12J	-	0.24	0.36	1.1	0.13J	0.02J	0.014J
Total Copper (ug/L)	3.7	4.5	1.2	4.9	-	10	16	37	36	10	20
Diss. Copper (ug/L)	2.1	4.4	0.85	0.78	-	4.3	12	21	8.2	5.2	5.6
Total Lead (ug/L)	3.4	1.7	0.66	24	-	21	21	65	16	3.4	21
Diss. Lead (ug/L)	0.46	1.3	0.24	0.37	-	1.3	3.1	7.2	2.2	0.48	1.3
Total Zinc (ug/L)	83	81	53	79	-	72	88	360	400	240	370
Diss. Zinc (ug/L)	72	79	42	34	-	32	49	210	140	51	41
Calculated Values[1]											
Oil&Grease$_{(COD)}$ (mg/L)	3.9	4.2	4	4.3	-	4.7	5.5	8.5	5.4	5.1	6.6
Oil&Grease$_{(DOC)}$ (mg/L)	0.74	1.2	0.57	0.46	-	1.7	4.1	6.3	2.5	1.7	1.3

1. An equipment malfunction prevented the autosampler from sampling.
2. Kayhanian, M, S. Khan, and M.K. Stenstrom. 2004. A new method to estimate oil and grease event mean concentration in highway runoff. StormCon 2004

U indicates the constituent is a not detected - the value is the reporting limit
J indicates the value is an estimate

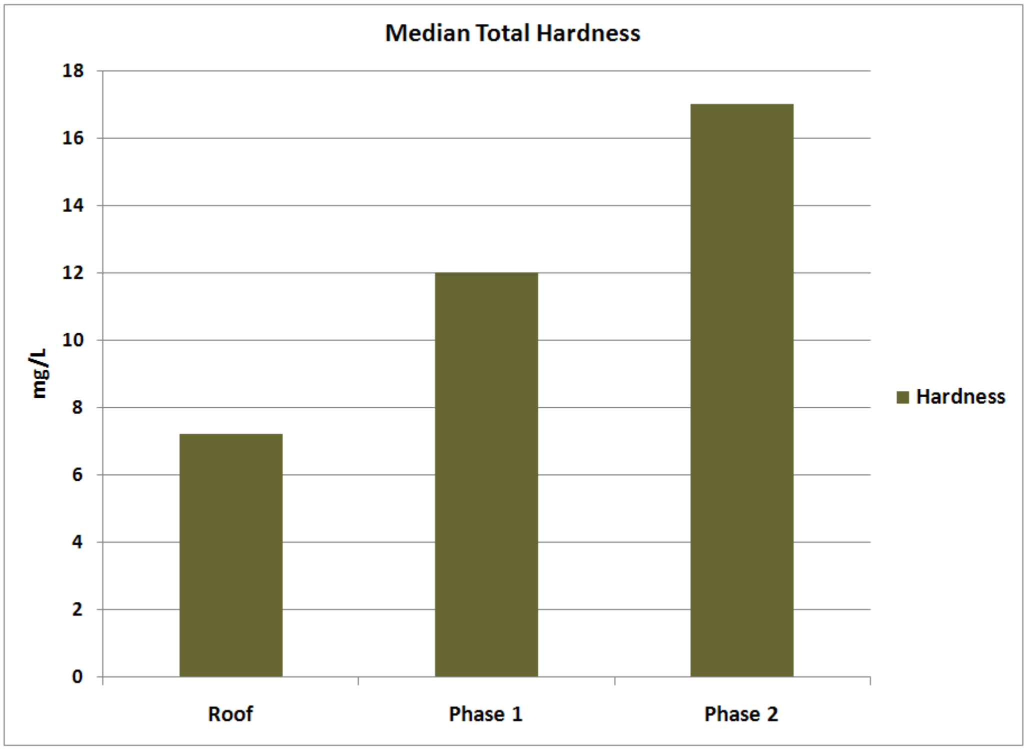


Figure 34. Comparison of Hardness as $CaCO_3$ measured in Runoff from the Three Reference Sites.

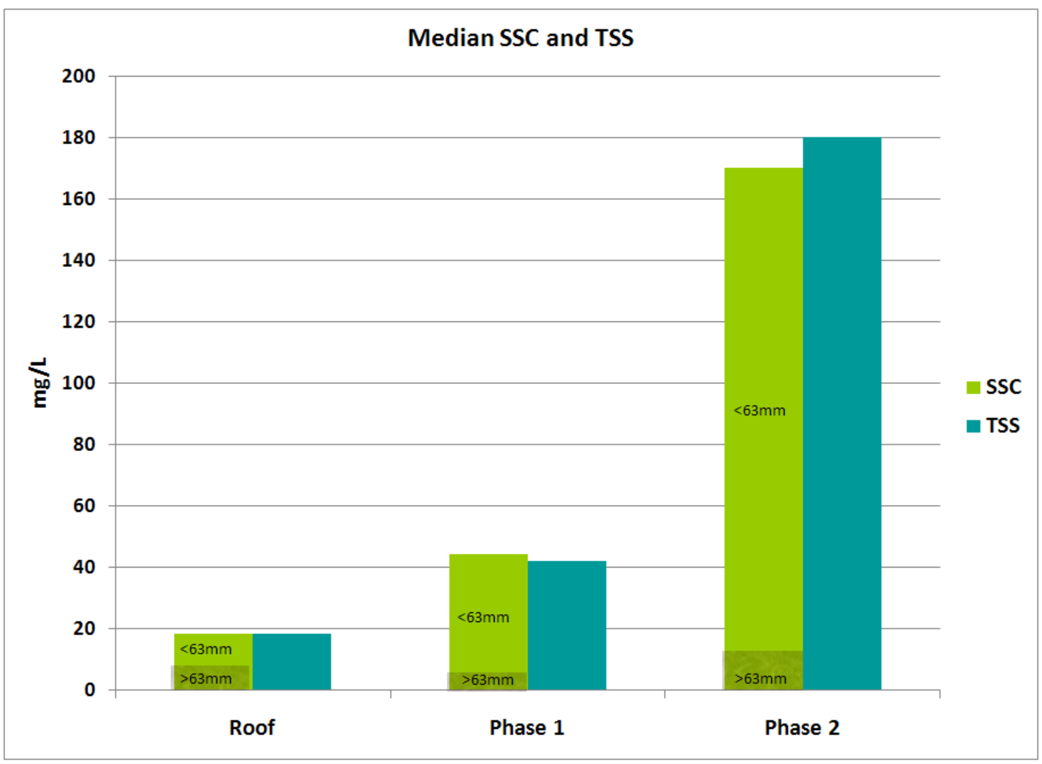


Figure 35. Comparison of Concentrations of Suspended Sediment measured in Runoff from the Three Reference Sites.

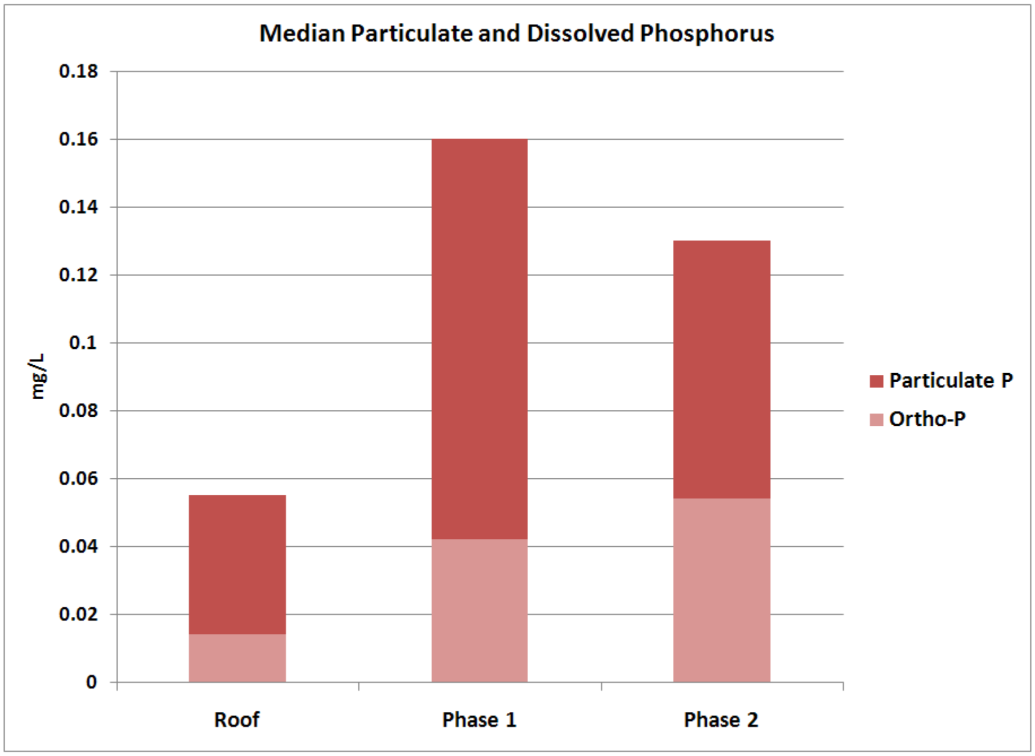


Figure 36. Comparison of Particulate-P and Ortho-P measured in Runoff from the Three Reference Sites.

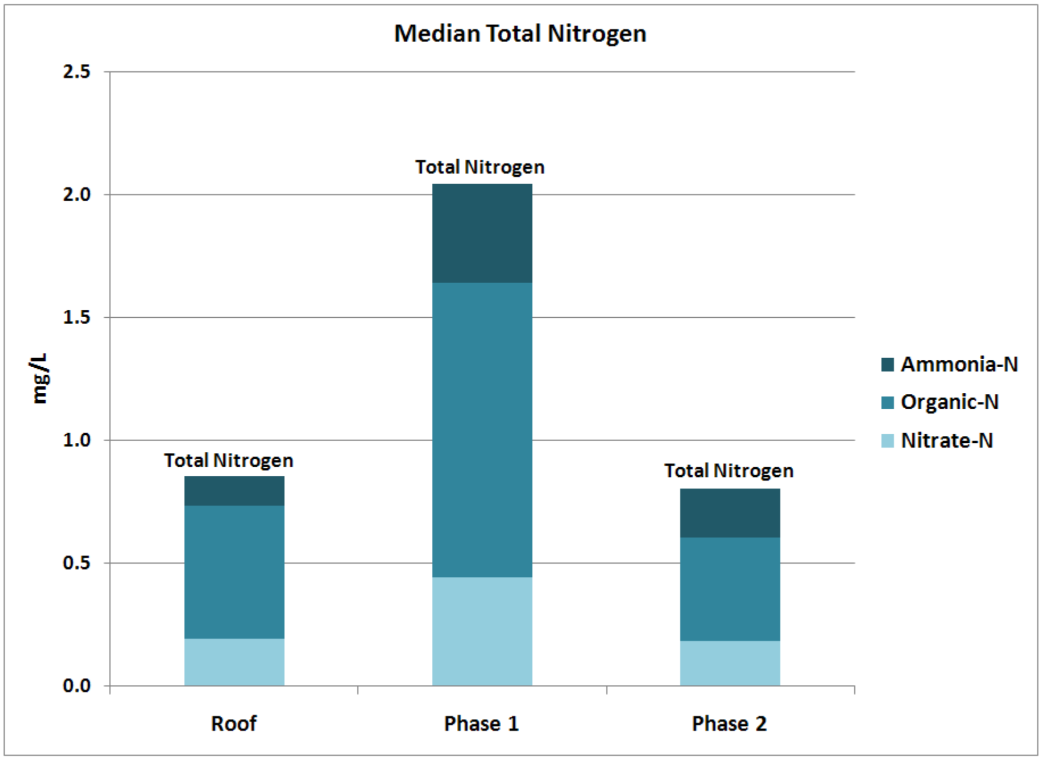


Figure 37. Comparison of Total Nitrogen measured in Runoff from the Three Reference Sites.

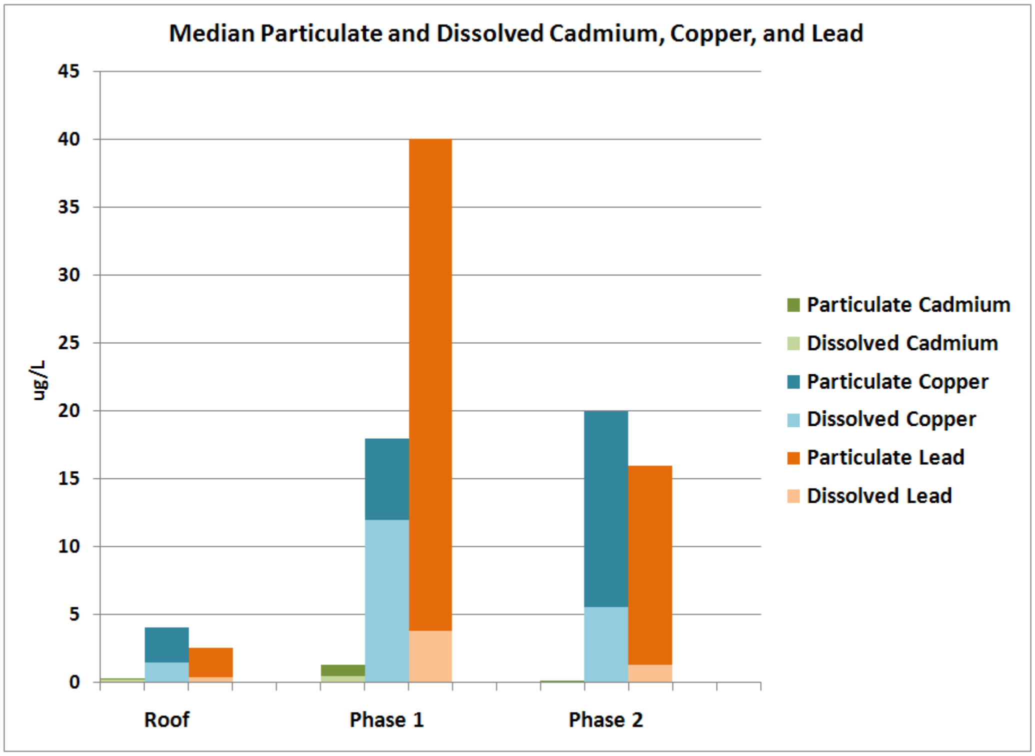


Figure 38. Comparison of Particulate and Dissolved Cadmium, Copper, and Lead measured in Runoff from the Three Reference Sites.

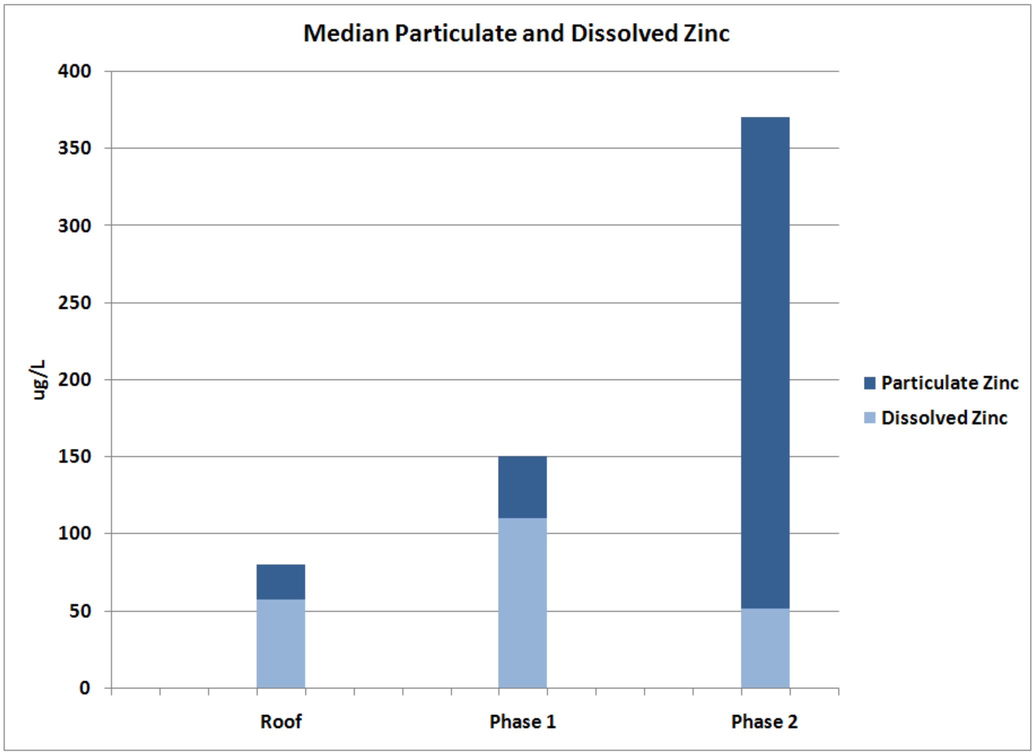


Figure 39. Comparison of Particulate and Dissolved Zinc measured in Runoff from the Three Reference Sites.

Table 8. Statistical Summary of 2005 - 2007 Event Mean Concentrations for all Constituents Measured in Stormwater Runoff from the Roof (n=3), Phase I Parking Lot (n=9) and Phase II Parking Lot (n=3) Reference Areas.

	Roof Reference (n=3)				Phase I Parking Lot Reference				Phase II Parking Lot Reference			
CONSTITUENT	1st quartile	3rd quartile	Median	Mean	1st quartile	3rd quartile	Median	Mean	1st quartile	3rd quartile	Median	Mean
Hardness (mg/L)	4.4	10.8	7.2	8.0	9	20	12	15	15	31.5	17	25.3
pH (units)	6.7	6.9	6.9	6.7					8.7	10	9.8	9.2
SSC (mg/L)	9.0	30	18	21	23	80	44	56	108	177	170	133
>63 microns	3.8	11	7.1	7.6	2.6	10.3	5.0	9.0	9.2	15	12	12
<63 microns	5.2	19	10	14	20	67	41	47	90	152	140	115
TSS (mg/L)	15	19	18	16	22	75	42	56	114	190	180	143
COD (mg/L)	6.3	15	11	10	59	130	68	83	42	63	46	54
DOC (mg/L)	1.4	2.5	1.8	2.1	13	22	15	16	4.8	6.9	5.4	6.0
Total P	0.031	0.08	0.055	0.057	0.15	0.23	0.16	0.21	0.13	0.15	0.13	0.14
Ortho-P (mg/L)	0.012	0.02	0.014	0.013	0.034	0.059	0.042	0.054	0.053	0.068	0.054	0.06
Ammonia-N (mg/L)	0.070	0.18	0.12	0.13	0.32	0.62	0.4	0.50	0.18	0.23	0.20	0.21
TKN (mg/L)	0.44	0.87	0.66	0.65	1.2	2.3	1.6	1.7	0.59	0.91	0.62	0.79
Nitrate-N (mg/L)	0.0.74	0.31	0.19	0.20	0.31	0.77	0.44	0.58	0.18	0.39	0.18	0.32
Total Cadmium (ug/L)	0.21	0.37	0.30	0.29	0.86	1.8	1.3	1.5	0.14	0.28	0.20	0.21
Diss. Cadmium (ug/L)	0.11	0.36	0.24	0.23	0.45	1.0	0.53	0.71	0.017	0.075	0.020	0.05
Total Copper (ug/L)	3.1	4.6	4.1	3.6	16	36	18	23	15	28	20	22
Diss. Copper (ug/L)	0.83	2.7	1.5	2.0	11	18	12	13	5.4	6.9	5.6	6.3
Total Lead (ug/L)	1.4	8.6	2.6	7.4	21	65	40	42	9.7	18.5	16	13.5
Diss. Lead (ug/L)	0.34	0.67	0.42	0.59	3.1	5.3	3.8	4.2	0.89	1.8	1.3	1.3
Total Zinc (ug/L)	72.5	82	80	74	140	220	150	193	305	385	370	337
Diss. Zinc (ug/L)	40.0	74	57	57	73	140	110	119	46	96	51	77
Calculated Values[1]												
Oil&Grease$_{(COD)}$ (mg/L)	4.0	4.2	4.1	4.1	5.9	8.5	6.2	6.8	5.3	6.0	5.4	5.7
Oil&Grease$_{(DOC)}$ (mg/L)	0.5	0.86	0.66	0.74	3.8	6.3	4.4	4.8	1.5	2.1	1.7	1.8

Table 9. San Diego County Operations Center Porous Pavement Treatment Stormwater Volumes for the 2006/2007 and 2007/2008 Wet Seasons.

Site	Area (square feet)	Total Rainfall (ft) [1]	Volume (cubic ft)	Volume (L)
2006/2007				
Concrete 1	14,936	0.379	5663	160365
Asphalt 1	41,092	0.379	15581	441197
Pavers	7,896	0.379	2994	84778
TOTAL	**63,924**		**24,238**	**686,340**
2007/2008				
Concrete 1	14,936	0.641	9,571	271,034
Concrete 2	12,100	0.641	7,754	219,571
Asphalt 1	41,092	0.641	26,333	745,671
Asphalt 2	41,900	0.641	26,850	760,333
Pavers	7,896	0.641	5,060	143,284
Roof [2]	25,000	0.641	16,020	453,659
TOTAL	**142,924**		**91,590**	**2,593,553**

1. Depicts total rainfall, in feet as measured by the Reference Site rain gauge. Rainfall totaled 4.5 inches in 2006/2007 and 7.7 inches in the 2007/2008 season.
2. Roof runoff discharges into Asphalt 2

Table 10. Estimated Annual Pollutant Load[1] from the Reference Site and Corresponding Load Reductions due to each Porous Treatment Type, 2006/2007

Constituent	Phase I Parking Lot Reference	Asphalt I	Concrete 1	Pavers	Total Load Reduction (Kg)
	Load (Kg)	Estimated Load Reduction (Kg)			
SSC	9.1	10.3	3.7	2.0	**16**
>63 microns	2.4	2.7	1.0	0.5	**4.2**
<63 microns)	8.2	9.3	3. 4	1.8	**15**
TSS	9.7	11.0	4.0	2.1	**17**
COD	19	21.6	7.9	4.1	**34**
DOC	5.4	6.2	2.2	1.2	**9.6**
Total P	0.058	0.066	0.024	0.013	**0.10**
Ortho-P	0.033	0.037	0.013	0.007	**0.058**
Ammonia-N	0.14	0.15	0.056	0.030	**0.24**
TKN	0.51	0.57	0.21	0.11	**0.89**
Nitrate-N	0.15	0.17	0.061	0.032	**0.26**
Total Cadmium	0.00026	0.000300	0.000109	0.000058	**0.00047**
Diss. Cadmium	0.00014	0.00016	0.000058	0.000031	**0.00025**
Total Copper	0.0062	0.007	0.0026	0.0014	**0.011**
Diss. Copper	0.0047	0.0053	0.0019	0.001	**0.0082**
Total Lead	0.0082	0.0093	0.0034	0.0018	**0.014**
Diss. Lead	0.0012	0.0014	0.00050	0.00026	**0.0021**
Total Zinc	0.034	0.0039	0.0014	0.007	**0.060**
Diss. Zinc	0.019	0.022	0.008	0.004	**0.034**
Calculated Values[2]					
Oil&Grease(COD)	2.1	2.4	0.88	0.47	**3.8**
Oil&Grease(DOC)	1.6	1.8	0.66	0.35	**2.8**

1. All load estimates based upon annual rainfall of 4.5 inches measured at the porous paving reference rain gauge.
2. Kayhanian, M, S. Khan, and M.K. Stenstrom. 2004. A new method to estimate oil and grease event mean concentration in highway runoff. StormCon 2004.

Table 11. Estimated Pollutant Loads at the Parking Lot Reference Site and Pollutant Load Reductions (in kilograms) at San Diego County Operations Center Porous Pavement Treatment Sites, 2007/2008

Constituent	Phase II Parking Lot Reference	San Diego County Porous Pavement Treatment Sites						TOTAL
		Asphalt 1	Asphalt 2	Concrete 1	Concrete 2	Roof	Pavers	
SSC	87	99	16	36	29	10	19	**209**
>63 microns	12	14	6	4.9	4.0	3.4	2.6	**34**
<63 microns	75	85	10	31	25	6.2	16	**175**
TSS	94	106	12	39	31	7.4	20	**217**
COD	35	40	8.0	15	12	4.8	7.7	**87**
DOC	3.9	4.5	1.6	1.6	1.3	1.0	0.9	**11**
Total P	0.092	0.10	0.043	0.038	0.031	0.026	0.020	**0.26**
Ortho-P	0.041	0.046	0.010	0.017	0.014	0.006	0.009	**0.10**
Ammonia-N	0.14	0.15	0.10	0.056	0.045	0.060	0.030	**0.45**
TKN	0.52	0.59	0.49	0.22	0.17	0.29	0.11	**1.9**
Nitrate-N	0.21	0.24	0.15	0.087	0.070	0.090	0.046	**0.68**
Total Cadmium	0.0014	0.0016	0.00022	0.00057	0.00046	0.00013	0.00030	**0.0033**
Diss. Cadmium	0.00036	0.00041	0.00018	0.00015	0.00012	0.00011	0.00008	**0.0010**
Total Copper	0.14	0.16	0.0027	0.060	0.048	0.0016	0.032	**0.31**
Diss. Copper	0.042	0.047	0.002	0.017	0.014	0.00092	0.0091	**0.090**
Total Lead	0.088	0.10	0.01	0.04	0.03	0.0034	0.019	**0.19**
Diss. Lead	0.0087	0.010	0.000	0.004	0.003	0.00027	0.0019	**0.019**
Total Zinc	2.2	2.5	0.06	0.91	0.74	0.034	0.48	**4.7**
Diss. Zinc	0.51	0.58	0.04	0.21	0.17	0.026	0.11	**1.1**
Calculated Values[1]								
Oil&Grease$_{(COD)}$	3.7	4.3	3.1	1.5	1.3	1.9	0.8	**13**
Oil&Grease$_{(DOC)}$	1.2	1.4	0.6	0.5	0.4	0.3	0.3	**3.4**

Note: All load estimates based upon annual rainfall of 7.7 inches measured at the porous paving reference rain gauge.

1. Kayhanian, M, S. Khan, and M.K. Stenstrom. 2004. A new method to estimate oil and grease event mean concentration in highway runoff. StormCon 2004.

Table 12. Comparison of Pollutant Concentrations measured in Runoff from the Phase I and II Parking Lot Reference Sites with Runoff from Parking and Maintenance Facilities[1], a Small Residential/Commercial Drainage[2] and Water Quality Criteria.

Analytical Parameter	Project Reporting Limits	COC Phase I Parking Lot Reference Site (means)	COC Phase II Parking Lot Reference Site (means)	Caltrans Maintenance Yards[2] (means)	Caltrans Park & Ride Lots[2] (means)	City of Long Beach Belmont Pump Station[1] (2004-2005 ranges)	CTR Acute Freshwater Criteria (based on hardness of 15 mg/L)[3]
Hardness (mg/L)	2.0	15	25.3	-	-	15-25	
SSC (mg/L)	1.0	56	133	-	-	-	
TSS (mg/L)	1.0	56	143	98	61.8	37-130	
COD(mg/L)	4.0	83	54	-	-	30-88	
DOC(mg/L)	1.0	16	6.0	17.8	19.8		
Total P (mg/L)	0.05	0.21	0.14	0.3	0.4	0.41-0.63	
Ortho-P (mg/L)	0.05	0.054	0.06	0.2	0.2	0.18-0.36	
Ammonia – N (mg/L)	0.1	0.50	0.21	-	-	0.1-0.26	
TKN (mg/L)	0.1	1.7	0.79	1.8	2.6	1.0-1.6	
Nitrate – N (mg/L)	0.1	0.58	0.32	0.7	0.7	0.33-0.90	
Total Cadmium (ug/L)	0.25	1.5	0.21	0.8	0.31	0.38-1.1	
Diss. Cadmium (ug/L)	0.25	***0.71***	0.05	0.32	0.14	0.074-0.25	0.54
Total Copper (ug/L)	1.0	23.4	22	34.9	16.7	17-49	
Diss. Copper (ug/L)	1.0	***13.1***	***6.3***	***13.3***	***9.0***	***6.1-10***	2.2
Total Lead (ug/L)	0.5	42.1	13.5	34.3	9.2	15-60	
Diss. Lead (ug/L)	0.5	4.2	1.3	2.5	1.2	0.63-1.4	7.8
Total Zinc (ug/L)	1.0	193	337	240	158	110-380	
Diss. Zinc (ug/L)	1.0	***119***	***77***	***110***	***79***	***31-60***	23.5

Bolded and Italicized values exceed CTR Acute Criterion. Hardness-based criteria were calculated using the mean hardness of runoff from the 6 events.

1. Kinnetic Laboratories, Inc. 2005c. City of Long Beach Stormwater Monitoring Report, 2004/2005.
2. Caltrans, 2003. Preliminary Report of Discharge Characterization Studies. CTSW-RT-03-023
3. For consistency, mean hardness of samples from the Phase I parking lot reference site (15 mg/L) used to calculate hardness-based criteria. Using the mean hardness from the Phase II parking lot reference site (25 mg/L) would not substantially impact assessment of CTR exceedances.

Lysimeter Water Quality

Both the Phase II porous asphalt and concrete lysimeters were sampled after each of three storms (Table 13). It was not possible to collect the full volume necessary to perform all analyses from each site during all events. The asphalt lysimeter proved most difficult to obtain adequate volumes thus only hardness and metals were analyzed during the first two storm events. Despite the poor infiltration at the concrete site, water was easier to obtain at the concrete lysimeters.

This apparent incongruity is believed to be due to differences in the soil profiles at each site. Digging was noted to be extremely difficult at both the lysimeters sites when holes were being augered. The last few inches of the hole at the concrete site proved to be most difficult suggesting the presence of a hard pan layer. It is theorized that deep infiltration was limited by the hard pan. The fine clays still made it difficult to collect the necessary water volumes within a 48-hour time period. Extra volume needed to measure pH was not obtained until the last storm event.

The quality of water extracted from the two lysimeters (Table 13) was very different at the two sites and appeared to exhibit very different trends over time. Due to the limited data, caution is necessary in the interpretation of any apparent trends. The hardness of water extracted from the asphalt lysimeters was initially 17 mg/L but increased to 840 and 930 mg/L during the latter two events. The hardness of water from the concrete lysimeters decreased over time. Water from the first storm event had a hardness concentration of 55 mg/L and by the last event, hardness had dropped to 11 mg/L. Both COD and DOC measured in water from the concrete lysimeter also declined from the levels measured during the first event. The concentrations of nitrate-N in water from the concrete lysimeter was low (<0.9 in all cases) and also showed as tendency to decline over time.

The four trace metals analyzed in water from the lysimeters (Table 13) did not all follow similar patterns. With the exception of total cadmium measured in water from the asphalt lysimeter (0.24 µg/L), concentrations of both total and dissolved cadmium were detected at concentrations below reporting limits at both sites during the three storms. These values are considered estimates (J) as they were detected between the Method Reporting Limit (MDL) and Reporting Limit (RL). Total and dissolved copper concentrations were similar at both sites although concentrations were more variable in water from the asphalt lysimeters. Lead was the only metal that showed evidence of substantial differences between sites. Dissolved lead in water from the asphalt lysimeters was always detected below reporting limits (0.066J to 0.074J µg/L). Dissolved lead measured in water from the concrete lysimeter was roughly an order of magnitude greater (0.64 to 2.2 µg/L). This large difference may be related to the differential infiltration properties at these two sites. The lack of substantial infiltration at the porous concrete site was associated with lower hardness values suggesting that the water was not picking up dissolved material from the soils and may have been short-circuiting from the rock basin to the lysimeter without passing through a substantial soil layer. The increasing hardness levels at the asphalt lysimeter and decreasing hardness at the concrete lysimeter suggest that this could be the case. Better filtration through the soils at the asphalt lysimeter would explain the lower concentrations of dissolved lead since lead is not considered to be very mobile in soils due to its tendency to associate strongly with fine-grained soils. Infiltrating water from both sites contained extremely low levels of total zinc (2.5 to 9J+ µg/L) and dissolved zinc (1.8 to 11J µg/L). The J values associated with the highest values of total and dissolved zinc were due to dissolved zinc exceeding the total zinc and a method blank that slightly exceeded the reporting limit for total zinc.

Table 13. Summary of Results of Chemical Analysis of Stormwater Runoff from the Phase II Asphalt and Concrete Lysimeters.

CONSTITUENT	ASPHALT LYSIMETER			CONCRETE LYSIMETER		
	8-Dec-07	6-Jan-08	26-Jan-08	8-Dec-07	6-Jan-08	25-Jan-08
Hardness (mg/L)	17	840	930	55	29	11
pH (units)	IS[2]	IS	IS	IS	IS	9.9
COD (mg/L)	IS	IS	190	96	59	48
DOC (mg/L)	IS	IS	48	23	10	7.7
Total P	IS	IS	0.58	0.43	0.36	0.52
Ortho-P (mg/L)	IS	IS	0.35	0.044	0.11	0.14
Ammonia-N (mg/L)	IS	IS	0.03J	0.071J	0.025J	0.045J
TKN (mg/L)	IS	IS	1.5	0.59	0.52	0.54
Nitrate-N (mg/L)	IS	IS	6.8	0.83	0.45	0.28
Total Cadmium (ug/L)	0.24	0.15J	0.042J	0.093J	0.044J	0.065J
Diss. Cadmium (ug/L)	0.18J	0.14J	0.032J	0.072J	0.042J	0.055J
Total Copper (ug/L)	2.5	13	8.0	5.3	4.4	4.8
Diss. Copper (ug/L)	1.4	9.4	6.1	4.4	3.4	3.5
Total Lead (ug/L)	0.14J	0.15J	0.18J	0.81	0.62	2.6
Diss. Lead (ug/L)	0.066J	0.068J	0.074J	0.64	0.47	2.2
Total Zinc (ug/L)	9J+	5	2.7	2.5	3.2	5.2
Diss. Zinc (ug/L)	11J	5.4	1.6	2	1.8	3.6
Calculated Values[1]						
Oil&Grease$_{(COD)}$ (mg/L)			11	7.3	5.9	5.5
Oil&Grease$_{(DOC)}$ (mg/L)			14	6.6	3.0	2.3

1. Kayhanian, M, S. Khan, and M.K. Stenstrom. 2004. A new method to estimate oil and grease event mean concentration in highway runoff. StormCon 2004.
2. IS indicates insufficient sample volumes for measurement.

U indicates the constituent is a not detected - the value is the reporting limit
J indicates the value is an estimate

Phase II Porous Concrete Infiltration Basin

Water that was retained and not infiltrated in the Phase II porous concrete infiltration basin was sampled in early June (2/6/08) to characterize the water before deciding if the water could be reused, discharged to the storm drain or would need to be redirected into the adjacent asphalt infiltration basin. An Isco peristaltic pump fitted with a pre-cleaned and blanked Teflon intake hose was used to obtain the sample. The hose was directed into the 8-foot perforated pipe that provides a connection to the infiltration basin in an effort to avoid the potential effects of materials that had dropped through the grating and into the box.

Figure 40. Sampling of Water from the Phase II Porous Concrete Infiltration Bed, 2 June 2008.

Analytical results of the standing water (Table 14) were compared against the lysimeter data and reference sites. Water from the basin was very hard (160 mg/L) as might be suspected after passing through the porous concrete matrix but other results were somewhat surprising. The total Suspended Sediment Concentration (SSC) was higher than anticipated given the earlier observations of extremely clear water in the basin. The SSC was also dominated by the <63 micron fraction which accounted for over 97% of the particulates. Total copper was over twice the mean concentrations reported for the Phase I and II parking lot reference areas.

The site was revisited on 21 July 2008 to obtain turbidity data and for further visual observations. The condition of the catch basin and water had visually changed since the June sampling event (Figure 41 and Figure 42). Crickets had become abundant in the catch basin and the surface film had increased. Water just under the surface was relatively clear with a measured turbidity of 7 NTU.

Water sampled from the perforated pipe was radically different than water undisturbed water within the catch basin (Figure 43 and Figure 44). Prior to allowing the sample to settle, turbidity was measured at 200 NTU. After allowing the sample to settle for just a few minutes, the supernatant water had a measured turbidity of 18.8 NTU.

Figure 41. Catch Basin and Standing Water in Phase II Porous Concrete Infiltration Basin during 2 June 2008 Sampling.

Figure 42. Catch Basin and Standing Water in Phase II Infiltration Basin during Revisit on 21 July 2008.

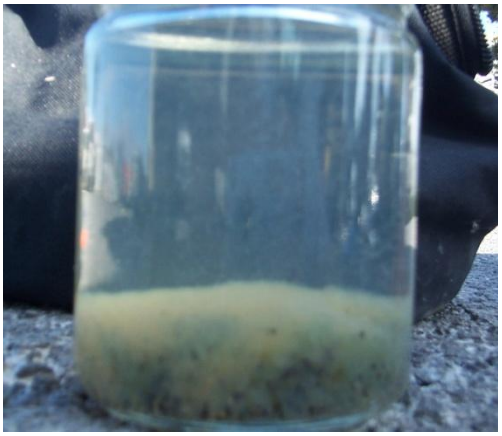


Figure 43. Water from Perforated Pipe connecting to the Porous Concrete Infiltration after Settling.

Figure 44. Water from Perforated Pipe connecting to the Porous Concrete Infiltration Basin prior to Settling.

Once settled, the flocculent material in the 250 ml sample container formed a layer that was approximately ½" deep. Material was suspended upon sampling, and settled fairly quickly. Visual field examination of the material in the containers indicated the presence of two separate types of suspended flocculent material. The light, beige colored floc settled fastest. A lighter flocculent material was green in color and settled at a slower rate. In addition to the flocculent materials, smaller amounts of heavy sands and debris that appeared to be of organic origins were present.

Table 14. Results of Chemical Analysis of Standing Water from the Phase II Porous Concrete Infiltration Basin compared to the Concrete Lysimeter and Reference Sites.

	CONCRETE		PARKING LOT REFERENCE		ROOF REFERENCE
CONSTITUENT	Infiltration Basin[1]	Lysimeter[2]	Phase I[2]	Phase II[2]	Phase II[2]
Hardness (mg/L)	160	32	15	25	7.2
pH (units)		9.9		9.2	6.9
SSC (mg/L)	20.8		56	133	21
>63 microns	0.57		9.0	12	7.6
<63 microns	20.2		47	115	14
TSS (mg/L)	-		56	143	16
COD (mg/L)	29	68	83	54	10
DOC (mg/L)	9.8	14	16	6.0	2.1
Total P	0.21	0.44	0.21	0.14	0.057
Ortho-P (mg/L)	0.20	0.10	0.054	0.060	0.013
Ammonia-N (mg/L)	0.013J	0.047	0.50	0.21	0.13
TKN (mg/L)	0.88	0.55	1.7	0.79	0.65
Nitrate-N (mg/L)	1.7	0.52	0.58	0.32	0.20
Total Cadmium (ug/L)	0.084J	0.067	1.45	0.21	0.29
Diss. Cadmium (ug/L)	0.076J	0.056	0.71	0.050	0.23
Total Copper (ug/L)	52	4.8	23	22	3.6
Diss. Copper (ug/L)	5.7	3.8	13	6.3	2.0
Total Lead (ug/L)	7.0	1.3	42	14	7.4
Diss. Lead (ug/L)	1.2	1.1	4.2	1.3	0.59
Total Zinc (ug/L)	140	3.6	193	337	74
Diss. Zinc (ug/L)	120	2.5	119	77	57
Calculated Values[1]					
Oil&Grease$_{(COD)}$ (mg/L)	7.1	6.2	6.8	5.7	4.1
Oil&Grease$_{(DOC)}$ (mg/L)	6.9	4.0	4.8	1.8	0.74

1. Water was sampled on 2-Jun-2008, 100 days after the last rainfall exceeding 0.1 inches. Antecedent rainfall was 0.16 inches on 23-Feb-2008.
2. All data other than the Phase II porous concrete infiltration basin are means.

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TREATMENT TRAIN

The following sections provide a discussion of monitoring methods utilized for the treatment train monitoring sites. Results are presented for the Phase II monitoring program. Monitoring conducted under the Phase II program started during the 2006/2007 wet season before construction of the Phase II improvements was complete. During that time period, the treatment train was still in the Phase I configuration with the CDS unit and a single MFS unit. The Phase II improvements were completed during the summer of 2007/2008. The discussion incorporates results of both Phase I and II of the Model Municipal Operations Center program.

METHODS

Prior to the 2007/2008 monitoring season work was conducted under the Phase I QAPP (MEC-Weston, 2004). After reconfiguration and construction of the Phase II improvements, all work was performed in accordance with a new QAPP/MP (Kinnetic Laboratories, Inc. 2007). The new QAPP/MP was developed to maintain consistency with the initial documents while incorporating changes necessary to reflect the restructuring of the treatment train. The following sections provide detailed descriptions of both Phase I and II treatment train configurations, sampling frequency, and sample collection and handling procedures.

Site Locations and Descriptions

Construction of the initial treatment train at the County Operations Center was completed on February 11, 2005. The Phase I treatment train (Figure 45) consisted of two structural BMPs developed by CDS Technologies. Primary treatment was provided by a Continuous Deflective Separation Pretreatment Unit (CDS Unit). The CDS Unit is a Model PSWC56_40 designed to treat up to 9.0 cfs of stormwater. The CDS unit was intended to remove gross pollutants which include trash, organic debris and coarse particulate matter. Secondary treatment was provided by a CDS Media Filtration System (MFS). The first MFS installed at the COC was an MFS 816 containing 42 cartridges and is designed to treat 1.75 cfs of stormwater. This unit was later designated as MFS2 when the additional filtration systems were installed. The filter cartridges for the MFS unit are designed to use a variety of filtration media. For this study, each cartridge utilized perlite media to filter very fine particulates in the stormwater.

A diversion weir was used to limit flows through the CDS Unit to 7.0 cubic feet per second (cfs) of stormwater runoff. Flows exceeding this magnitude bypassed the entire Treatment Train. During Phase I all water treated by the CDS unit entered another box that served to split flows to the single MFS unit. Excess flow was redirected back to the main storm drain.

Initially flow entering the MFS was controlled by an 8-inch pipe that was intended to prevent flow from exceeding the capacity of the MFS unit. A second internal bypass provided additional protection by assuring that flows through the filter cartridges did not exceed design capacity. Whenever flows exceeded the capacity of the cartridges, water in the chamber passed over a weir and discharged downstream of the MFS unit.

Evaluation of the overall performance of the Phase I Treatment Train required accurate measurement of flows at a number of points in the system. Measuring performance of the CDS unit required the ability to continuously monitor the volume of water passing through the system as well as any system bypasses that might occur during periods of high flow. With the MFS unit it was critical to obtain measurements of flows coming into the system, treated stormwater exiting the system and untreated stormwater that flows over the internal bypass weir. The initial monitoring configuration used to measure these flows and obtain flow-rated composite samples of water entering the MFS and the treated effluent is described in the following section.

Monitoring Configuration – Phase I

Stormwater flows approaching the Treatment Train were measured with an American Sigma Doppler flow sensor. Flow approaching the Treatment Train was monitored continuously throughout the project however, due to the nature of Doppler flow meters, only stormwater flows were quantified. Dry weather flows tend to lack suspended sediments necessary for the sensor to obtain a valid signal. This very characteristic would also mean that dry weather flows are not likely to transport significant loads of gross pollutants that could be removed by the CDS unit. A secondary pressure sensor was used to measure water levels at the face of the diversion weir. Both the Doppler flow measurements and water levels were measured at one-minute intervals and the averages recorded every five minutes. Water levels were then post-processed to calculate bypass flows using the weir equation for a 5.5 foot rectangular weir without end contractions.

During the 2006/2007 season, the configuration of the Treatment Train (Figure 45) was identical to the Phase I program. The initial MFS unit, later designated as MFS2, required a very advanced monitoring package to effectively measure flow and collect representative samples of the influent and effluent. CDS Technologies was instrumental in providing concepts for alternative approach and implementing the necessary site modifications. Four major modifications were necessary. These included:

- Developing an improved system to limit flow entering the MFS to the design capacity,

- Improving the accuracy of precision of measurements of total flow passing through the unit by installation of a V-notch weir,
- Enabling accurate measurement of water that bypasses the MFS unit over the internal weir by modifying the overflow with a rectangular sharp-crested weir, and
- Enabling access to a location within the MFS unit where only the treated water would be sampled.

The original design of constricting the MFS inlet to an 8-inch pipe turned out to be a problem. During storm events, hydraulic head would increase to levels that forced excessive quantities of water through the system. To correct this, CDS designed a riser with orifices that provided the necessary control to limit flows to the 1.75 cfs design capacity (Figure 46).

Improvements in the accuracy of total flow measurements was achieved by installation of a 60 degree V-notch weir in the junction box located immediately downstream of the MFS unit. Flow at this location was monitored with a pressure sensor encased in a stilling well.

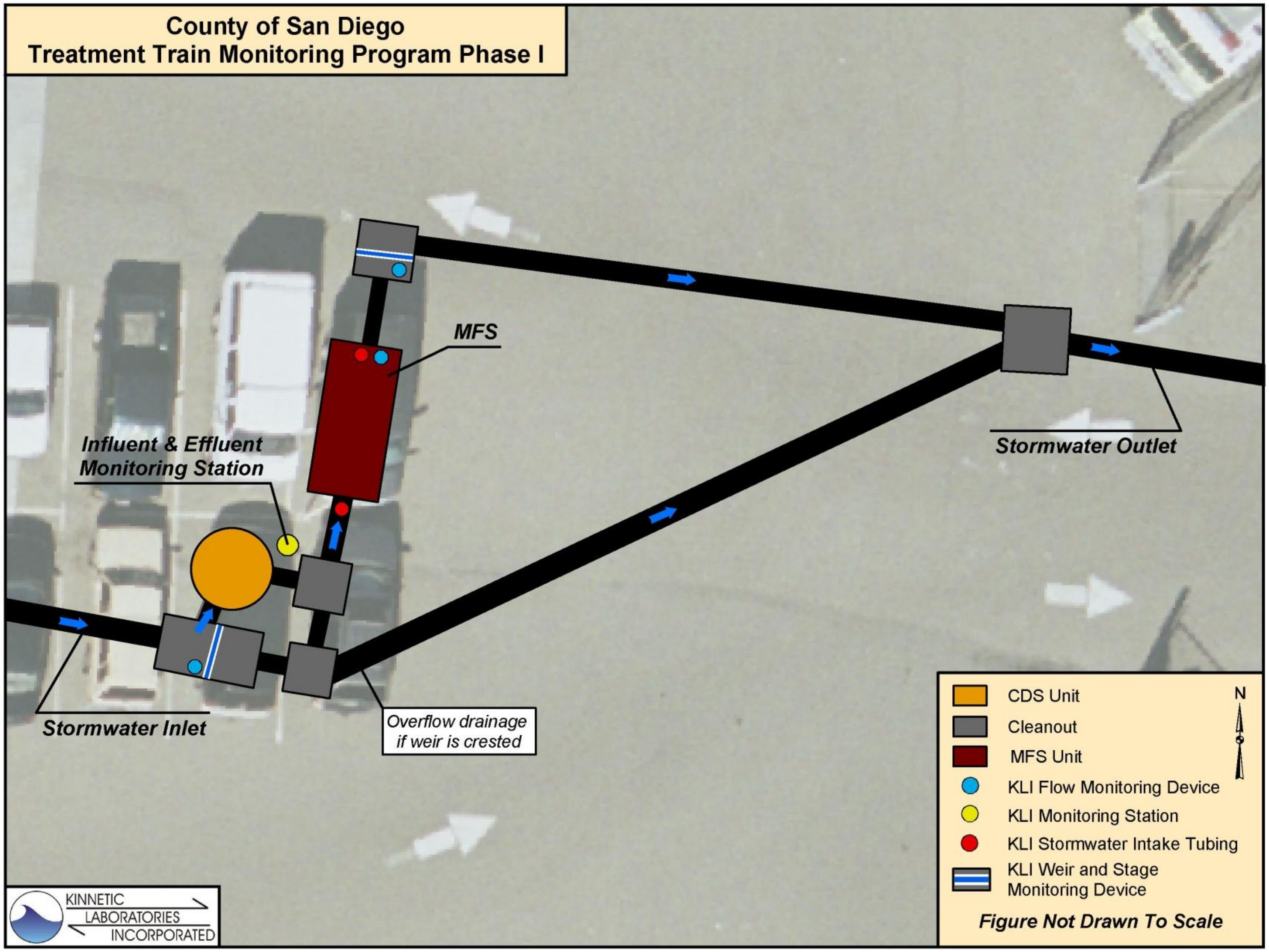


Figure 45. Generalized Plan View of Phase I CDS Treatment Train and Monitoring System.

Measurement of internal bypasses required modification of the bypass weir by installation of a 1-foot rectangular weir. A high precision pressure sensor was used to provide water level measurements necessary to calculate flow rates.

Figure 46. Flow Splitting Riser

The occurrence of bypasses in the system during high flow events resulted in a blend of treated and untreated stormwater exiting the MFS unit. Evaluation of the performance of the MFS unit required accessing a location in the MFS unit that contained only treated stormwater. CDS provided an additional sampling port just downstream of the filter cartridges before the water mixed with any untreated water that bypassed the system.

KLI's standard stormwater monitoring program was modified to enable the flow and sampling to be controlled through a single Campbell Scientific CR-10X. The V-notch weir was used to provide a real-time measure of flow into the MFS. The influent sampler was paced by this measurement. The flow of treated stormwater was calculated based upon the total flow minus flow going over the bypass weir. This flow was used to pace the sampler for the treated effluent. All flow and water sampling data was stored in the datalogger. The entire system was radio linked to the hard-wire telephone line used for the porous pavement monitoring. During storm events, data were downloaded at 15-minute intervals and posted to KLI's internal storm control computer where the information could be readily accessed to monitor progress and performance.

Monitoring Configuration – Phase II

Phase II of the treatment train was built-out during the summer and early fall of 2007 (Figure 47). An additional MFS unit, designated as MFS1, was added to the east of the existing unit. The existing MFS unit was then designated as MFS2. The other two filtration units, labeled SF1 and SF2, were both StormFilter units built by CONTECH. These had a larger footprint and used entirely different technology to control flows through the structure. The StormFilter units control flow at the individual cartridges while the MFS units control flow through all the cartridges by use of a float valve.

The filtration media/filter construction was unique in each of the four systems. MFS1 used ZPG (zeolite/perlite granules) media. MFS2 was refitted with perlite media as was used in the unit during the Phase I studies. The SF1 unit used the proprietary StormFilter cartridges also filled with perlite media. The fourth unit, SF2, used StormFilter cartridges containing CSF, a proprietary compost-based media designed to provide both physical filtration and treatment of dissolved metals. Each of the new StormFilter systems was designed to provide a maximum treatment capacity of 1.5 cfs. The two MFS unit were also designed to provide a maximum of 1.5 cfs to balance the system. This required a reduction of filters in the original MFS unit (MFS2) to change the design capacity from 1.75 to 1.5 cfs.

With the expanded filtration capacity none of the systems had internal bypasses. The weir preceding the CDS unit was designed to limit flows passing through the treatment train to 7.0 cfs to avoid exceeding the combined capacity of the four filtration units. Flows exceeding capacity were directed through the bypass.

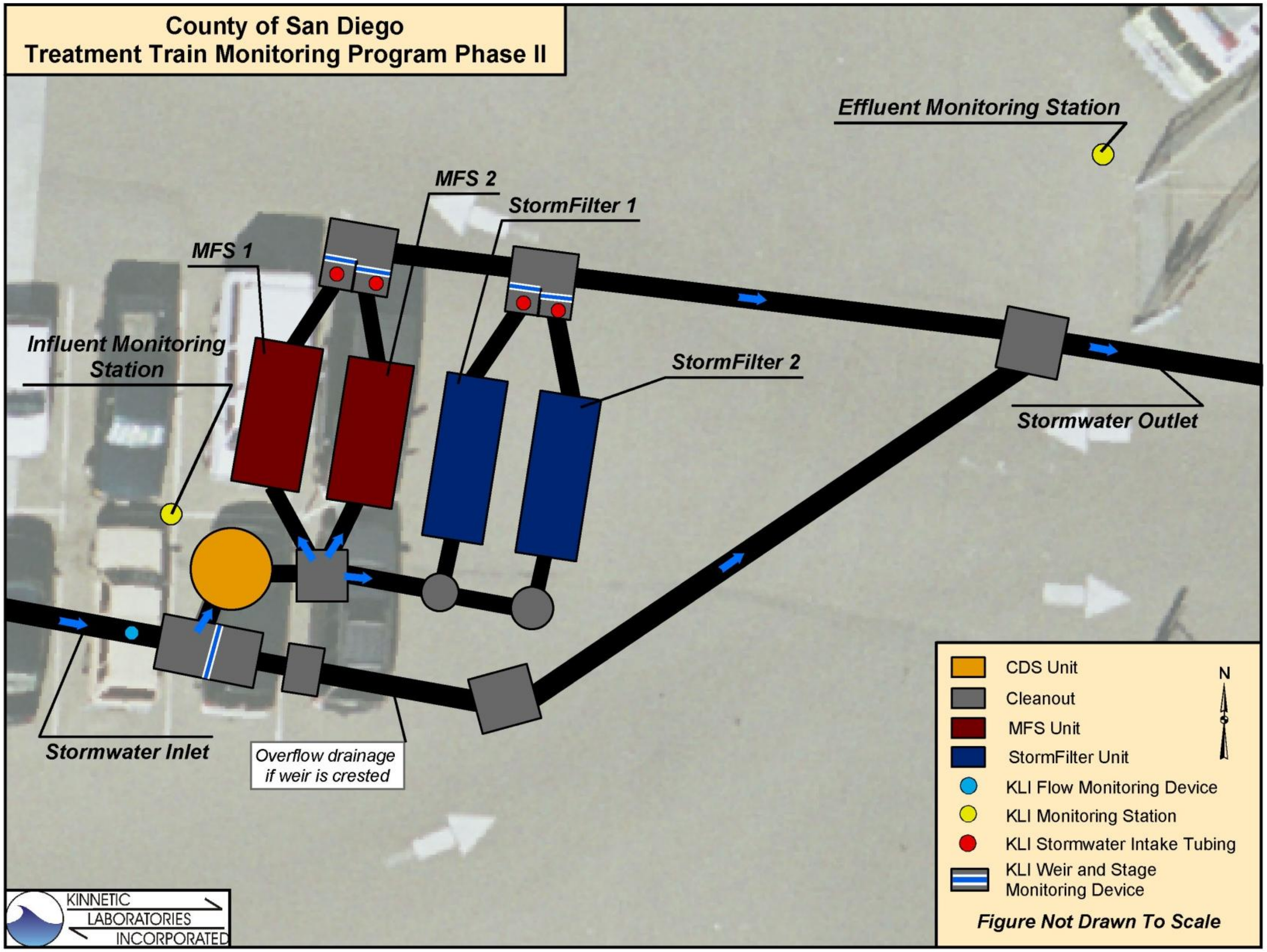


Figure 47. Treatment Train Configuration and Sampling Points for Phase II Monitoring, 2007/2008.

Sampling Frequency

Stormwater runoff at the treatment train was monitored continuously throughout the 2006-2008 wet seasons (October 1 through April 30). The water quality monitoring goal was to sample system performance during as many storms as possible during the 2006/2007 wet season with a target of at least three storm events total for full chemical characterization. Similarly, a total of three events were targeted for the 2007/2008 season. Criteria for storm monitoring were the same as used for the Porous Paving element. Storm events were considered viable for monitoring activities if they were predicted to achieve greater than 0.25 inches of rainfall.

Sample Collection and Handling

Sample collection and handing procedures were also consistent with the Porous Paving element of this program. Composite sample bottles were subsampled at KLI's Carlsbad facility. Prior to subsampling the composite bottles were placed on a magnetic stir-plate. A pre-cleaned Teflon stir bar was inserted into the bottle and the sample was stirred to ensure homogeneity. The subsample bottles were then delivered to the analytical laboratory for chemistry analyses under appropriate chain of custody procedures.

Flow-weighted composite samples were analyzed for the following constituents: hardness, suspended sediment concentration (SSC), total suspended solids (TSS), chemical oxygen demand (COD), dissolved organic carbon (DOC), total phosphorus, orthophosphate-P, ammonia-N, total Kjeldahl nitrogen (TKN), nitrate-N, and total and dissolved cadmium, copper, lead, and zinc. Analytical methods were identical to those used in the Porous Paving study (Table 3).

Hypothesis Testing

The primary data set for the treatment train involves paired influent and effluent samples at each of the filtration systems. Only one configuration, the Phase I MFS2 unit, had sufficient data to conduct hypothesis testing. A paired T-test was first used to test the null hypothesis that influent concentrations equaled effluent concentrations. Tests were considered to be significant at probabilities of ≤ 0.05.

The original objective was to then evaluate the data using the "effluent probability method" recommended by USEPA/ASCE (2002). This method provides a more robust measure of performance than just reporting efficiency as percent removal but requires a large sample size. Due to our more limited sample size, data were examined graphically by plotting effluent concentrations against influent concentrations. Over the range of concentrations encountered most parameters exhibited linear relationships and were typically distributed well across the range of values. Linear regression using the origin as the intercept was used to obtain an approximation of removal efficiencies. Due to the fact that removal efficiencies are not likely to remain linear with increasing loads, interpretation of removal efficiencies is limited to the range of concentrations encountered in this study.

Analysis of Phase II treatment train data was limited to graphical analysis since only three events were available for each filtration system.

RESULTS AND DISCUSSION

The following sections summarize the results of 1) monitoring rainfall, runoff and the representativeness of water quality samples, 2) flow measurements indicating the total volumes of stormwater treated by each component of the treatment train or that bypassed the system and 3) characterization of water quality associated with runoff.

Rainfall, Runoff and Percent of Stormwater Treated

Rainfall and runoff was measured continuously at all monitoring sites from January 2007 through April 2008. A total of eight storm events were monitored for rainfall and flow volumes during the 2006/2007 storm season while the treatment train was still in the Phase I configuration. An additional 16 events were characterized during the2007/2008 storm season after all Phase II modifications were completed (Figure 48 and Figure 49; Table 15 through Table 17). Hydrographs all treatment train rainfall events are included as Appendix B.

Stormwater discharges exceeding 7.0 cfs were intended to bypass the entire Treatment Train. Since the Phase I configuration of the treatment train only had a single MFS unit (MFS2) with a design capacity of 1.75 cfs, much of the stormwater treated by the initial CDS unit also had to be redirected around the MFS unit (Table 15). Between January and April 2007 the CDS treated 95.4% of the runoff from the COC. About a third of the runoff was directed into the MFS unit (Table 16) but only 68% of the water entering the MFS unit was fully treated. The remainder was discharged through the internal bypass. During individual storm events in early 2007, the percent of influent flow to the MFS that was effectively treated ranged from 45 to 95 percent of the water entering the unit. These percentages varied due to differences in duration and intensity of storm events.

With completion of the Phase II improvements all runoff passing through the CDS unit was subsequently passed through the four filtration units. During the 2007/2008 season 99.4 percent of the runoff from the COC passed through the treatment train (Table 15). This totaled 696,695 cubic feet of water. The total flow measured at all four filtration systems was 726,189 cubic feet (Table 17). This demonstrates outstanding correspondence between the two flow monitoring points. The difference between the two measurements is approximately 5%. The V-notch weirs installed in the filtration units are capable of measuring very low flows and likely provided the most accurate estimate of total flow through the systems.

Flows varied substantially through each of the four filtration systems with flow through the SF2 unit being less than half the flow through passing through the MFS2 unit (Table 17). A post season inspection by the vendor revealed that anti-floatation beams designed to hold the cartridges in place were apparently not bolted down when they were replaced by an independent maintenance contractor at the end of the 2006/2007 rainy season. Cartridges were found in a jumbled mess throughout the vault, some connecter hoses were ripped apart and some beams bent. As a result, this site provided no treatment other than additional settling in the filter chamber. The lack of flow resistance that would have been provided by the cartridges explained the greater flow through this unit.

This inspection also noted less severe issues associated with some of the other filtration systems. MFS1, which was fitted with cartridges containing ZPG media, was found to have a small amount of fugitive media in the vault that apparently escaped from one or more of the cartridges. SF1, a StormFilter unit with perlite, also had some fugitive media present. This was traced to a single cartridge that had broken loose. The vendor visually examined the cartridges at SF1 and noted that sediment had penetrated well into the media. SF2, a StormFilter unit with the CSF media, had evidence of a high water mark above that of the other units. The CSF media was noted to lack structure and appear degraded.

Hydrographs for the all monitored events are presented in Figure 50 through Figure 57. Hydrographs for the Phase I configuration of the MFS2 site include both total flow and treated flow in order to show internal bypasses. In this configuration, the system had a maximum treatment capacity of approximately 0.6 cfs. Any flows greater than this went through the internal bypass. The vendor later concluded that the float valve installed in the unit was likely undersized for the rated capacity of 1.70 cfs.

In the Phase II treatment train configuration (Figure 55 through Figure 57; Appendix B) all filtration units were rated at a maximum of 1.5 cfs per unit. During the more intense rain events, flows through the MFS1, MFS2 and SF1 units well exceeded the design capacity. Peak flows through MFS1 reached over 3 cfs during the final storm event. MFS2 flows also peaked over 3 cfs but this was not unexpected with disconnected cartridges. Flow through the SF1 unit reached a maximum of 2.0 cfs. The SF2 unit with CSF media was the only system that never exceeded the design capacity. This was reflected in the overall lower flows through this unit (Table 17).

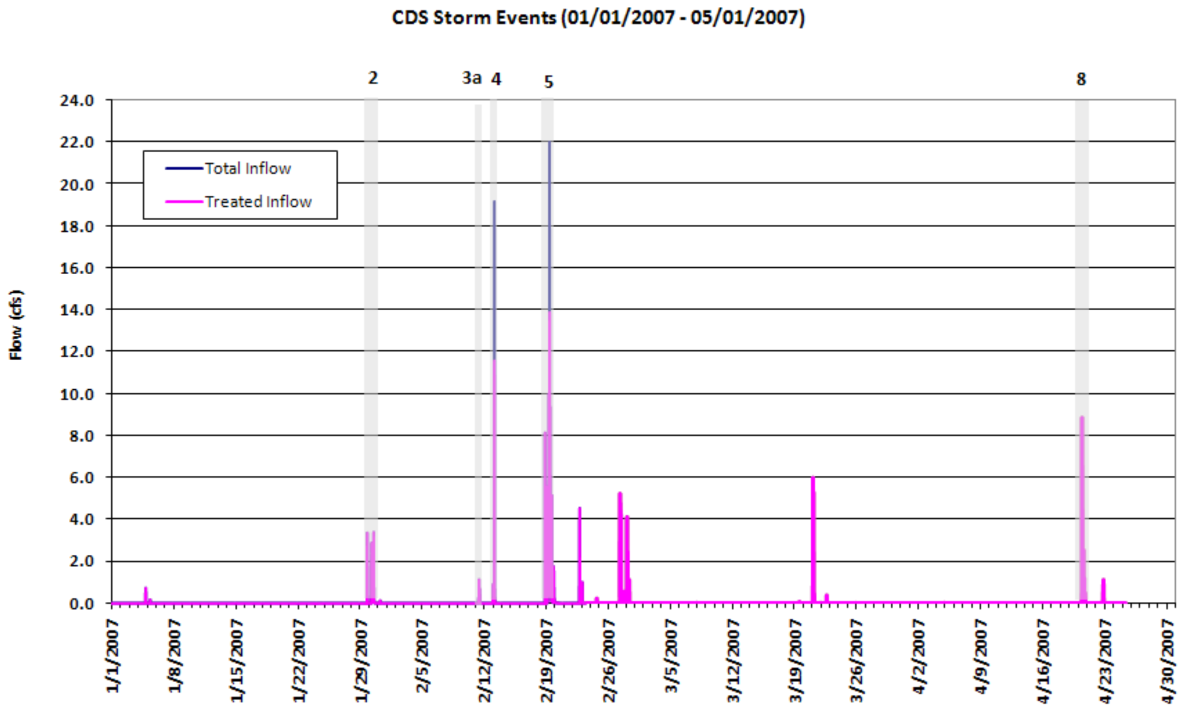
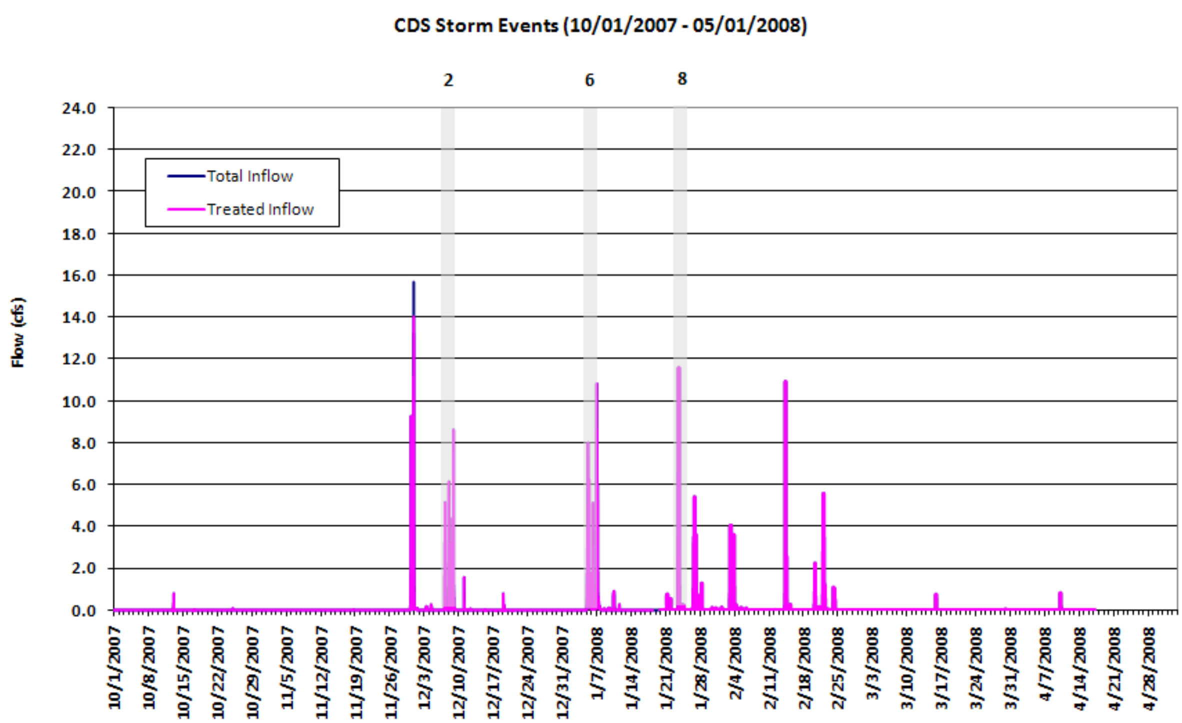


Figure 48. Total and Treated Flow through the CDS unit, January through May 2007.



Numbered gray areas indicate storm events monitored for water quality at MFS unit.

Figure 49. Total and Treated Flow through the CDS unit, October 2007 through May 2008.

Table 15. Summary of Rainfall and Treated/Untreated Runoff at the CDS Unit that Comprises the First Stage of the Treatment Train.

Event	Date	Rainfall (inches)	CDS		
			Total Runoff Volume (cf)	Treated Flow (cf)	% Treated
1	01/04/2007	0.04	2,547[2]	2,547	100
2	01/29-02/01/2007	0.50	44,530	44,530	100
3	02/11-14/2007	0.29	22,544	17,980	80
3a[4]	02/11/2007	(0.10)	(5,975)	(5,975)	(100)
4	02/18-20/2007	1.31	152,801	142,539	93
5	02/22-24/2007	0.16	14,487	14,487	100
6	02/27-02/28/2007	0.40	34,000	34,000	100
7	03/20-23/2007	0.28	21,388	21,388	100
8	4/20/2007	0.44	33,153	33,153	100
	2006/2007 TOTALS	**3.42**	**325,450**	**310,624**	**95.4**
1	11/30-12/01/2007	1.67	143,709	140,406	98
2	12/07/2007	0.36	33,654	33,654	100
3	12/8-9/2007	0.67	56,666	56,666	100
4	12/11/2007	0.04	2,368	2,368	100
5	12/19-20/2007	0.20	19,218[3]	19,218[3]	100[3]
6	1/4-7/2008	1.90	217,906	217,906	100
7	1/21-22/2008	0.12	3,354	3,354	100
8	1/23-24/2008	0.56	41,756	41,756	100
9	1/26-28/2008	0.63	54,608	54,608	100
10	2/3-4/2008	0.61	49,156	49,156	100
11	2/14-15/2008	0.34	19,625	19,401	99
12	2/20/2008	0.11	7,204	7,204	100
13	2/22/2008	0.45	40,515	40,515	100
14	2/24/2008	0.16	9,383	9,383	100
15	3/16/2008	0.06	1,036	1,036	100
16	3/30/2008	0.03	64	64	100
	2007/2008 TOTALS	**7.82**	**700,222**	**696,695**	**99.5**

Shaded events indicate those monitored for water quality.

1. Flows through the CDS are measured with a sensor that uses an area-velocity meter. Records indicate that the velocity sensor failed prior to this event.
2. Flows through the CDS are measured with a sensor that uses an area-velocity meter. These sensors are not accurate at very low flows. In contrast, flow through the MFS unit is measured by a V-notch weir that is capable of very accurate flow measurement at lower flows. The fact that the total flow measured entering the CDS unit is lower than the total flow passing through the MFS unit can be attributed to these differences. Total rainfall during the "event" was only 0.04 inches.
3. Velocity sensor failed during the 12/19-20/2007 event. Sensor was erratic and showing negative velocities. Flow was estimated from linear regression model of all 2007/2008 data. (Flow in cf= 96091 * Rainfall in inches; r^2=0.95). Based on the low rainfall volume, 100% treatment was assumed.
4. Event 3a is a subset of Event 3. This minor event was the first wave of a small, extended event. This first wave of rain ended on 2/11/07 at 14:00. A second wave of light showers came 1.5 days later and yielded another 0.19 inches of rain.

Table 16. Summary of Rainfall, Inflow and Treated Flow at the MFS2 Unit during the 2006/2007 Season.

Event	Date	Rainfall (inches)	MFS2[2] Inflow (cf)	MFS2[2] Treated Flow (cf)	MFS2[2] % Treated
1	01/04/07	0.04	3,304[1]	3,110	94
2	01/29-02/01/07	0.50	18,037	9,927	55
3	02/11-14/07	0.29	9,405	7,080	75
3a[4]	02/11/2007	(0.10)	(4,396)	(4,396)	(100)
4	02/18-20/07	1.31	37,710	18,028	48
5	02/22-24/07	0.16	7,023	6,679	95
6	02/27-02/28/07	0.40	14,809	12,764	86
7	03/20-23/07	0.28	8,218	7,344	89
8	4/20/07	0.44	13,636	11,221	82
TOTAL		**3.42**	**112,142**	**76,153**	**68**

Shaded events indicate events monitored for water quality

1. Flows through the CDS are measured with a sensor that uses an area-velocity meter. These sensors are not accurate at very low flows. In contrast, flow through the MFS unit is measured by a V-notch weir that is capable of very accurate flow measurement at lower flows. The fact that the total flow measured entering the CDS unit is lower than the total flow passing through the MFS unit can be attributed to these differences. Total rainfall during the "event" was only 0.04 inches.
2. The MFS2 unit was still in the Phase I configuration during the 2006/2007 monitoring period. This configuration included an internal bypass.

Table 17. Summary of Rainfall and Flow through each Media Filtration System and StormFilter Unit during the 2007/2008 Season.

Event	Date	Rainfall (inches)	MFS1 Total Runoff Volume (cf)	MFS2 Total Runoff Volume (cf)	SF1 Total Runoff Volume (cf)	SF2 Total Runoff Volume (cf)
1	11/30-12/01/2007	1.67	33,815	44,244	43,916	27,853
2	12/07/2007	0.44	7,498	9,593	8,218-	8,611
3	12/8-9/2007	0.74	14,116	21,207	10,947-	5,572
4	12/11/2007	0.04	756	1,890	218	464
5	12/19/2007	0.16	1,448	4,439	1,364	992
6	12/20/2007	0.04	76	587	75	1
7	1/4-1/7/2008	1.90	50,783	65,641	54,797	33,614
8	1/21-1/22/2008	0.12	1,692	2,794	853	216
9	1/23-1/24/2008	0.56	13,238	13,355	12,590	8,219
10	1/26-1/28/2008	0.63	21,888	22,183	16,744	8,586
11	2/3-2/4/2008	0.61	17,608	21,380	19,951	6,361
12	2/14/-2/152008	0.34	9,241	9,886	6,023	2,434
13	2/20/2008	0.11	3,571	4,277	1,735	1,955
14	2/22/2008	0.45	16,535	13,288	12,524	5,728
15	2/24/2008	0.16	5,713	5,944	2,138	1,714
16	3/16/2008	0.06	1,047	781	363	464
17	3/30/2008	0.03	309	644	11	0
TOTAL		**8.06**	**199,334**	**242,133**	**171,938**	**112,784**

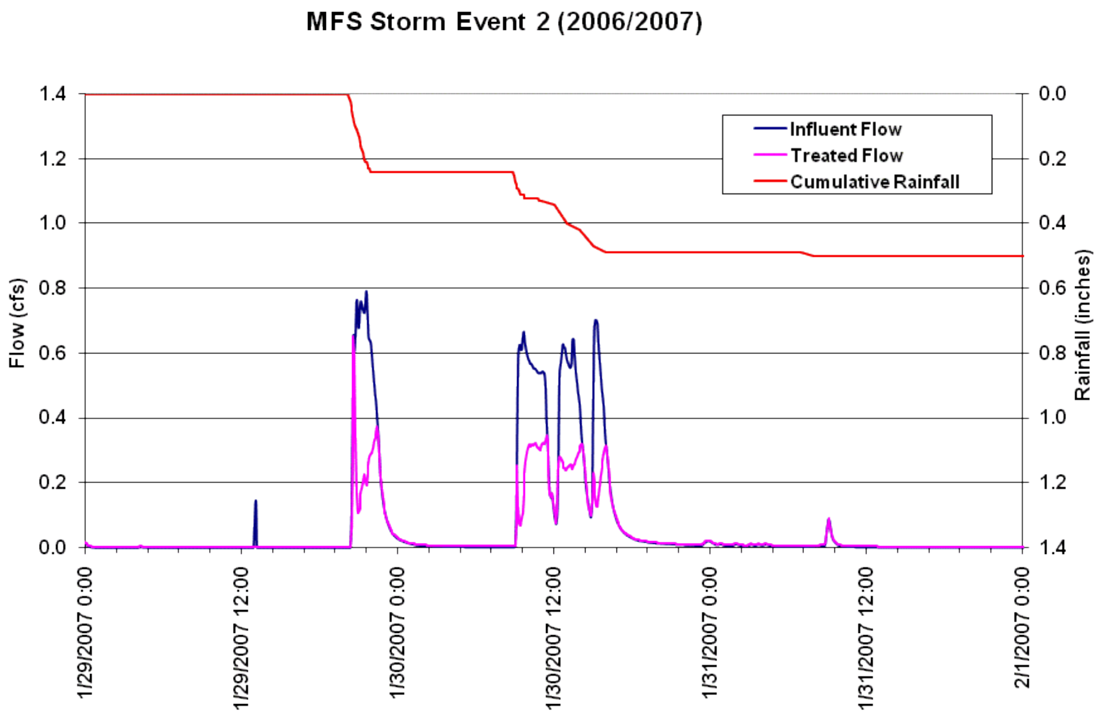


Figure 50. Cumulative Rainfall and Flow Response at Phase I MFS2 Unit during the 1/29-30/07 Storm Event.

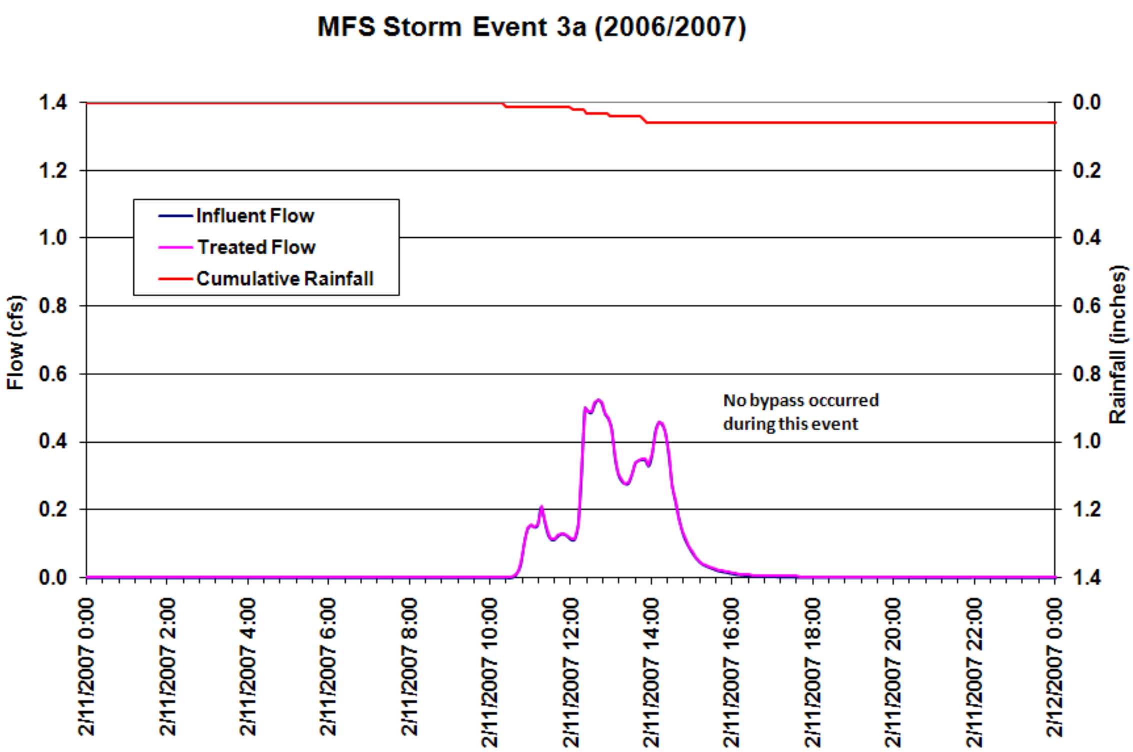


Figure 51. Cumulative Rainfall and Flow Response at Phase I MFS2 Unit during the 2/11/07 Storm Event.

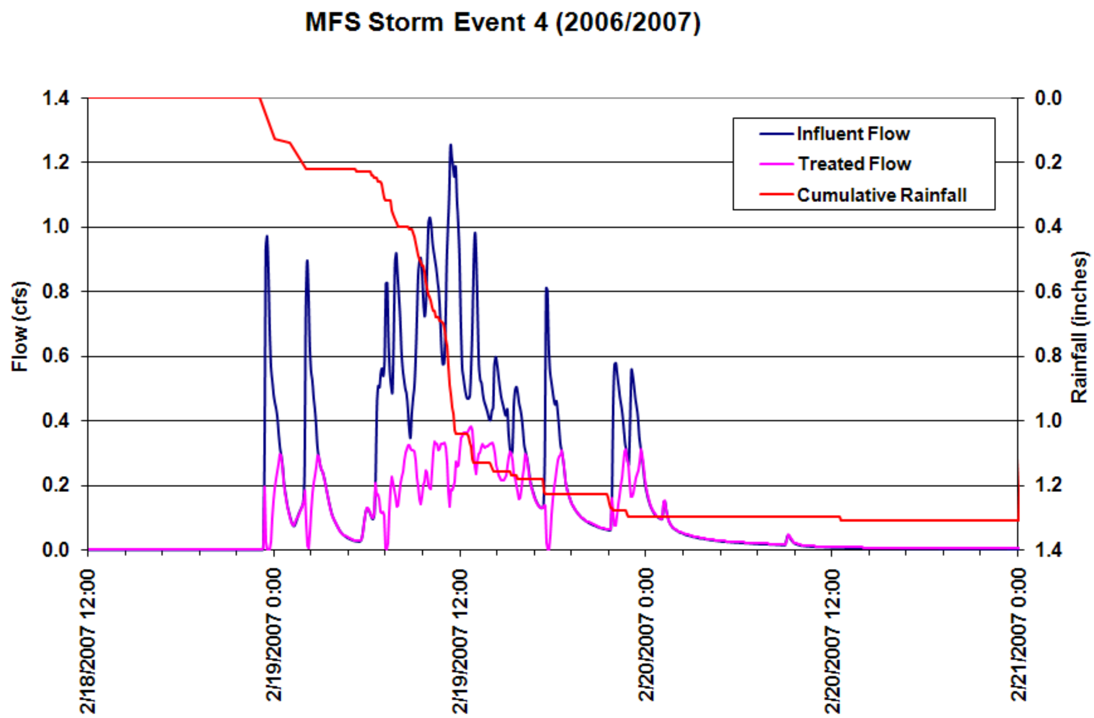


Figure 52. Cumulative Rainfall and Flow Response at Phase I MFS2 Unit during the 2/19-20/07 Storm Event.

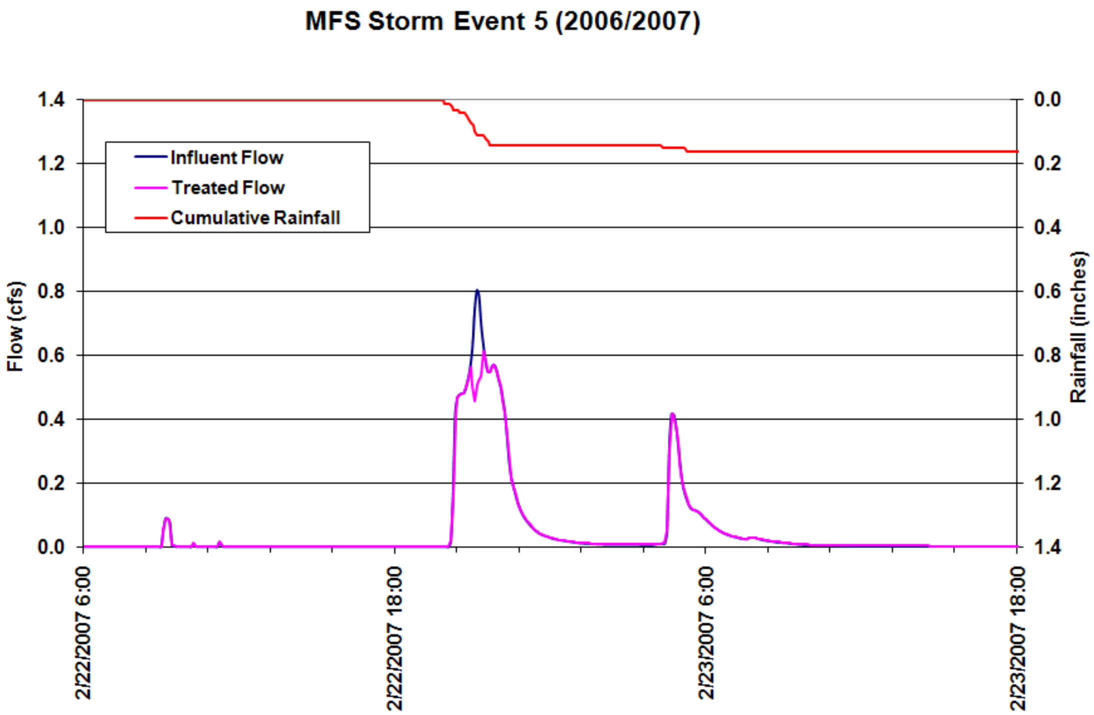


Figure 53. Cumulative Rainfall and Flow Response at Phase I MFS2 Unit during the 2/22-23/07 Storm Event.

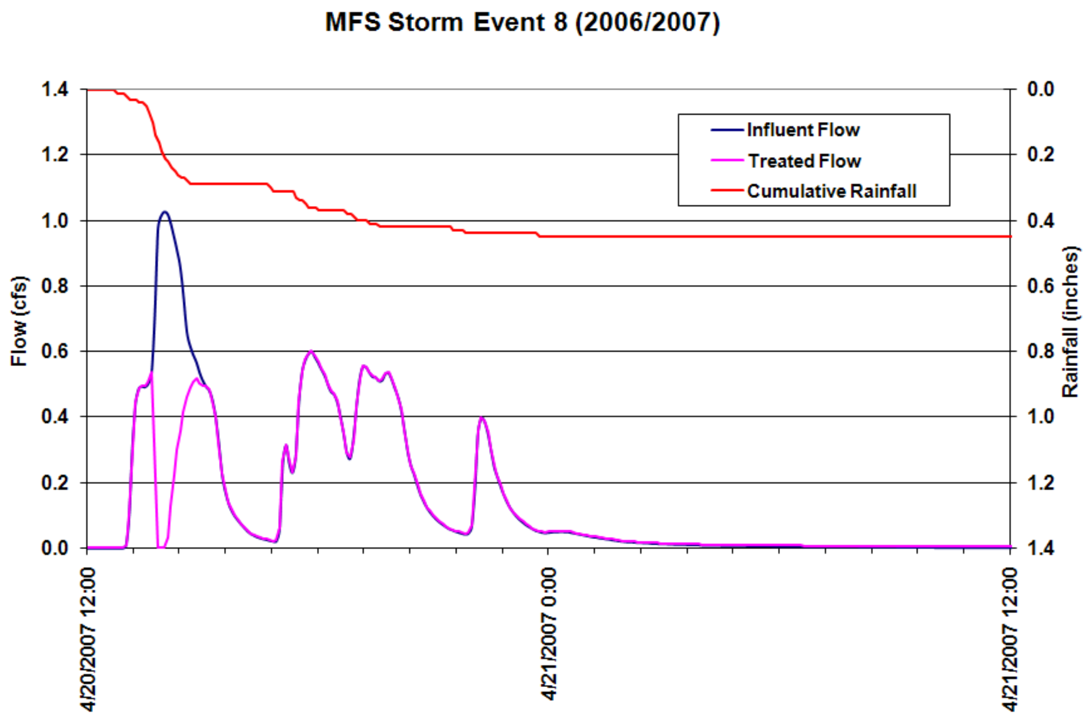


Figure 54. Cumulative Rainfall and Flow Response at Phase I MFS2 Unit during the 4/21/07 Storm Event.

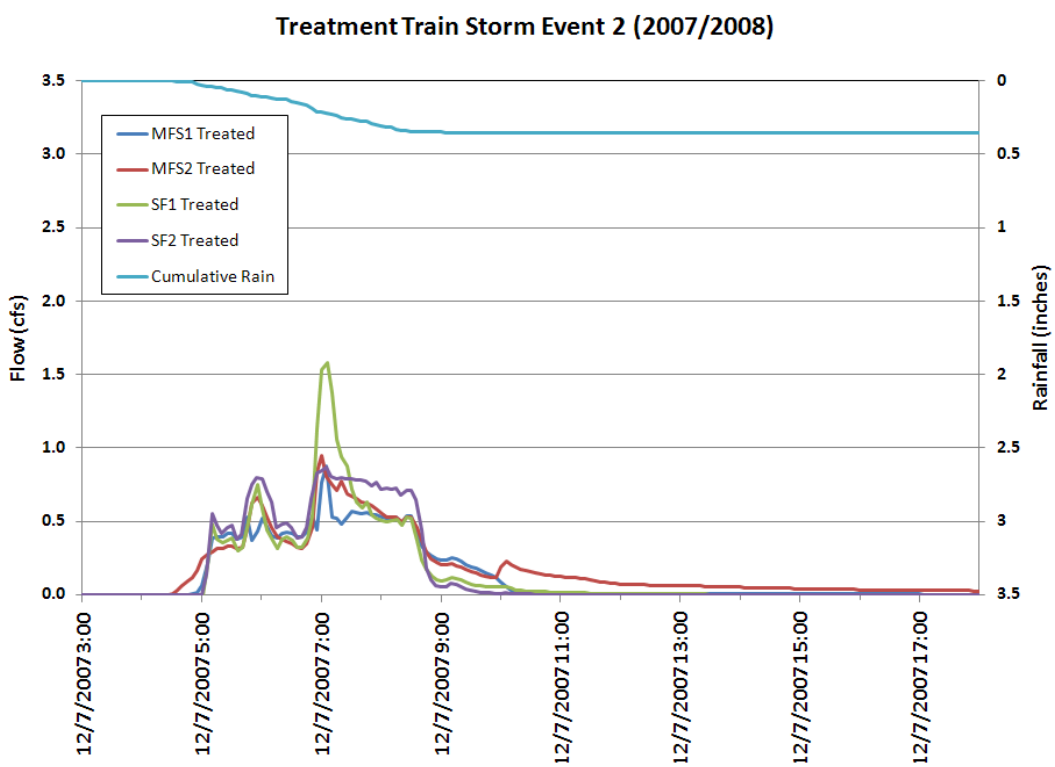


Figure 55. Cumulative Rainfall and Flow Response through the Four Filtration Systems during the 12/7/2007 Storm Event.

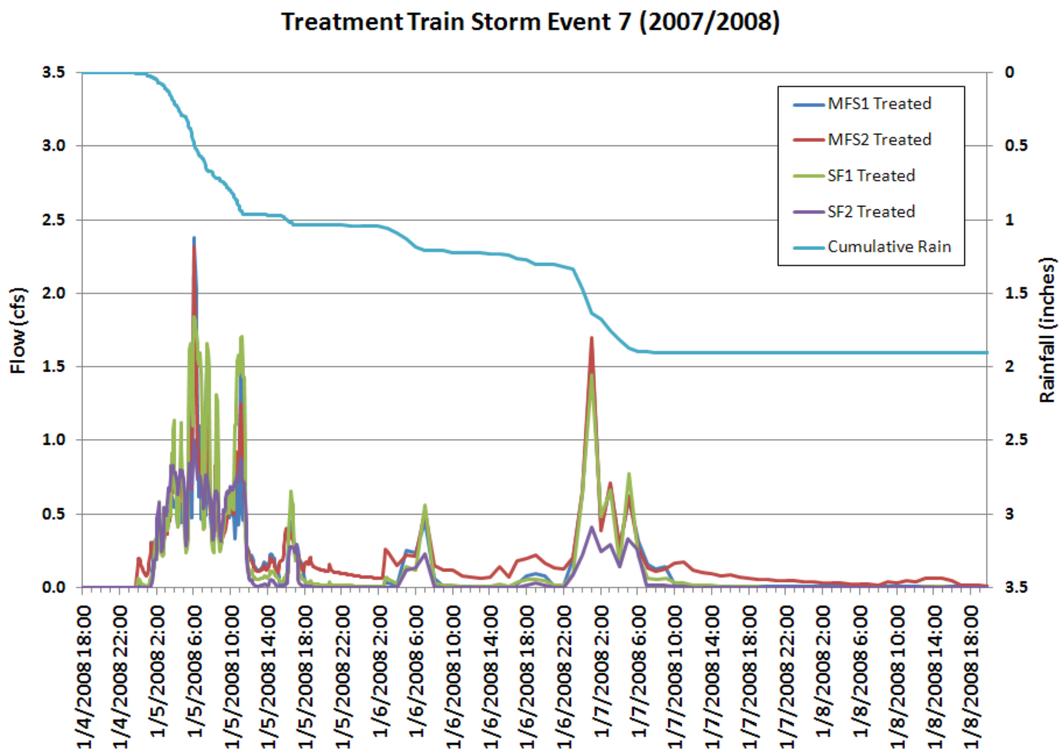


Figure 56. Cumulative Rainfall and Flow Response through the Four Filtration Systems during the 1/4-7/2007 Storm Event.

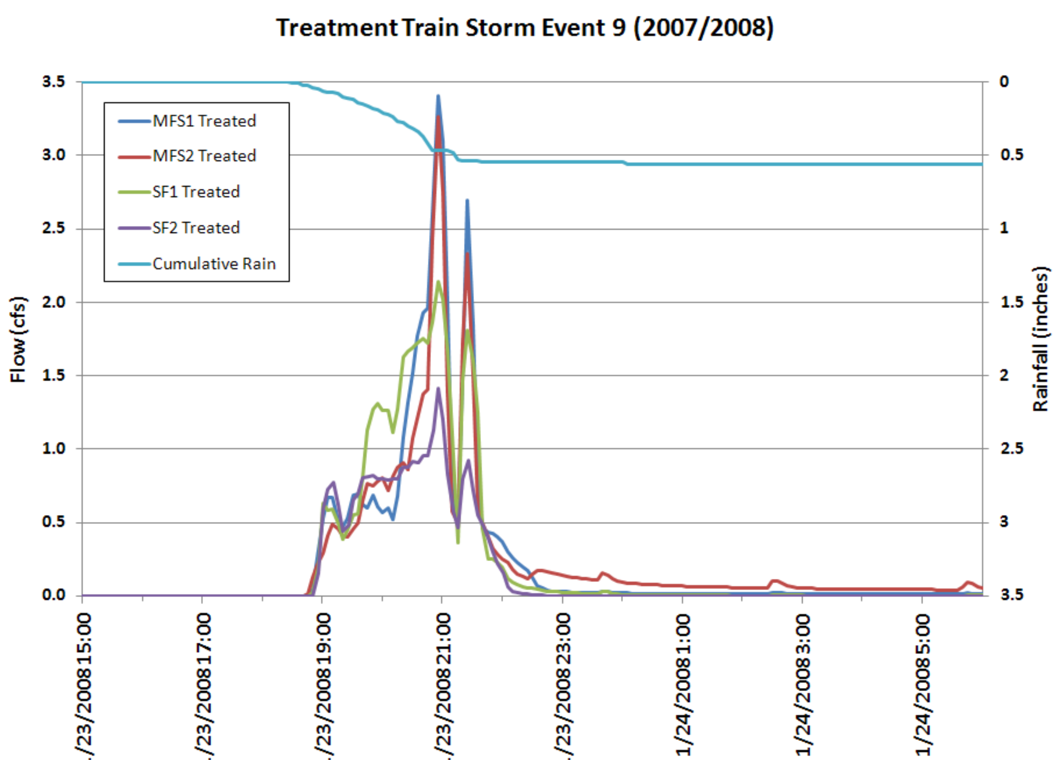


Figure 57. Cumulative Rainfall and Flow Response through the Four Filtration Systems during the 1/23-24/2008 Storm Event.

Stormwater Quality and Filtration System Treatment Efficiency

The Phase 1 Media Filter System (MFS2) was monitored for three events during the Phase I program and five events in early 2007. As such, this configuration provided the largest body of data for evaluating performance. The results of water quality monitoring during the 2006/2007 season are summarized in Table 18. These data were grouped with data from the Phase 1 program to provide eight storm events of paired influent and effluent samples.

Table 18. Summary of Results of Chemical Analysis of CDS-treated Stormwater Runoff entering the Phase I Media Filter System (MFS2) portion of the Treatment Train and Treated Effluent from the MFS2 Unit during Events 2, 3a, 4, 5 and 8 of the 2006/2007 Wet Season.

	Event 2		Event 3a[2]		Event 4		Event 5		Event 8	
CONSTITUENT	Influent 1/30/07	Treated Effluent 1/30/07	Influent 2/11/07	Treated Effluent 2/11/07	Influent 2/19/07	Treated Effluent 2/19/07	Influent 2/23/07	Treated Effluent 2/23/07	Influent 4/21/07	Treated Effluent 4/21/07
Hardness (mg/L)	37	38	35	38	12	13	13	15	20	25
SSC (mg/L)	93.9	28	33.7	15.7	24.7	5.58	18.7	10.7	46.6	16.1
>63 microns	19.1	1.4	9.64	2.45	11.1	0.5U	4.84	0.5U	14.4	1.5
<63 microns	74.8	26.6	24.0	13.2	13.7	5.58	13.9	10.7	32.2	14.6
TSS (mg/L)	75	29	35	14	17	6.0	18	10	46	18
COD (mg/L)	92	76	120	110	25	21	36	33	89	83
DOC (mg/L)	24	25	33	33	5.7	5.6	8.7	9.5	19	22
Total P	0.26	0.23	0.34	0.32	0.14	0.14	0.13	0.14	0.27	0.24
Ortho-P (mg/L)	0.13	0.14	0.10	0.12	0.084	0.098	0.086	0.094	0.14	0.15
Ammonia-N (mg/L)	0.65	0.75	0.92	0.87	0.26	0.26	0.31	0.25	0.55	0.62
TKN (mg/L)	1.9	2.0	2.7	2.7	0.74J+	0.74J+	0.78	0.79	1.6	1.5
Nitrate-N (mg/L)	0.77	1.2	1.9	2.2	0.52	0.68	0.39	0.48	0.75	1.1
Total Cadmium (ug/L)	0.52	0.44	0.42	0.34	0.22	0.16	0.28	0.68	0.70	0.48
Diss. Cadmium (ug/L)	0.25	0.29	0.30	0.29	0.12J	0.11J	0.14	0.17	0.36	0.35
Total Copper (ug/L)	46	35	55	48	16	13	24	16	47	45
Diss. Copper (ug/L)	22	24	41	39	8.7	9.1	16	12	30	34
Total Lead (ug/L)	54	36	47	26	14	7.2	17	15	55	30
Diss. Lead (ug/L)	8.9	9.9	13	11	1.9	2.1	2.8	3.0	11	11
Total Zinc (ug/L)	320	300	330	270	130	86	150	130	370	340
Diss. Zinc (ug/L)	190	230	250	220	74	63	99	89	250	270
Calculated Values[1]										
$Oil\&Grease_{(COD)}$ (mg/L)	7.1	6.5	8.1	7.8	4.6	4.5	5.0	4.9	7.0	6.8
$Oil\&Grease_{(DOC)}$ (mg/L)	6.9	7.2	9.4	94	1.7	1.7	2.6	2.8	5.5	6.3

1. Kayhanian, M, S. Khan, and M.K. Stenstrom. 2004. A new method to estimate oil and grease event mean concentration in highway runoff. StormCon 2004.
2. This event was the first of two widely spaced showers. The first pulse yielded only 0.1 inches of rain which was well below the forecast. Only water collected at the MFS unit was adequate for testing. Holding times prevented waiting for the second pulse of rain.

U indicates the constituent is a not detected - the value is the reporting limit

J indicates the value is an estimate

A paired T-test was first used to determine if significant differences existed between the influent and effluent samples (Table 19). This test indicated that concentrations of total SSC, both fractions of SSC, TSS and COD were all significantly ($p \leq 0.05$) reduced in the MFS unit. Correspondingly, total copper, lead and zinc were also significantly reduced by the filtration system. Three soluble nutrients (orthophosphate-P, ammonia-N, and nitrate-N) showed significant increase in concentration. Increases in concentrations of these nutrients are suspected to be due to degradation of organic material trapped in the vault and filters that get flushed out with storm events.

The efficiency of removal of selected constituents was examined by plotting effluent concentrations against the influent concentrations for each event (Figure 58 through Figure 64). Values located on the green equivalency line indicate no change in concentration between influent and effluent concentrations. Values over the line show an increase in concentration while those below the line indicate a decrease. Over the range of concentrations measured in COC stormwater, most parameters exhibited a linear response and data were adequately distributed over the range to develop performance estimates based upon regression on concentrations. The slope of the regression provides a rough estimate of percent reduction when the slope is less than one. Although several of the parameters appear to be effectively treated by the MFS unit, it is important to note that these analyses do not represent efficiency of the entire BMP due to the bypasses. They simply illustrate the differences between the quality of water as it enters the BMP and the portion of the water that actually passed through the filters. Furthermore, they should only be considered as estimates over the range of concentrations reported in these studies. It is unlikely that these relationships would remain linear at higher influent concentrations.

The Phase I MFS2 unit efficiently removed of total SSC, fine SSC, coarse SSC and TSS over the ranges encountered at the treatment train. Although removal of total copper, lead and zinc was statistically significant, only lead showed evidence of substantial improvements in the final effluent. The regression suggested that effluent concentrations were roughly 55% of influent concentrations. Given the strong tendency for lead to associate with fine particulates, it was not surprising to see effective treatment by a filtration BMP.

As with the low but statistically significant removal of total copper and zinc, the increases in soluble nutrients were minor (10-20 percent) and occurred at low concentrations. Neither the small increases in dissolved nutrients nor the small decreases in total metals should be considered characteristic of this BMP at higher loading rates.

Table 19. Results of Paired T-Tests comparing EMCs for Key Constituents measured in the Phase I MFS2 Influent and Effluent Samples.

CONSTITUENT	Paired T-Test Probability	Difference
SSC (mg/L)	**0.007**	**In>Out**
>63 microns	**0.001**	**In>Out**
<63 microns	**0.016**	**In>Out**
TSS (mg/L)	**0.002**	**In>Out**
COD (mg/L)	**0.040**	**In>Out**
DOC (mg/L)	0.142	
Total P	0.160	
Ortho-P (mg/L)	**0.016**	**Out>In**
Ammonia-N (mg/L)	**0.011**	**Out>In**
TKN (mg/L)	0.239	
Nitrate-N (mg/L)	**0.005**	**Out>In**
Total Cadmium (ug/L)	0.646	
Diss. Cadmium (ug/L)	0.365	
Total Copper (ug/L)	0.001	**In>Out**
Diss. Copper (ug/L)	0.645	
Total Lead (ug/L)	0.002	**In>Out**
Diss. Lead (ug/L)	0.532	
Total Zinc (ug/L)	0.000	**In>Out**
Diss. Zinc (ug/L)	0.888	

Significant Difference ($p \leq 0.05$) and Influent is greater than the effluent (green)
Significant Difference ($p \leq 0.05$) and effluent is greater than the influent (red)

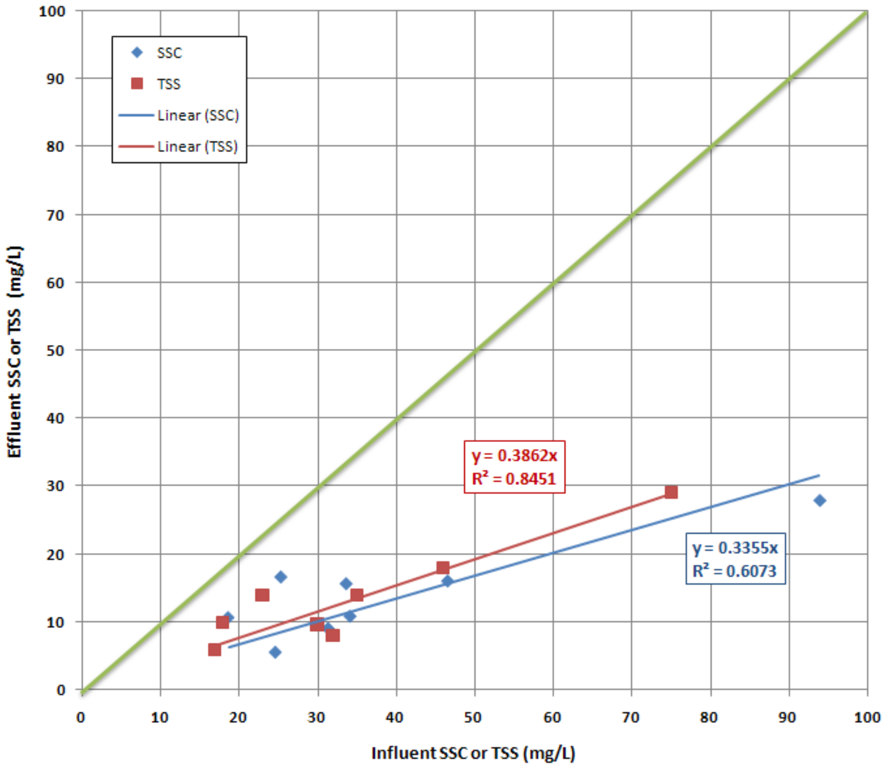


Figure 58. Efficiency of Phase I MFS Configuration in Treatment of Suspended Sediment.

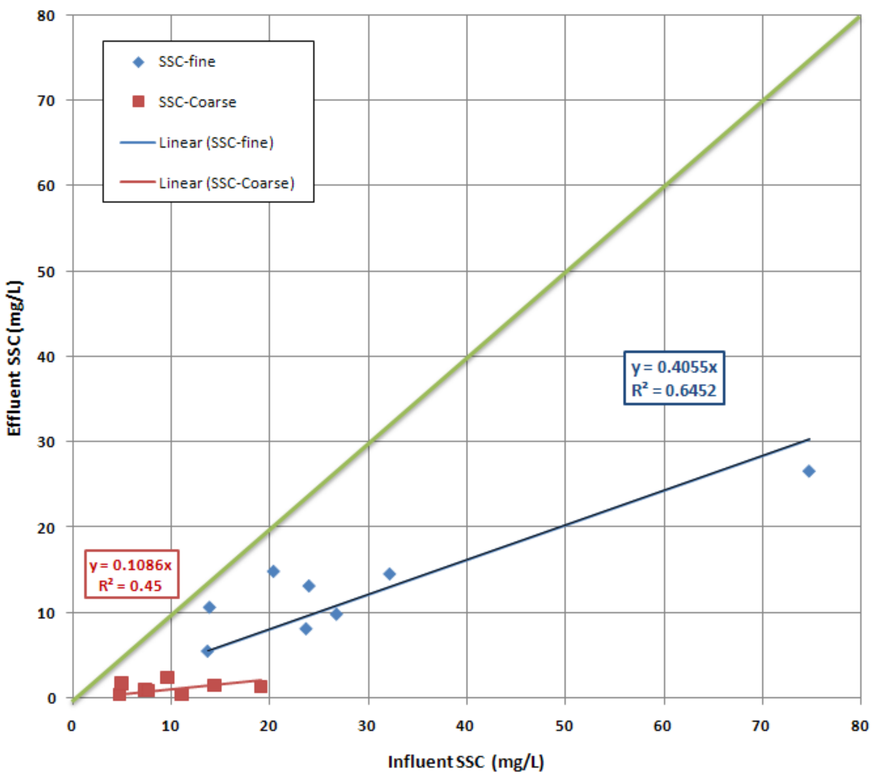


Figure 59. Efficiency of Phase I MFS Configuration in Treatment of Fine and Coarse Suspended Sediment Concentrations (SSC).

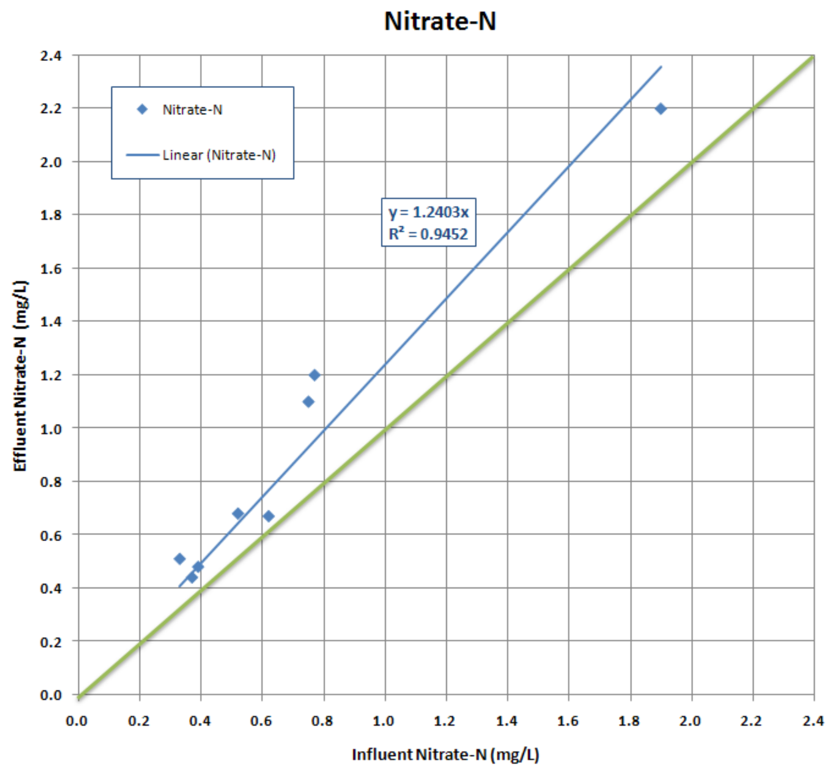


Figure 60. Efficiency of Phase I MFS Configuration in Treatment of Nitrate-N.

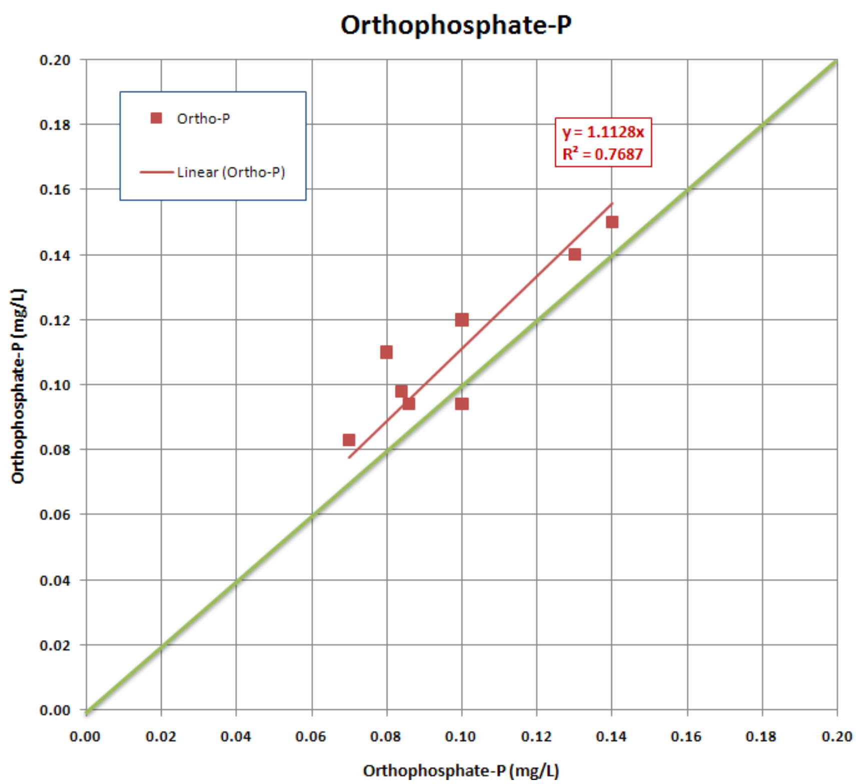


Figure 61. Efficiency of Phase I MFS Configuration in Treatment of Orthophosphate-P.

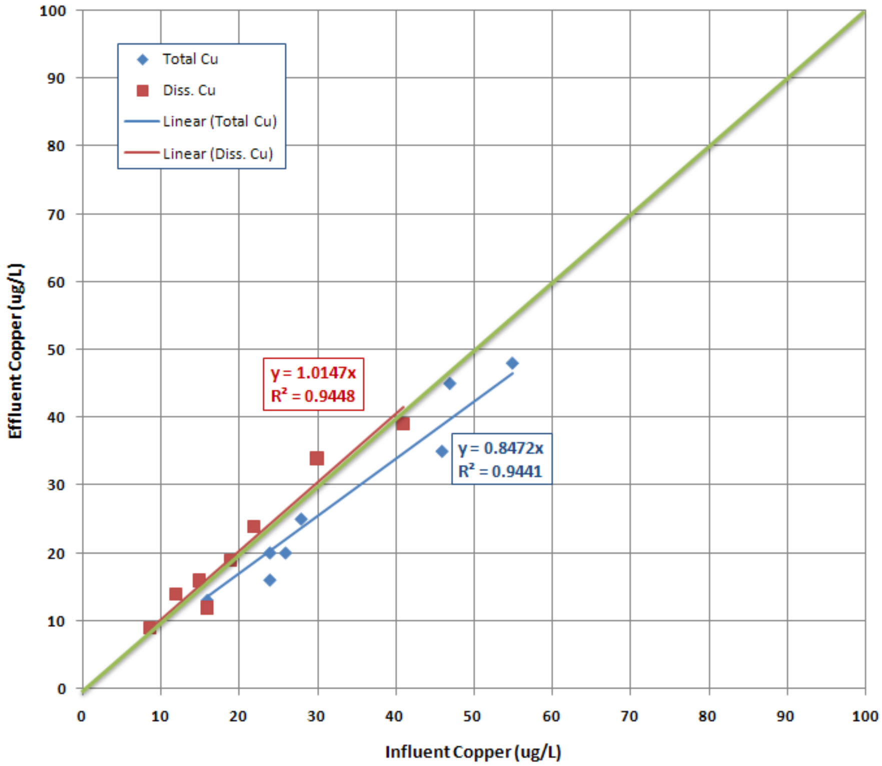


Figure 62. Efficiency of Phase I MFS Configuration in Treatment of Total and Dissolved Copper.

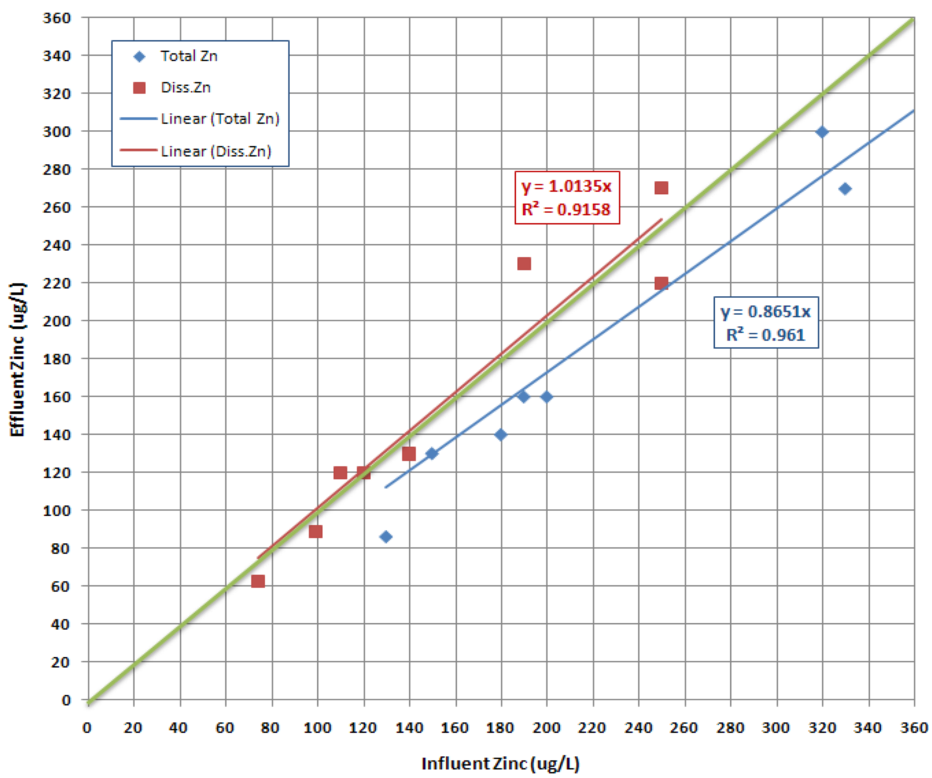


Figure 63. Efficiency of Phase I MFS2 Configuration in Treatment of Total and Dissolved Zinc.

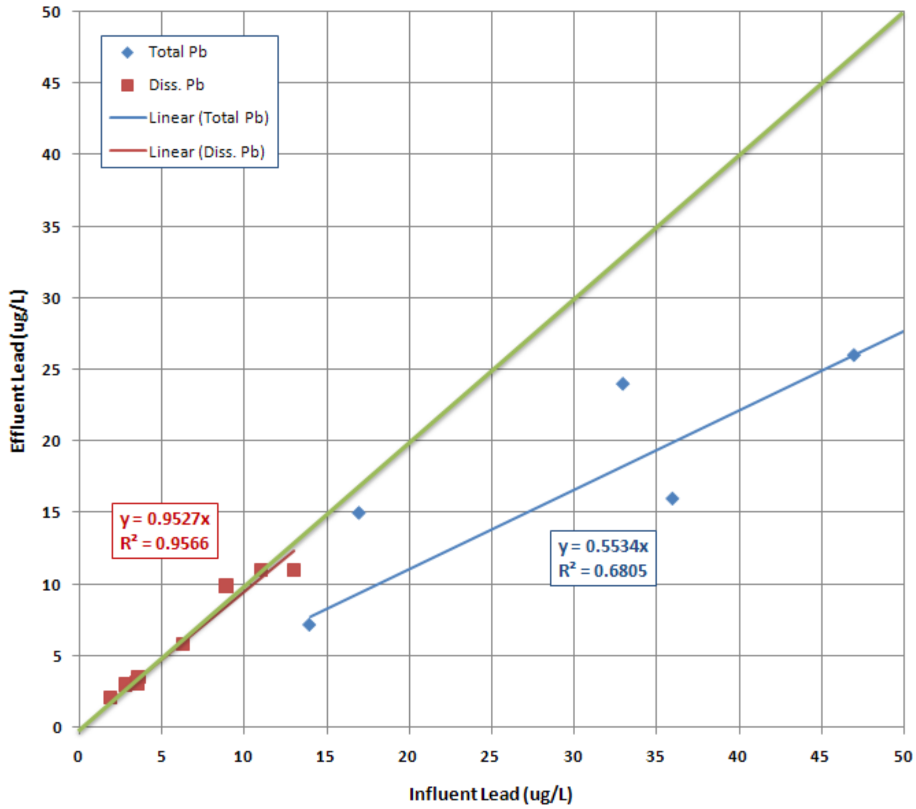


Figure 64. Efficiency of Phase I MFS2 Configuration in Treatment of Total and Dissolved Lead.

Results of monitoring conducted at each of the Phase II filtration systems are summarized in Table 20 through Table 23. They are also graphically presented in Figure 58 through Figure 81. Due to the limited number of replicates, performance can only be qualitatively examined. The effluent/influent plots show all four filtration systems including the MFS2 unit where the filter cartridges were nonfunctional.

The monitoring data show some degree of removal of solids by all filtration units including MFS2 (Figure 65 through Figure 68) where water was not being filtered. Some degree of treatment was apparently provided by settling within the vault. The post season inspection by the vendor indicated that sediment was present in the vault. The coarse fraction of SSC which consists of particles greater than 63 micron was most effectively removed. Most of this fraction would be expected to have been removed by the CDS unit which provided pretreatment.

This initial data set does suggest the CSF media in SF2 was a source of very small concentrations of both total phosphate-P (Figure 69) and orthophosphate-P (Figure 70). Evidence of export was strongest for orthophosphate since the other three media filters all had effluent concentrations essentially equal to the influent concentrations. Dissolved organic carbon (DOC) also appeared higher in effluent from the CSF media but additional data would be necessary to verify this. An increase in DOC would be consistent with observed increases in phosphorous. The source of phosphorous and possibly DOC is likely due to some breakdown of the CSF media.

Data also suggest some removal of total metals at higher concentrations at all monitoring sites. Lower concentrations of total metals were consistent with observed decreases of solids.

Table 20. Summary of Results of Chemical Analysis of Stormwater Runoff from the Media Filter System (Unit 1) of the Treatment Train.

CONSTITUENT	Media Filter 1					
	7-Dec-07		5-Jan-08		23-Jan-08	
	MFS 1 In	MFS 1 Out	MFS 1 In	MFS 1 Out	MFS 1 In	MFS 1 Out
Hardness (mg/L)	19	22	14	13	6.9	10
SSC (mg/L)	74.5	76.8	73.5	65.3	122	94.3
>63 microns	6.04	1.04	6.52	2.71	21.3	6.77
<63 microns	68.4	75.7	67	62.6	101	87.5
TSS (mg/L)	84	85	72	58	120	93
COD (mg/L)	33	26	37	32	55	38
DOC (mg/L)	5.4	6	4.9	4.6	2.4	2.9
Total P	0.14	0.14	0.16	0.16	0.096	0.097
Ortho-P (mg/L)	0.086	0.085	0.064	0.061	0.045J	0.054J
Ammonia-N (mg/L)	0.32	0.25	0.13	0.1	0.22	0.17
TKN (mg/L)	0.89	1	0.65	0.55	0.73	0.57
Nitrate-N (mg/L)	0.56	0.61	0.24	0.25	0.18J	0.25J
Total Cadmium (ug/L)	0.16J	0.16J	0.099J	0.084J	0.28	0.21
Diss. Cadmium (ug/L)	0.063J	0.073J	0.032J	0.042J	0.041J	0.024J
Total Copper (ug/L)	21	22	10	12	31	24
Diss. Copper (ug/L)	10	11	5.4	6.4	5	5.3
Total Lead (ug/L)	13	12	5.2	6.1	44	31
Diss. Lead (ug/L)	1.9	2	0.95	1.1	1.4	1.1
Total Zinc (ug/L)	160	140	68	74	200	150
Diss. Zinc (ug/L)	83	66	32	37	38	17
Calculated Values[1]						
Oil&Grease$_{(COD)}$ (mg/L)	4.9	4.7	5.1	4.9	5.7	5.1
Oil&Grease$_{(DOC)}$ (mg/L)	1.7	1.8	1.5	1.4	0.82	0.96

1. Kayhanian, M, S. Khan, and M.K. Stenstrom. 2004. A new method to estimate oil and grease event mean concentration in highway runoff. StormCon 2004.

U indicates the constituent is a not detected - the value is the reporting limit

J indicates the value is an estimate

Table 21. Summary of Results of Chemical Analysis of Stormwater Runoff from the Media Filter System (Unit 2) of the Treatment Train.

	Media Filter 2[1]					
	7-Dec-07		6-Jan-08		23-Jan-08	
CONSTITUENT	MFS 2 In	MFS 2 Out	MFS 2 In	MFS 2 Out	MFS 2 In	MFS 2 Out
Hardness (mg/L)	29	31	17	16	7.5	7.2
SSC (mg/L)	108	97.1	72	55.1	125	92.4
>63 microns	6.25	1.92	6.89	3.13	26.2	8.41
<63 microns	102	95.2	65.1	52	98.9	84
TSS (mg/L)	110	100	66	58	110	91
COD (mg/L)	36	39	37	30	49	45
DOC (mg/L)	5.8	7.2	5.2	5.5	2.6	2.8
Total P	0.16	0.16	0.17	0.18	0.15	0.12
Ortho-P (mg/L)	0.099	0.099	0.073	0.069	0.047J	0.047J
Ammonia-N (mg/L)	0.24	0.26	0.16	0.14	0.18	0.19
TKN (mg/L)	0.99	1.1	0.8	0.62	0.73	0.62
Nitrate-N (mg/L)	0.87	0.89	0.36	0.37	0.20J	0.22J
Total Cadmium (ug/L)	0.19J	0.19J	0.091J	0.077J	0.26	0.24
Diss. Cadmium (ug/L)	0.069J	0.07J	0.034J	0.033J	0.025J	0.032J
Total Copper (ug/L)	24	25	13	12	30	27
Diss. Copper (ug/L)	9.4	9.9	7.1	6.9	4.8	5.1
Total Lead (ug/L)	15	14	5.7	6	42	37
Diss. Lead (ug/L)	2.2	2.3	1.5	0.88	1.3	1.5
Total Zinc (ug/L)	160	150	77	76	190	170
Diss. Zinc (ug/L)	58	70	32	36	30	35
Calculated Values[2]						
Oil&Grease$_{(COD)}$ (mg/L)	5	5.1	5.1	4.8	5.5	5.4
Oil&Grease$_{(DOC)}$ (mg/L)	1.8	2.2	1.6	1.7	0.88	0.93

1. The new perlite filters installed at the beginning of the storm season were not pinned in place. The filters floated free in the unit and are therefore considered to be completely non functional for the entire season.
2. Kayhanian, M, S. Khan, and M.K. Stenstrom. 2004. A new method to estimate oil and grease event mean concentration in highway runoff. StormCon 2004.

U indicates the constituent is a not detected - the value is the reporting limit

J indicates the value is an estimate

Table 22. Summary of Results of Chemical Analysis of Stormwater Runoff from the Storm Filter (SF1) of the Treatment Train.

CONSTITUENT	Storm Filter 1					
	7-Dec-07		6-Jan-08		23-Jan-08	
	SF1 In	SF1 Out	SF1 In	SF1 Out	SF1 In	SF1 Out
Hardness (mg/L)	18	19	15	15	7.1	7.2
SSC (mg/L)	85.3	82.9	62.7	50	124	82
>63 microns	6.05	0.907	5.95	2.18	28.3	4.12
<63 microns	79.3	82	56.8	47.8	95.7	77.9
TSS (mg/L)	90	78	66	44	100	77
COD (mg/L)	38	28	27	26	56	46
DOC (mg/L)	5.6	5.7	4.9	4.6	2.5	2.5
Total P	0.14	0.12	0.18	0.15	0.13	0.094
Ortho-P (mg/L)	0.08	0.081	0.07	0.072	0.045J	0.047J
Ammonia-N (mg/L)	0.3	0.31	0.16	0.15	0.23	0.2
TKN (mg/L)	0.97	0.9	0.68	0.62	0.89	0.26
Nitrate-N (mg/L)	0.55	0.59	0.28	0.33	0.18J	0.2J
Total Cadmium (ug/L)	0.18J	0.17J	0.098J	0.089J	0.24	0.23
Diss. Cadmium (ug/L)	0.068J	0.057J	0.04J	0.035J	0.032J	0.029J
Total Copper (ug/L)	23	21	11	11	28	23
Diss. Copper (ug/L)	9.5	9.3	6.6	6.1	5.2	5.8
Total Lead (ug/L)	14	12	5.4	5.3	45	38
Diss. Lead (ug/L)	1.8	2	1.1	0.3	1.7	1.7
Total Zinc (ug/L)	160	140	74	68	190	160
Diss. Zinc (ug/L)	78	69	37	28	41	39
Calculated Values[1]						
Oil&Grease$_{(COD)}$ (mg/L)	5.1	4.7	4.7	4.7	5.8	5.4
Oil&Grease$_{(DOC)}$ (mg/L)	1.7	1.7	1.5	1.4	0.85	0.85

1. Kayhanian, M, S. Khan, and M.K. Stenstrom. 2004. A new method to estimate oil and grease event mean concentration in highway runoff. StormCon 2004.

U indicates the constituent is a not detected - the value is the reporting limit

J indicates the value is an estimate

Table 23. Summary of Results of Chemical Analysis of Stormwater Runoff from the Storm Filter (SF2) of the Treatment Train.

CONSTITUENT	Storm Filter 2					
	7-Dec-07		5-Jan-08		23-Jan-08	
	SF 2 In	SF 2 Out	SF 2 In	SF 2 Out	SF 2 In	SF 2 Out
Hardness (mg/L)	17	20	12	14	7.3	9.4
SSC (mg/L)	66.1	60.6	74.8	54.5	114	72.2
>63 microns	4.75	1.15	6.51	1.86	21	2.5
<63 microns	61.3	59.4	68.3	52.6	92.9	69.7
TSS (mg/L)	78	69	72	52	100	72
COD (mg/L)	29	30	29	27	66	45
DOC (mg/L)	5.6	6.6	3.8	4.4	2.8	4
Total P	0.14	0.25	0.14	0.23	0.14	0.16
Ortho-P (mg/L)	0.08	0.18	0.057	0.14	0.046J	0.12J
Ammonia-N (mg/L)	0.31	0.33	0.12	0.068J	0.22	0.18
TKN (mg/L)	0.95	1	0.93	0.67	0.89	0.41
Nitrate-N (mg/L)	0.51	0.64	0.19	0.22	0.20J	0.23J
Total Cadmium (ug/L)	0.16J	0.13J	0.076J	0.085J	0.27	0.21
Diss. Cadmium (ug/L)	0.062J	0.052J	0.044J	0.041J	0.032J	0.038J
Total Copper (ug/L)	20	19	10	11	26	22
Diss. Copper (ug/L)	9.8	10	6	6.7	5.3	6.3
Total Lead (ug/L)	12	11	5.4	5.3	45	36
Diss. Lead (ug/L)	1.7	1.4	1.2	1.1	1.7	2
Total Zinc (ug/L)	150	110	72	64	190	150
Diss. Zinc (ug/L)	78	57	43	35	40	33
Calculated Values[1]						
Oil&Grease$_{(COD)}$ (mg/L)	4.8	4.8	4.8	4.7	6.1	5.4
Oil&Grease$_{(DOC)}$ (mg/L)	1.7	2	1.2	1.4	0.93	1.3

1. Kayhanian, M, S. Khan, and M.K. Stenstrom. 2004. A new method to estimate oil and grease event mean concentration in highway runoff. StormCon 2004.

U indicates the constituent is a not detected - the value is the reporting limit

J indicates the value is an estimate

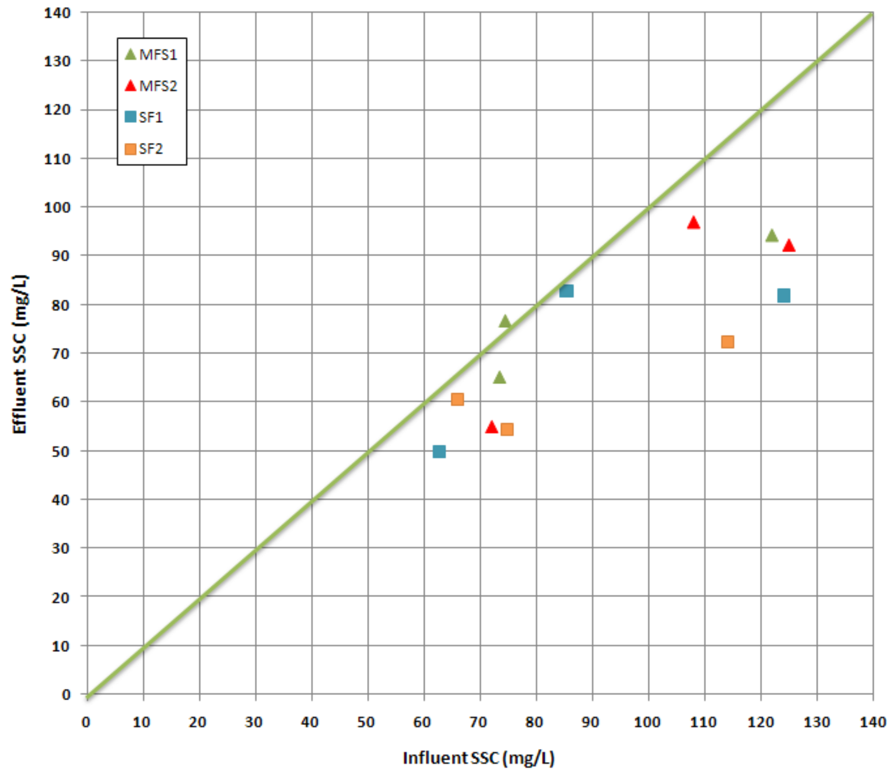


Figure 65. Efficiency of Phase II Filtration BMP in the Treatment of Suspended Solids Concentrations (SSC).

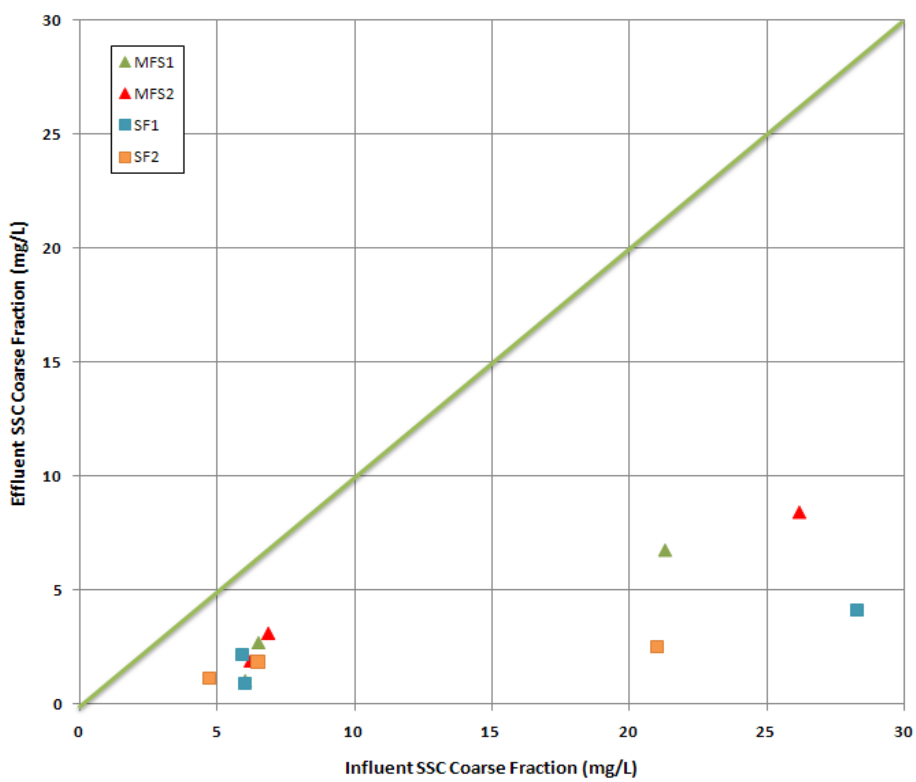


Figure 66. Efficiency of Phase II Filtration BMP in the Treatment of the Coarse Fraction of Suspended Solids Concentrations (SSC-Coarse).

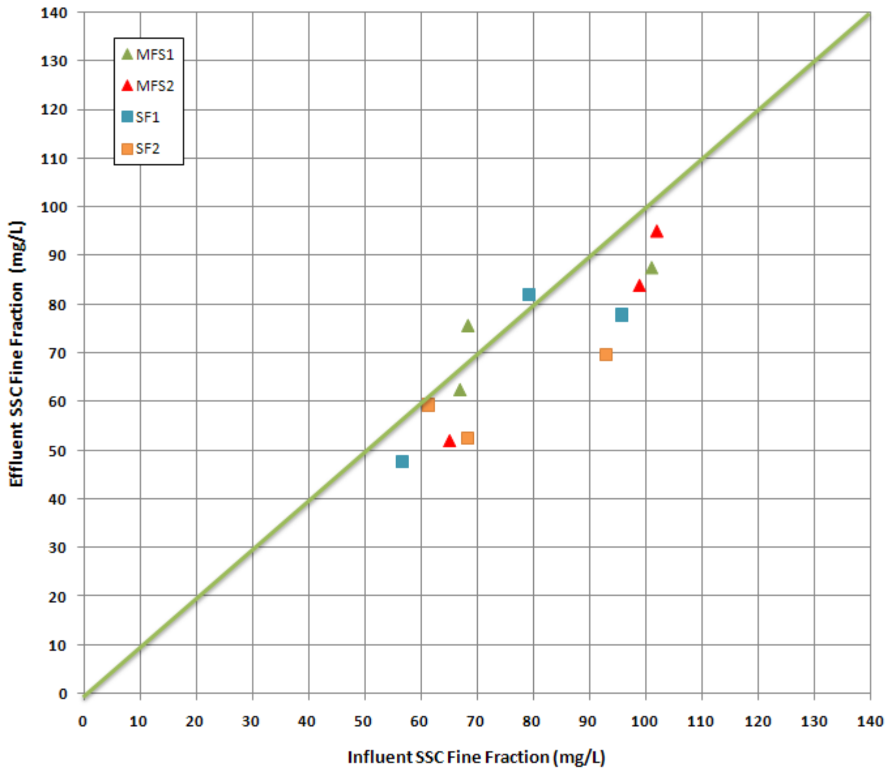


Figure 67. Efficiency of Phase II Filtration BMP in the Treatment of the Fine Fraction of Suspended Solids Concentrations (SSC-Fine).

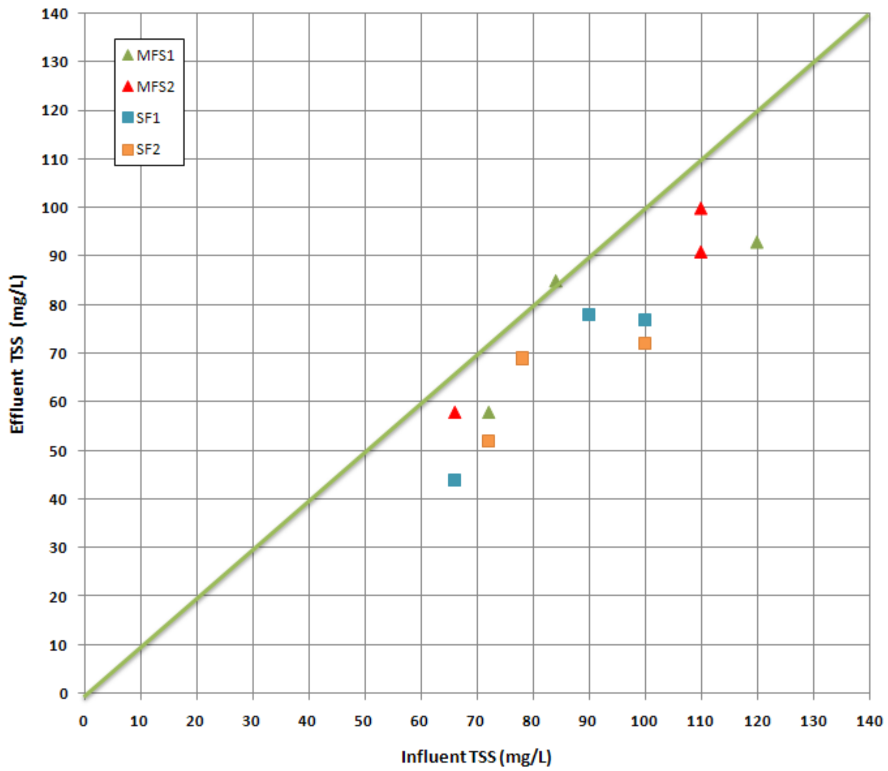


Figure 68. Efficiency of Phase II Filtration BMP in the Treatment of Total Suspended Solids (TSS).

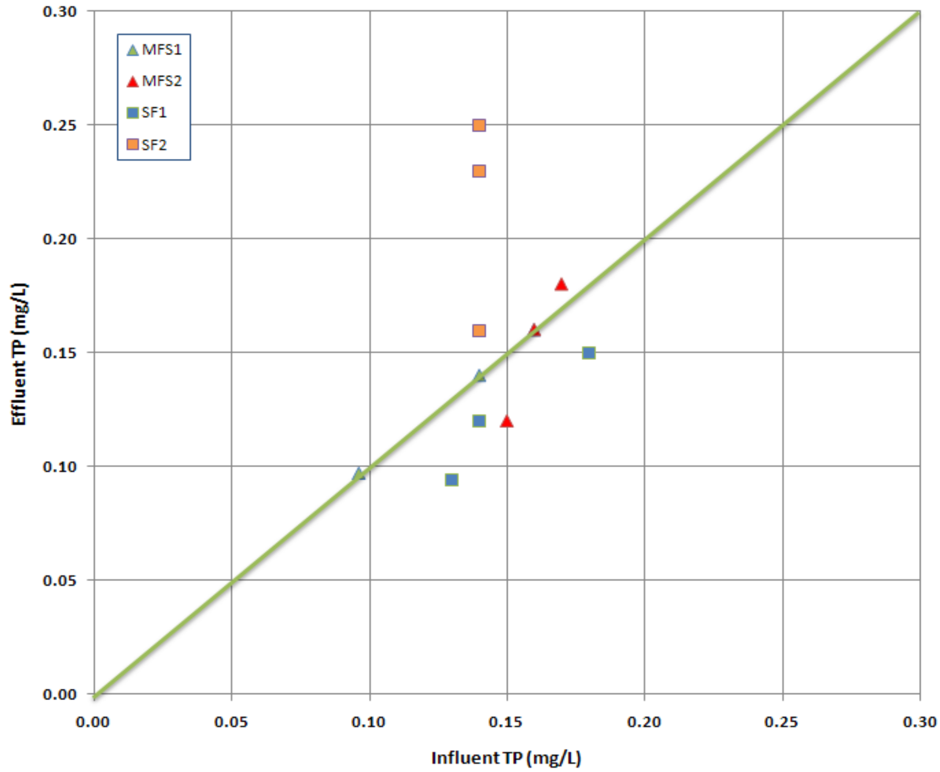


Figure 69. Efficiency of Phase II Filtration BMP in the Treatment of Total Phosphorous (TP).

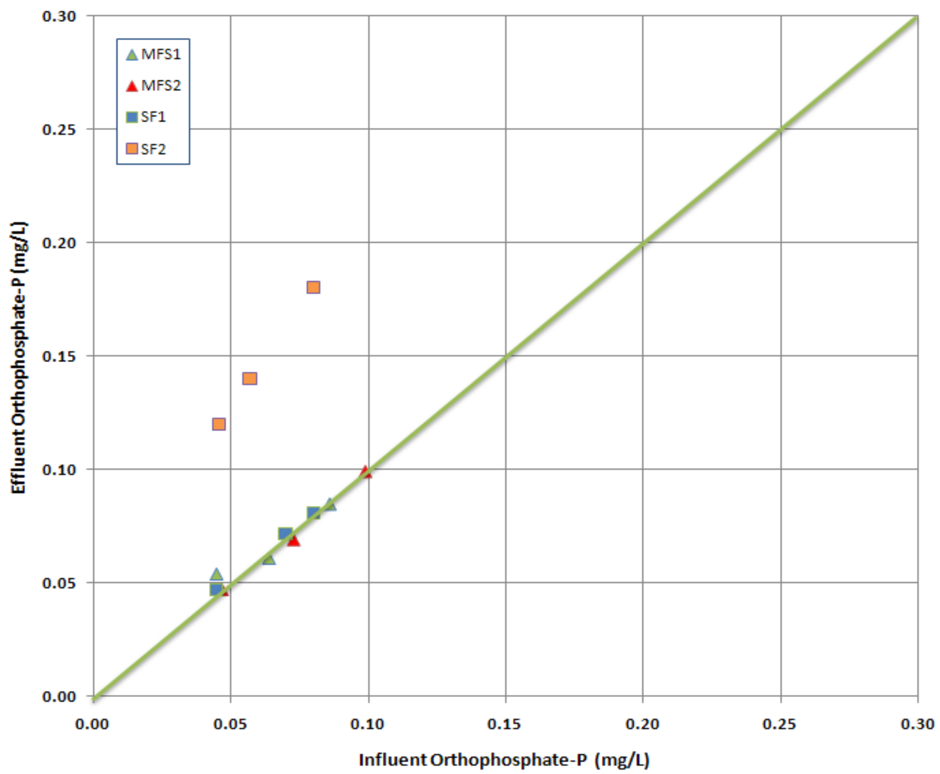


Figure 70. Efficiency of Phase II Filtration BMP in the Treatment of Orthophosphate-P (Ortho-P).

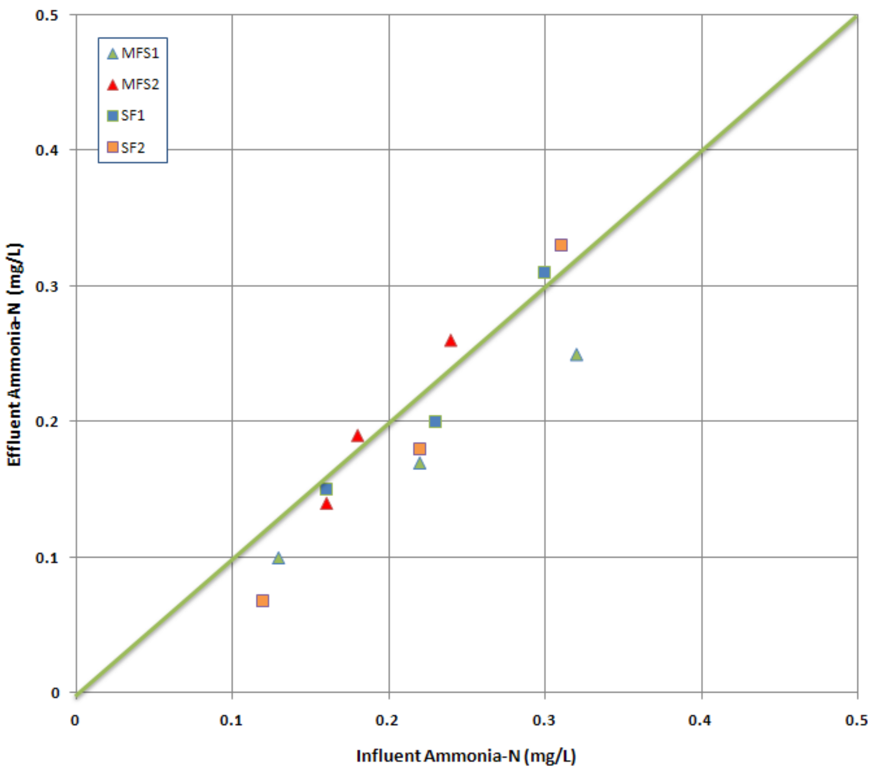


Figure 71. Efficiency of Phase II Filtration BMP in the Treatment of Ammonia-Nitrogen (Ammonia-N).

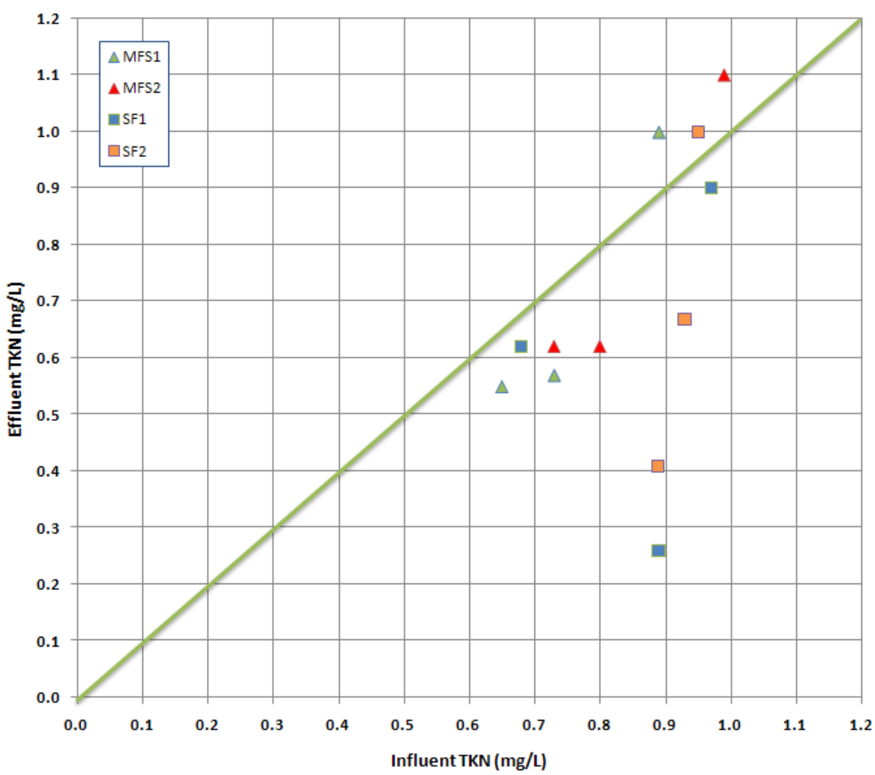


Figure 72. Efficiency of Phase II Filtration BMP in the Treatment of Total Kjeldahl Nitrogen (TKN).

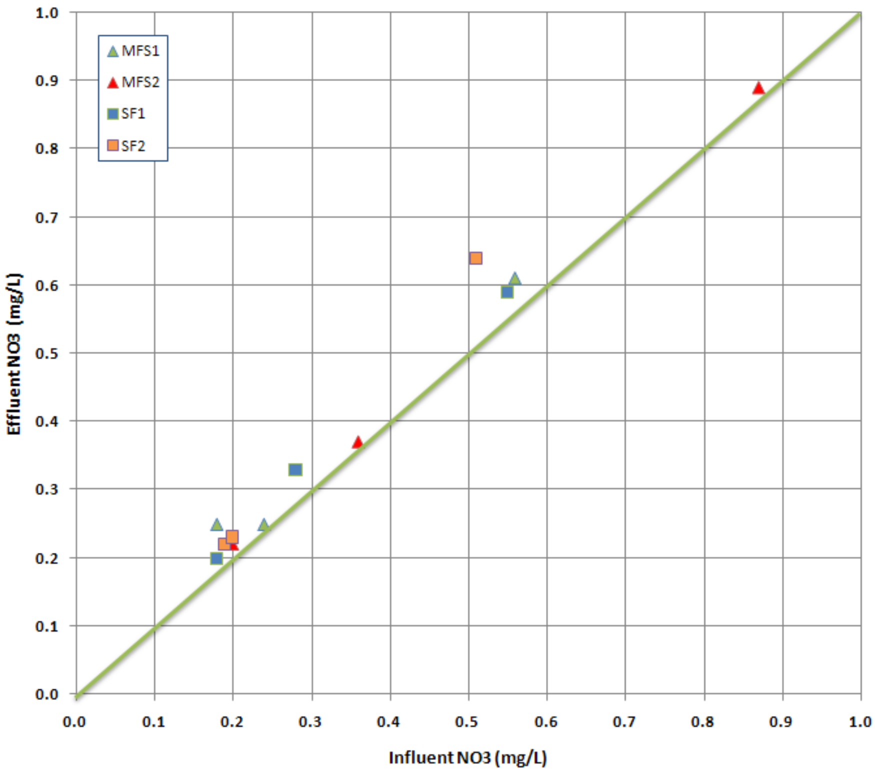


Figure 73. Efficiency of Phase II Filtration BMP in the Treatment of Nitrate-Nitrogen (NO_3-N)

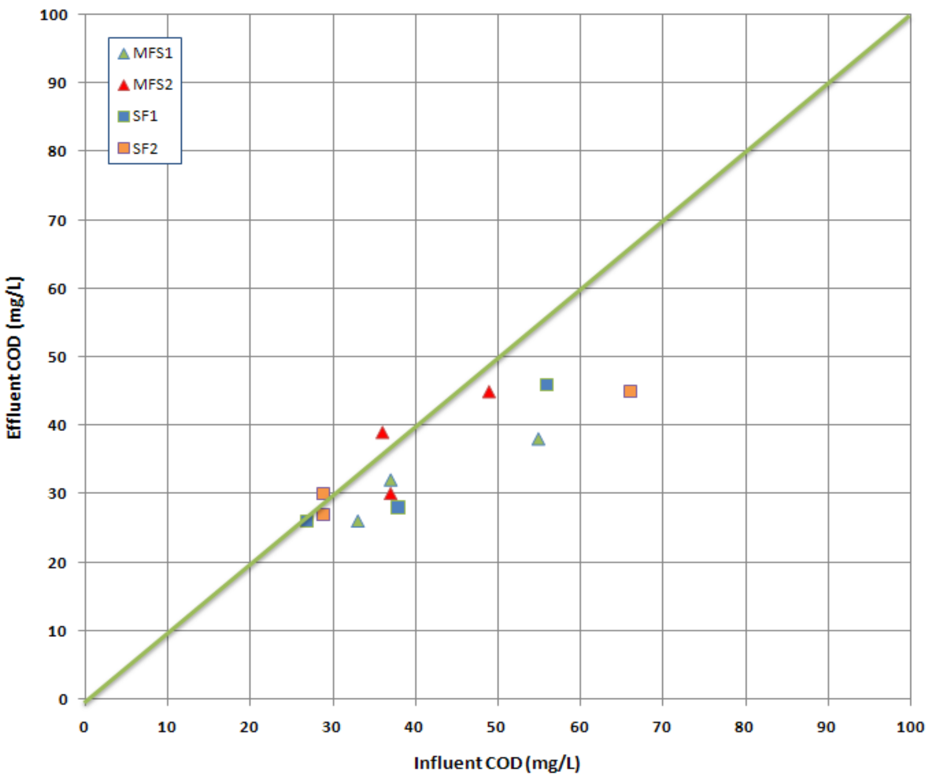


Figure 74. Efficiency of Phase II Filtration BMP in the Treatment of Chemical Oxygen Demand (COD)

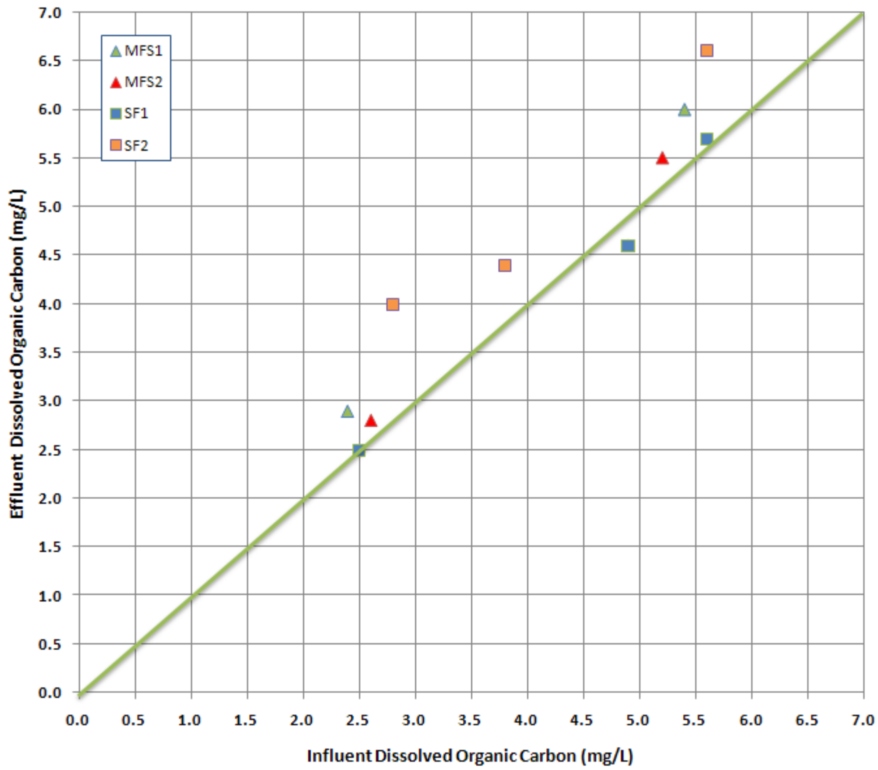


Figure 75. Efficiency of Phase II Filtration BMP in the Treatment of Dissolved Organic Carbon (DOC).

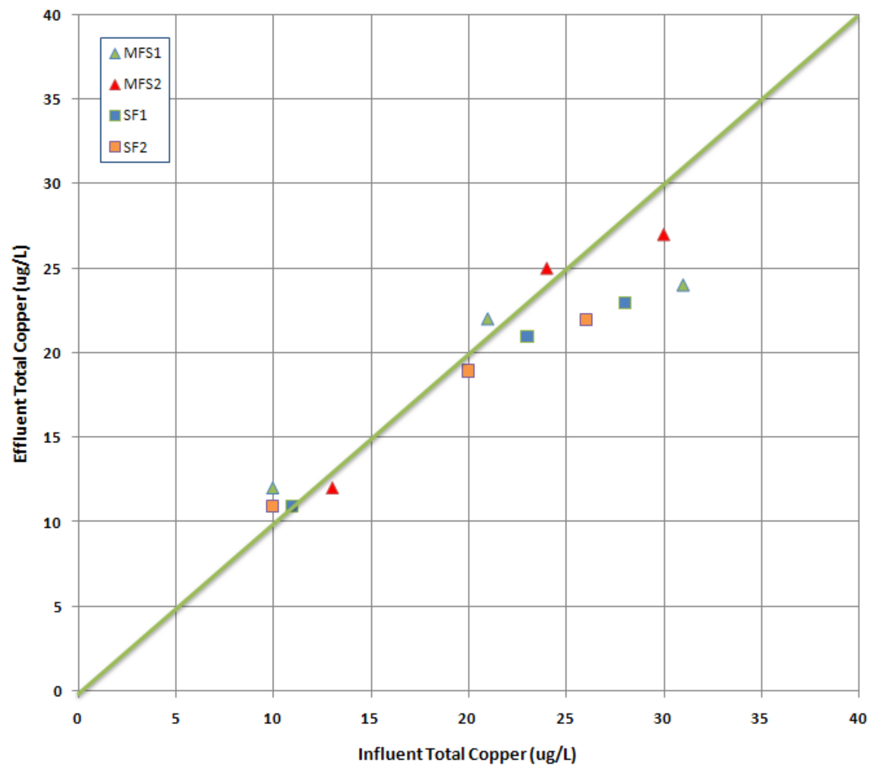


Figure 76. Efficiency of Phase II Filtration BMP in the Treatment of Total Copper.

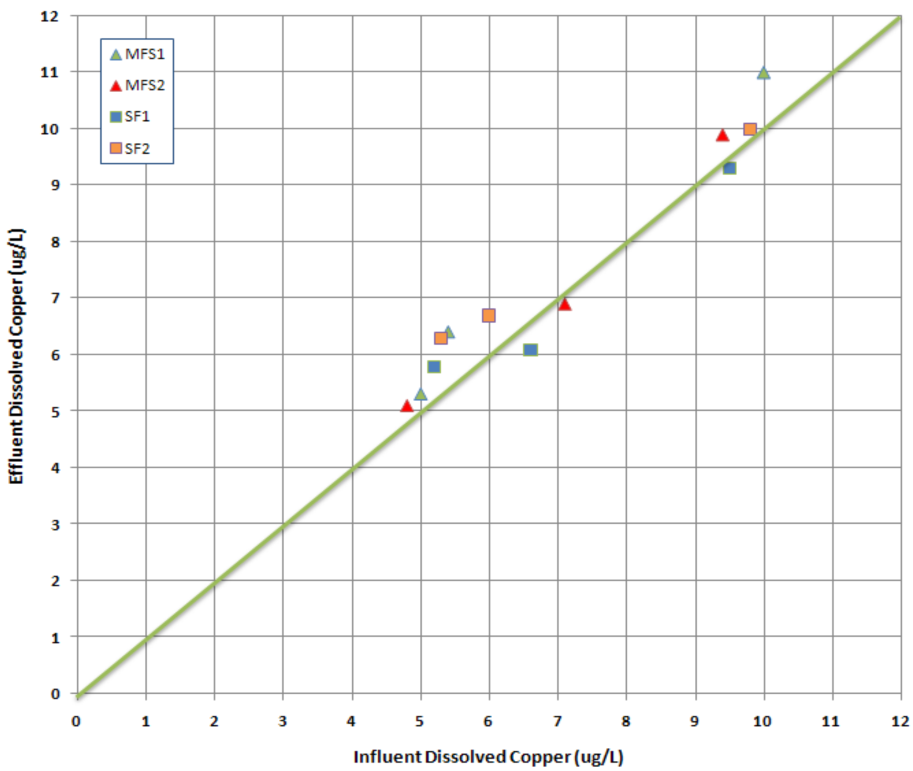


Figure 77. Efficiency of Phase II Filtration BMP in the Treatment of Dissolved Copper.

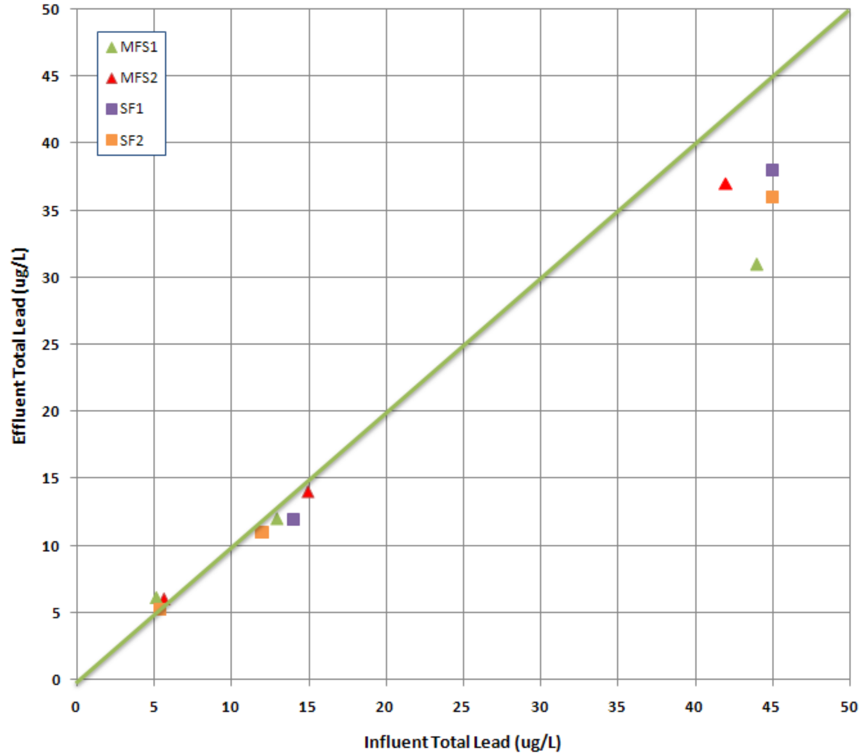


Figure 78. Efficiency of Phase II Filtration BMP in the Treatment of Total Lead.

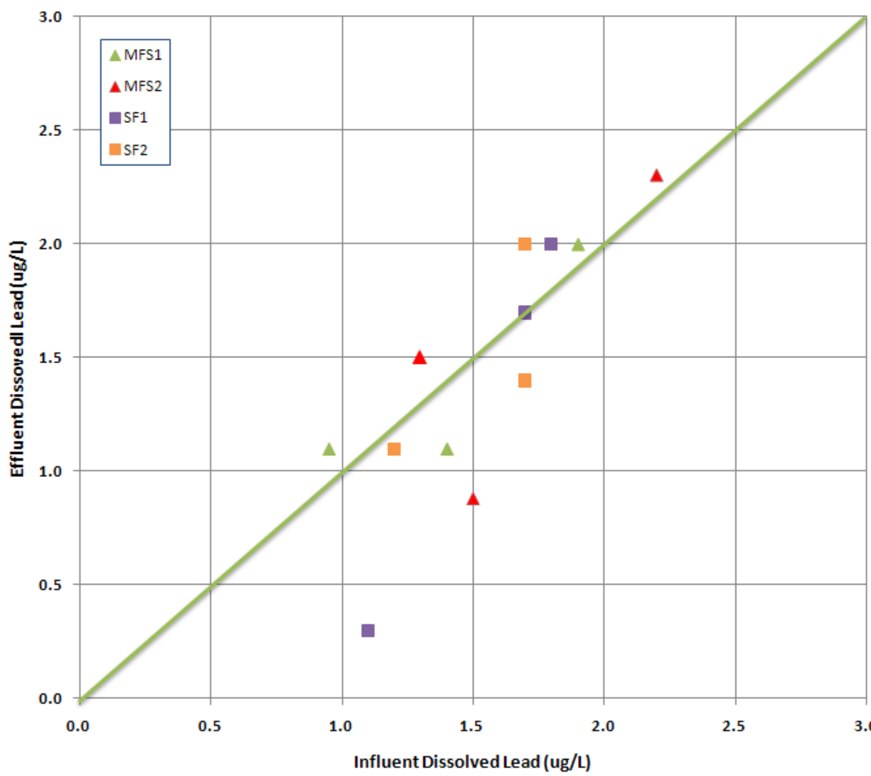


Figure 79. Efficiency of Phase II Filtration BMP in the Treatment of Dissolved Lead.

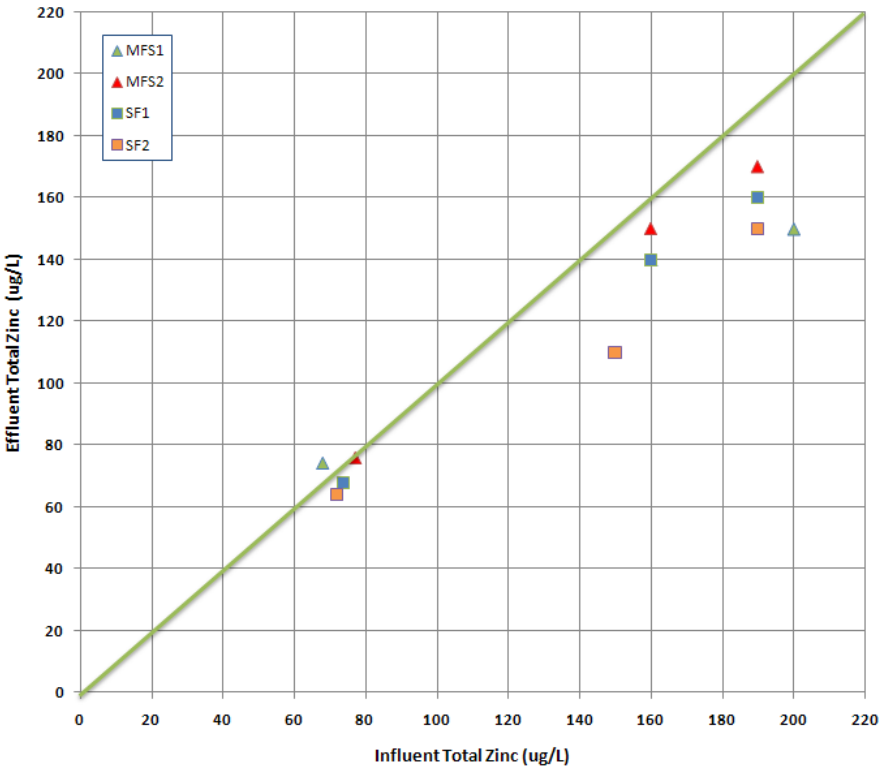


Figure 80. Efficiency of Phase II Filtration BMP in the Treatment of Total Zinc.

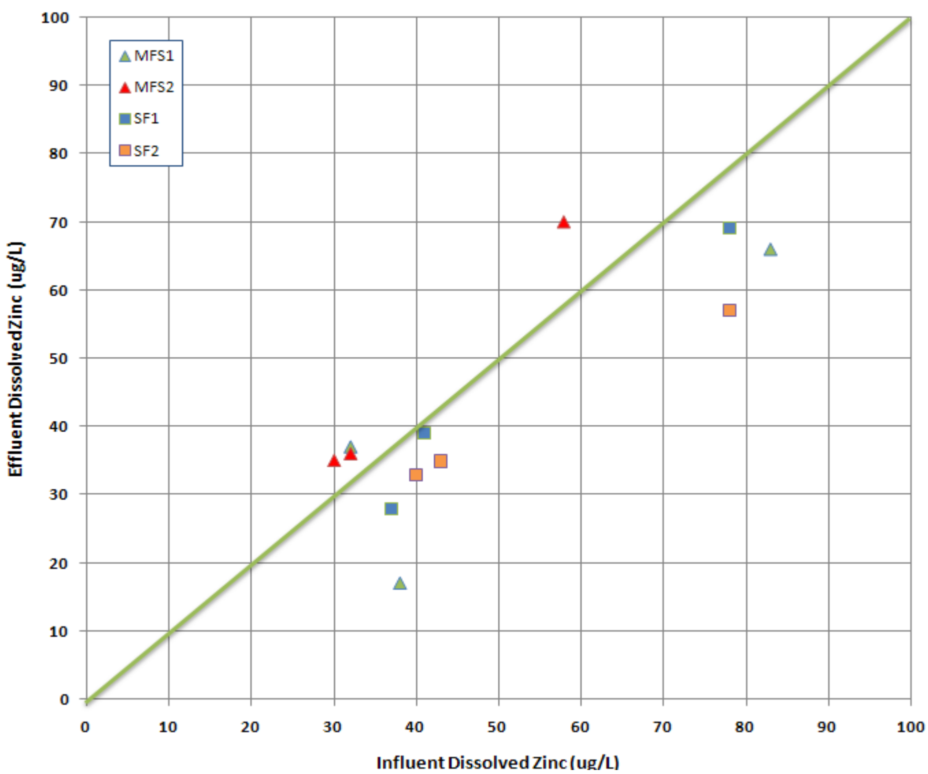


Figure 81. Efficiency of Phase II Filtration BMP in the Treatment of Dissolved Zinc.

Regardless of influent concentrations, an effective structural BMP should produce water of a consistent nature that is not likely to cause or contribute to exceedances of water quality in the receiving waters. Table 24 provides a comparison all effluent data from the Phase I MFS2 configuration with water quality criteria specified in the Project QAPP (Kinnetic Laboratories, Inc. 2007). This comparison includes all Phase I and II monitoring data for the initial configuration of the treatment train. Table 25 and Table 26 then provide a comparison of final effluent data from each filtration unit in the Phase II treatment train configuration. Although data from MFS2 are included in this comparison, this site was considered nonfunctional due to the detached filter cartridges.

Final effluent from the initial Phase I MFS configuration was substantially different than final effluent from the Phase II filtration systems (Table 24 through Table 26). TSS in effluent from the Phase I MFS configuration averaged 14 mg/L compared to 70 mg/L in effluent from the three functioning Phase II filtration systems. Similar differences existed for SSC concentrations. Both the Phase I and II systems had minimal concentrations (2-3 mg/L) of sediment particles greater than 63 microns. The differences in suspended sediment were solely due to a large increase in the fine fraction of SSC.

A comparison of metals in the Phase I and II effluent also suggested large differences, but in this case, concentrations of both total and dissolved metals were substantially lower in the Phase II effluent. The dissolved fractions were also a much lower proportion of the total concentrations for copper, lead and zinc. Decreases in the concentrations of dissolved metals are consistent with changes observed in the quality of runoff from the parking lot reference site.

Ambient acute receiving water quality criteria were used as a reference point to evaluate dissolved metal concentrations in the final effluent. An average hardness value of 21 mg/L was used to calculate water quality criteria for monitoring conducted with the treatment train in the Phase I configuration. An average hardness value of 15 mg/L was used to calculate water quality criteria for all sampling conducted while the treatment train was in the Phase II configuration. During both time periods, the extremely low hardness of the final effluent resulted in very low water quality criteria. Both dissolved copper and zinc commonly exceeded the acute water quality criteria at these hardness levels. Total hardness in the San Diego River receiving waters are typically 400 mg/L or greater. If one were to very conservatively evaluate dissolved metal water quality exceedances of all effluent data at a hardness of 100 mg/L, none of the Phase II effluent (including effluent from the nonfunctional MFS2 site) would have exceeded the criteria. Seventy-five (75) percent of the dissolved copper and zinc measurements in the Phase I configuration would still have exceeded the water quality criteria.

Table 24. Comparison of Final Effluent from the Phase I Treatment Train Configuration (CDS and MFS2) with available Water Quality Criteria and Guidelines.

CONSTITUENT	1/28/06	3/12/06	3/19/06	1/30/07	2/11/07	2/19/07	2/23/07	4/21/07	Reference Criteria	Source
Hardness (mg/L)	12	17	13	38	38	13	15	25		
SSC (mg/L)	16.7	10.9	9.1	28	15.7	5.58	10.7	16.1		
>63 microns	1.8	1	0.9	1.4	2.45	0.5U	0.5U	1.5		
<63 microns	14.9	9.9	8.2	26.6	13.2	5.58	10.7	14.6		
TSS (mg/L)	14	9.7	8.1	29	14	6	10	18	100 mg/L	Multi-Sector General Permit (USEPA 2000b)
COD (mg/L)	43J	26	26	76	110	21	33	83	120 mg/L	Multi-Sector General Permit (USEPA 2000b)
DOC (mg/L)	12	7.2	8.3	25	33	5.6	9.5	22		
Total P (mg/L)	0.21	0.18	0.13	0.23	0.32	0.14	0.14	0.24	2 mg/L	Multi-Sector General Permit (USEPA 2000b)
Ortho-P (mg/L)	0.094	0.11	0.083	0.14	0.12	0.098	0.094	0.15		
Ammonia-N (mg/L)	0.48	0.15	0.15	0.75	0.87	0.26	0.25	0.62		
TKN (mg/L)	1.1J	0.6	0.53	2	2.7	0.74	0.79	1.5		
Nitrate-N (mg/L)	0.67	0.51	0.44	1.2	2.2	0.68	0.48	1.1	10 mg/L	Basin Plan (RWQCB 1994)
Total Cadmium (ug/L)	0.28	0.28	0.2	0.44	0.34	0.16	0.68	0.48		
Diss. Cadmium (ug/L)	0.20U	0.17	0.14	0.29	0.29	0.11J	0.17	0.35	0.78[2]	40 CFR 131 (USEPA 2000a)
Total Copper (ug/L)	25	20	20	35	48	13	16	45		
Diss. Copper (ug/L)	***19***	***14***	***16***	***24***	***39***	***9.1***	***12***	***34***	3.1[2]	40 CFR 131 (USEPA 2000a)
Total Lead (ug/L)	24	21	16	36	26	7.2	15	30		
Diss. Lead (ug/L)	5.8	3.1	3.5	9.9	***11***	2.1	3	***11***	11[2]	40 CFR 131 (USEPA 2000a)
Total Zinc (ug/L)	160	160	140	300	270	86	130	340		
Diss. Zinc (ug/L)	***130***	***120***	***120***	***230***	***220***	***63***	***89***	***270***	31[2]	40 CFR 131 (USEPA 2000a)
Calculated Values[1]										
Oil&Grease$_{(COD)}$ (mg/L)	5.3	4.7	4.7	6.5	7.8	4.5	4.9	6.8		
Oil&Grease$_{(DOC)}$ (mg/L)	3.5	2.2	2.5	7.2	9.4	1.7	2.8	6.3		

1. Kayhanian, M, S. Khan, and M.K. Stenstrom. 2004. A new method to estimate oil and grease event mean concentration in highway runoff. StormCon 2004.
2. Dissolved metals criteria are CMC (acute values) and are hardness based. Reference criteria were calculated based upon the average hardness of 21 mg/L.

U indicates the constituent is a not detected - the value is the reporting limit

J indicates the value is an estimate

Bold and Italicized values exceed the reference criteria.

Table 25. Comparison of Final Effluent from Media Filtration Systems in the Phase II Treatment Train Configuration (CDS, MFS1, MFS2) with available Water Quality Criteria and Guidelines.

	MFS1			MFS2[3]				
CONSTITUENT	12/7/07	1/5/08	1/23/08	12/7/07	1/5/08	1/23/08	Reference Criteria	Source
Hardness (mg/L)	22	13	10	31	16	7.2		
SSC (mg/L)	76.8	65.3	94.3	97.1	55.1	92.4		
>63 microns	1.04	2.71	6.77	1.92	3.13	8.41		
<63 microns	75.7	62.6	87.5	95.2	52	84		
TSS (mg/L)	85	58	93	***100***	58	91	100 mg/L	Multi-Sector General Permit (USEPA 2000b)
COD (mg/L)	26	32	38	39	30	45	120 mg/L	Multi-Sector General Permit (USEPA 2000b)
DOC (mg/L)	6	4.6	2.9	7.2	5.5	2.8		
Total P (mg/L)	0.14	0.16	0.097	0.16	0.18	0.12	2 mg/L	Multi-Sector General Permit (USEPA 2000b)
Ortho-P (mg/L)	0.085	0.061	0.054J	0.099	0.069	0.047J		
Ammonia-N (mg/L)	0.25	0.1	0.17	0.26	0.14	0.19		
TKN (mg/L)	1	0.55	0.57	1.1	0.62	0.62		
Nitrate-N (mg/L)	0.61	0.25	0.25J	0.89	0.37	0.22J	10 mg/L	Basin Plan (RWQCB 1994)
Total Cadmium (ug/L)	0.16J	0.084J	0.21	0.19J	0.077J	0.24		
Diss. Cadmium (ug/L)	0.073J	0.042J	0.024J	0.07J	0.033J	0.032J	0.78[2]	40 CFR 131 (USEPA 2000a)
Total Copper (ug/L)	22	12	24	25	12	27		
Diss. Copper (ug/L)	***11***	***6.4***	***5.3***	***9.9***	***6.9***	***5.1***	2.2[2]	40 CFR 131 (USEPA 2000a)
Total Lead (ug/L)	12	6.1	31	14	6	37		
Diss. Lead (ug/L)	2	1.1	1.1	2.3	0.88	1.5	7.8[2]	40 CFR 131 (USEPA 2000a)
Total Zinc (ug/L)	140	74	150	150	76	170		
Diss. Zinc (ug/L)	***66***	***37***	17	***70***	***36***	***35***	24[2]	40 CFR 131 (USEPA 2000a)
Calculated Values[1]								
Oil&Grease$_{(COD)}$ (mg/L)	4.7	4.9	5.1	5.1	4.8	5.4		
Oil&Grease$_{(DOC)}$ (mg/L)	1.8	1.4	0.96	2.2	1.7	0.93		

1. Kayhanian, M, S. Khan, and M.K. Stenstrom. 2004. A new method to estimate oil and grease event mean concentration in highway runoff. StormCon 2004.
2. Dissolved metals criteria are CMC (acute values) and are hardness based. Reference criteria were calculated based upon the average hardness of 15 mg/L.
3. Due to the filtration cartridges not being properly anchored, effluent from the MFS2 site did not receive additional treatment other than some removal within the vault as a result of additional settling. Shading is intended to distinguish this data set from the other three functional systems.

U indicates the constituent is a not detected - the value is the reporting limit

J indicates the value is an estimate

Bold and Italicized values exceed the reference criteria.

Table 26. Comparison of Final Effluent from the StormFilter Units in thePhase II Treatment Train Configuration (CDS, SF1 and SF2) with available Water Quality Criteria and Guidelines.

	SF1			SF2				
CONSTITUENT	**12/7/07**	**1/5/08**	**1/23/08**	**12/7/07**	**1/5/08**	**1/23/08**	**Reference Criteria**	**Source**
Hardness (mg/L)	19	15	7.2	20	14	9.4		
SSC (mg/L)	82.9	50	82	60.6	54.5	72.2		
>63 microns	0.907	2.18	4.12	1.15	1.86	2.5		
<63 microns	82	47.8	77.9	59.4	52.6	69.7		
TSS (mg/L)	78	44	77	69	52	72	100 mg/L	Multi-Sector General Permit (USEPA 2000b)
COD (mg/L)	28	26	46	30	27	45	120 mg/L	Multi-Sector General Permit (USEPA 2000b)
DOC (mg/L)	5.7	4.6	2.5	6.6	4.4	4		
Total P (mg/L)	0.12	0.15	0.094	0.25	0.23	0.16	2 mg/L	Multi-Sector General Permit (USEPA 2000b)
Ortho-P (mg/L)	0.081	0.072	0.047J	0.18	0.14	0.12J		
Ammonia-N (mg/L)	0.31	0.15	0.2	0.33	0.068J	0.18		
TKN (mg/L)	0.9	0.62	0.26	1	0.67	0.41		
Nitrate-N (mg/L)	0.59	0.33	0.2J	0.64	0.22	0.23J	10 mg/L	Basin Plan (RWQCB 1994)
Total Cadmium (ug/L)	0.17J	0.089J	0.23	0.13J	0.085J	0.21		
Diss. Cadmium (ug/L)	0.057J	0.035J	0.029J	0.052J	0.041J	0.038J	0.78[2]	40 CFR 131 (USEPA 2000a)
Total Copper (ug/L)	21	11	23	19	11	22		
Diss. Copper (ug/L)	***9.3***	***6.1***	***5.8***	***10***	***6.7***	***6.3***	2.2[2]	40 CFR 131 (USEPA 2000a)
Total Lead (ug/L)	12	5.3	38	11	5.3	36		
Diss. Lead (ug/L)	2	0.3	1.7	1.4	1.1	2	7.8[2]	40 CFR 131 (USEPA 2000a)
Total Zinc (ug/L)	140	68	160	110	64	150		
Diss. Zinc (ug/L)	***69***	***28***	***39***	***57***	***35***	***33***	24[2]	40 CFR 131 (USEPA 2000a)
Calculated Values[1]								
Oil&Grease$_{(COD)}$ (mg/L)	4.7	4.7	5.4	4.8	4.7	5.4		
Oil&Grease$_{(DOC)}$ (mg/L)	1.7	1.4	0.85	2	1.4	1.3		

1. Kayhanian, M, S. Khan, and M.K. Stenstrom. 2004. A new method to estimate oil and grease event mean concentration in highway runoff. StormCon 2004.
2. Dissolved metals criteria are CMC (acute values) and are hardness based. Reference criteria were calculated based upon the average hardness of 15 mg/L.

U indicates the constituent is a not detected - the value is the reporting limit

J indicates the value is an estimate

Bold and Italicized values exceed the reference criteria.

CDS Gross Pollutant Assessment

This task consists of quantification of gross pollutants and sediments trapped in the sump of the CDS unit over the monitoring period. The CDS unit was cleaned prior to the 2007/2008 storm season but material was not quantified at that time. A flow metering system was used at this site to measure flows entering and bypassing the CDS unit. Flow was continuously monitored at this site until June 28, 2008 when the sump was cleaned and the waste material quantified. Over 20 million liters of stormwater resulting from 8.15 inches of rain were treated by the CDS unit during this time period.

A total 2565 Kg of material (wet weight) was removed (Table 27). Visual estimates indicated that the material consisted primarily of fine sediments. Of the roughly 94 cubic feet of material found in the CDS sump, floating materials were estimated at less than 1 cubic foot. A subsample of the settled material in the sump was taken and sent to the laboratory for quantitative determination of the relative mass of the trash and other gross pollutants relative to sediments. A #4 sieve (4.75 mm or 3/16 inch) was used as the delineation between gross pollutants and sediments per recommendations from CDS and draft ASCE protocol being developed for assessment of stormwater gross solids (England and Rushton, 2005). Only 1.6 percent of the sump material were considered gross pollutants thus 98.4 of the sump material was classified as sediment.

Results of the solids assessment are summarized in Table 27 along with a comparison of the results of sampling the CDS sump at the end of the 2005/2006 season. This year, sediment removed from the sump was predominantly fine material consisting of 52.7 percent clay and 13.2 percent silt sized particles. This is in sharp contrast to material removed from the CDS sump in the first survey. At that time, sediment removed from the sump consisted of 97.3 percent sand and gravel. Graphical presentations of particle size distributions for samples from 2005/2006 (Figure 82) and 2007/2008 (Figure 83) clearly illustrate the strong difference in sediment size composition between the two seasons. The reason for these large differences in sump sediment characteristics can be attributed to sediment discharged from the ME construction site both during and between storm events. The site required frequent dewatering starting in January 2008 in order to minimize uncontrolled discharges during storm events.

Sediment removed from the CDS sump at the end of the 2007/2008 season also had very different concentrations of key constituents of concern relative to the sampling conducted at the end of the 2005/2006 season. Concentrations of oil and grease and TRPH were 20 to 30% of concentrations reported during the initial sampling event. The concentration of total phosphate –P was less than 15% of concentration from 2006 and TKN was close to 10% of the previously reported level. Ammonia-N was the only nutrient that increased substantially between the two periods. The concentration of ammonia-N increased from just 2.3 to 64 mg/Kg.

Three of the four trace metals analyzed in the sump sediments during the recent cleanout were also analyzed in sediment removed in 2006. Concentrations of both lead and zinc decreased by about 1/3 in the recent sump samples while copper levels increased by about 20%. Concentrations of metals in the sump sediments were not dramatically different from background soils (Bradford et al. 1996) from San Diego County (near the intersection of the I-5 and I-805 freeways). Soils at this background site were classified as clays. Concentrations of cadmium, copper, lead and zinc at the background site were 0.11, 36.6, 57 and 172 mg/Kg-dry, respectively. Cadmium, copper, lead and zinc in the sump samples were 0.33, 54, 45 and 220 mg/Kg-dry, respectively.

Estimates of the equivalent concentrations removed from stormwater were developed by using the total mass of each measured constituent and the total volume of stormwater treated since the last cleanout (Table 28). This very rough approximation was useful in providing a general perspective on effectiveness of the CDS unit. Sediment in the sump would have represented an average concentration of 30.7 mg/L of SSC in all stormwater runoff from the COC. This compares to a median concentration of 170 mg/L of SSC from the Phase II parking lot reference site. Compared to median concentrations in runoff from the Phase II parking lot reference area, copper and lead present in the sump would represent roughly 10 percent of the load from the COC. Zinc present in the sump would have represented only 2% of the load. Dewatering of the ME construction site contributed an unknown load of sediment that would not be accounted for using this approach.

The removal of gross pollutants by the CDS unit provides the important pretreatment necessary for the filtration units to function correctly. The filtration units are intended to provide further treatment of the stormwater by filtration of the finer particulates and contaminants that might be associated with the fine fraction. Data from the 2007/2008 season demonstrated that, as expected, the CDS unit was effective at removing the coarse material but it also removed a substantial amount of fine material since over 2/3 of the sediment removed from the unit was less than 63 microns in size.

Table 27. Summary Data for the Evaluation of Gross Solids Retained by the CDS Unit.

PARAMETER	2005/2006	2007/2008
CDS SUMP TREATMENT STATISTICS		
Total Treated Water Volume (Liters)	14,383,146	20,129,064
Total Rainfall (inches) – KEA rain gage	5.75	8.15
Total Sump Material Removal (Kg – wet)	259	2565
Total Sediment (≤4.75 mm; Kg – dry)	139	618
CDS SUMP SEDIMENT PHYSICAL CHARACTERISTICS		
Sediment Particle Size (percent)		
Gravel	14.6	3.1
Sand	82.7	31.0
Silt	1.7	13.2
Clay	0.97	52.7
SEDIMENT CONTAMINANT CONCENTRATIONS		
Percent Solids (% wet weight)	65.1	25.4
Oil & Grease (mg/Kg – dry)	4200	730
TRPH (mg/Kg – dry)	750	240
Total P (mg/Kg – dry)	33000	890
TKN (mg/Kg – dry)	1100	120
Ammonia-N (mg/Kg – dry)	2.3	64
Total Cadmium (mg/Kg-dry)		0.33
Total Copper (mg/Kg – dry)	44	54
Total Lead (mg/Kg – dry)	61	45
Total Zinc (mg/Kg – dry)	340	220
SEDIMENT CONTAMINANT MASS (Grams)		
Oil &Grease	584	451
TRPH	104	148
Total P	4587	550
TKN	153	74
Ammonia-N	0.3	40
Total Cadmium		0.20
Total Copper	6.1	33
Total Lead	8.5	28
Total Zinc	47.3	136

Table 28. Estimates of Mean Equivalent Stormwater Concentrations removed by the CDS Unit for the 2007/2008 and 2005/2006 Wet Seasons.

PARAMETER	2005/2006	2007/2008
SSC (mg/L)	9.7	30.7
Oil &Grease (mg/L)	0.041	0.022
TRPH (mg/L)	0.007	0.007
Total P (mg/L)	0.32	0.03
TKN (mg/L)	0.011	0.004
Ammonia-N (mg/L)	0.00002	0.022
Total Cadmium (µg/L)		0.01
Total Copper (µg/L)	0.43	1.7
Total Lead (µg/L)	0.59	1.4
Total Zinc (µg/L)	3.3	6.8

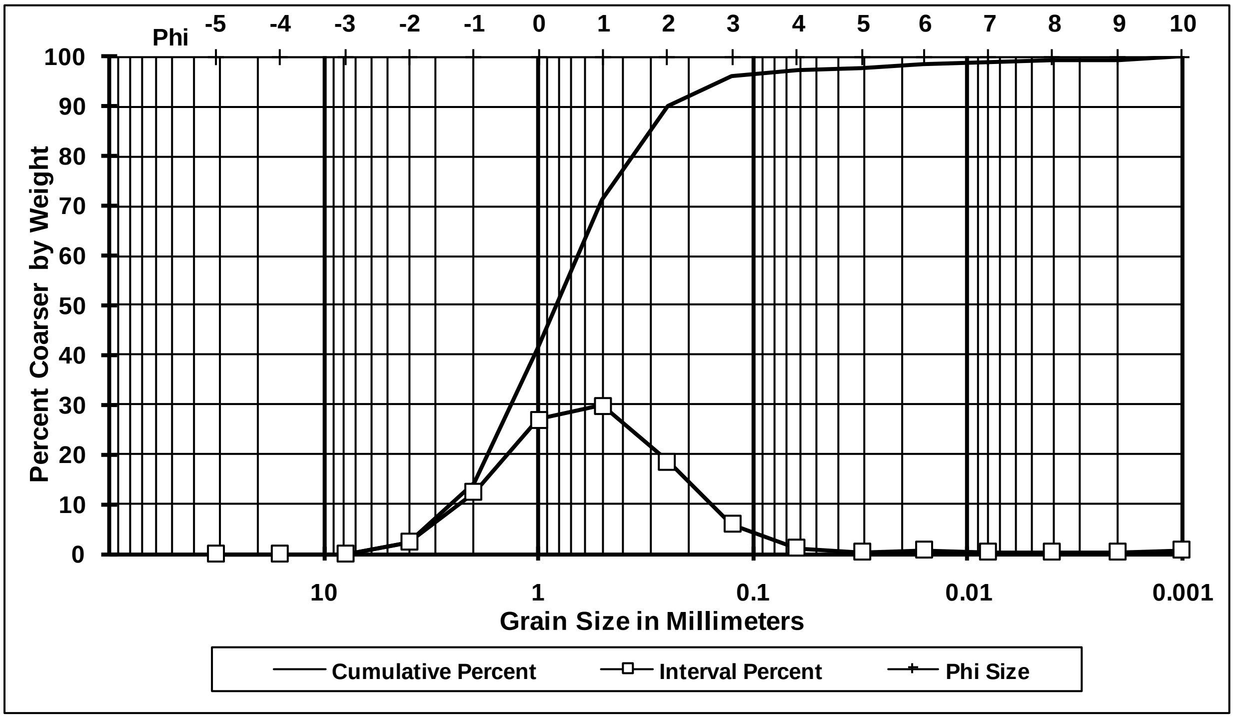


Figure 82. Particle Size Analysis of the Sediment Fraction (<4.75 mm) of Gross Pollutants collected from the CDS Sump - 2006.

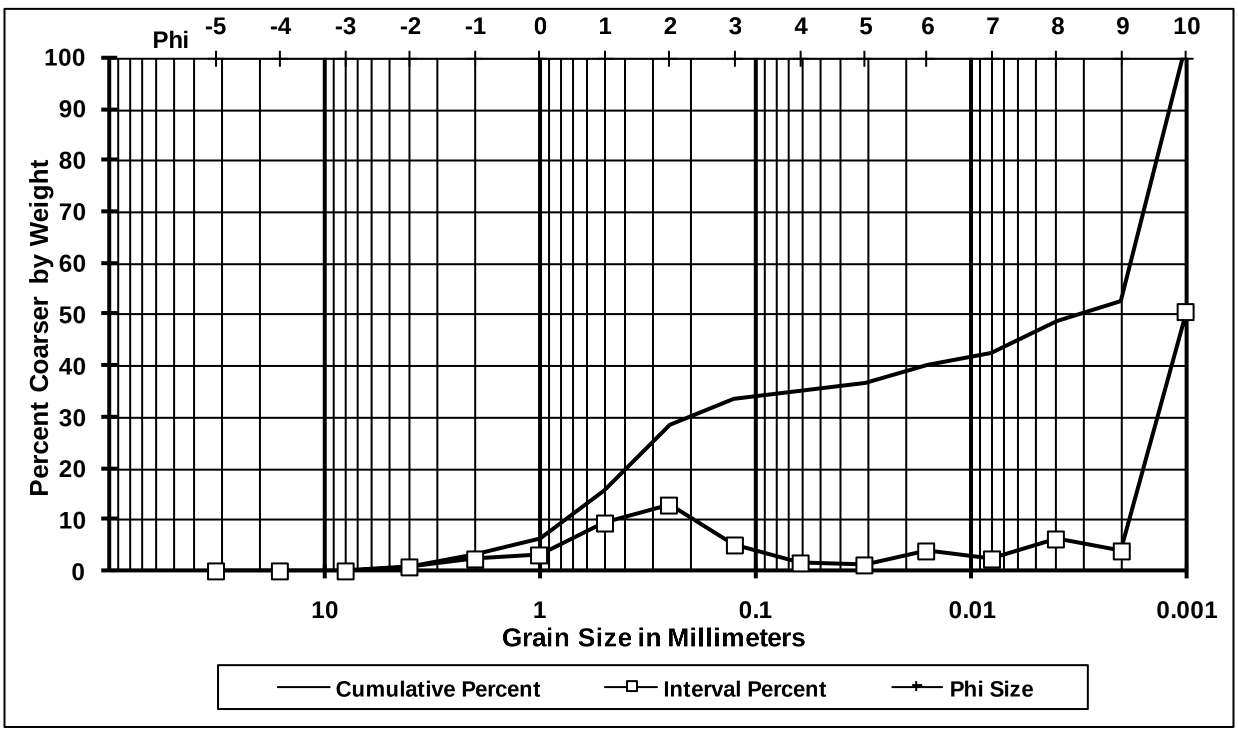


Figure 83. Particle Size Analysis of the Sediment Fraction (<4.75 mm) of Gross Pollutants collected from the CDS Sump - 2008.

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CONCLUSIONS

This program was designed to address a number of specific questions. Each of the major questions is addressed in the following sections.

POROUS PAVEMENT

1. *How do normalized stormwater discharges from each treatment type (porous asphalt, porous concrete and pavers) compare to normalized runoff from the reference area by both individual storm events and for the entire storm season.*

No runoff was observed at any of the porous pavement test sites. Since the intent of normalizing runoff was to standardize the data to unit area, this comparison was not necessary. The Phase II porous concrete site nearly discharged on two occasions but never overflowed the control basin weir. The total elimination of runoff from all porous pavement test sites was extremely notable given the poor quality of the soils for infiltration.

2. *How does water quality of stormwater discharges from each treatment type, measured in terms of flow-rated event mean concentrations, compare to the quality of runoff from the reference area?*

The effectiveness of all five porous pavement test sites precludes this comparison since no discharges occurred throughout the season. The mean water quality of runoff from the Phase I and II parking lot reference areas was compared with runoff from Caltrans maintenance facilities, Caltrans park and ride lots, and a small, highly impervious urban watershed in Long Beach, California. The results of this comparison indicated that runoff from the two reference sites varied substantially between the Phase I and II monitoring periods but still did not substantially differ from these other studies.

3. *How do the infiltration basins associated with each of the porous surface treatments impact stormwater discharge hydrographs?*

One would expect that infiltration facilities would reduce total flow, peak flow and extend the duration of discharge. The complete elimination of discharges from the three Phase I porous paving sites during the 2006/2007 season prevented an estimated 24,238 cubic feet (686,340 liters) of runoff and associated pollutants resulting from 4.5 inches of rain from being discharged to the San Diego River. The Phase II improvements more than doubled the treated area including the porous paving areas and roof reference site that discharged to the Phase II porous asphalt infiltration basin. With the increased annual rainfall of 7.7 inches during the 2007/2008, an estimated 91,590 cubic feet (2,593,553 liters) of runoff and associated pollutants were prevented from discharging off the COC property.

4. *How do normalized pollutant loading rates associated with each porous surface treatment compare to those of the adjacent impervious reference area?*

The pollutant loading rates for all constituents of concern were zero at all porous pavement treatments.

5. *At what rates do water levels in the infiltration basins of each treatment type change during and between storm events?*

Infiltration rates, as assessed by changes in water levels within the infiltration beds of all porous pavement treatment sites, were highly variable among the five sites. Some of the early changes in water levels at the Phase I sites were attributed to water leaving the infiltration beds either by leaking into the storm drain system at defective joints in drain pipes or possibly by escaping the infiltration beds through the rock bedding used for the pipes. The potential for water following the rock bedding of the drain pipes was eliminated during construction of the Phase II improvements by installation of concrete anti-seep collars at all critical locations. Leaks into the drain pipes were still an issue during early Phase II storm events at both the porous concrete and asphalt sites. Repairs could not be immediately addressed due to persistence of water within the two infiltration beds.

Water levels in the three Phase I porous paving infiltration beds tended to be undetectable after a period of one to two days. Water levels in the Phase I asphalt infiltration basin were found to drop at greater rate than the adjacent Phase I concrete infiltration basin despite a likely connection between the two beds where the Rates of decline in water levels at the Phase II porous paving sites were far less. Once leaks were corrected at the Phase II concrete site, water levels progressively increased over the season nearly discharging during two events. Water levels in the Phase II asphalt infiltration basin took 2-3 weeks following a large event or series of events to be undetectable in the basins.

6. *How does water quality and pollutant loading from building roofs compare to runoff from the parking lot reference area.*

Runoff from the roof reference site was characterized by very low concentrations of all contaminants of concern except for dissolved zinc. Concentrations of dissolved lead were an order of magnitude lower than measured in runoff from the Phase I and II parking lot reference sites. In comparison to the two parking lot reference areas, mean concentrations of both total and dissolved copper where 50 to 80 percent lower in stormwater runoff coming from the roof reference site. Total zinc in roof runoff was approximately 20 to 50 percent of concentrations measured at the parking lot reference sites.

Zinc measured in the roof runoff was largely in the dissolved form. Roughly 70 percent of the total zinc found in roof runoff was dissolved. The median concentration of dissolved zinc in roof runoff was 57 µg/L which was about 50% of the median concentration measured at the Phase I parking lot reference area (101 µg/L) and equivalent to concentrations measured at the Phase II parking lot reference area (57 µg/L). In addition, the average hardness (8 mg/L as $CaCO_3$) of roof runoff was the lowest of the three reference areas. Rainwater is typically low in hardness.

Concentrations of phosphorous were between 33 percent and 50 percent of those measured at the two parking lot reference sites. Concentrations of total nitrogen in roof runoff (median = 0.75 mg/L) were similar to those measured at the Phase II parking lot reference area but less than half of the total nitrogen measured at the Phase I parking lot reference area.

7. *Is water infiltrating through soils underlying the infiltration basin and how does water quality change during the process of infiltration?*

Infiltration was not occurring below the Phase II concrete infiltration basin. Although water was obtained from the lysimeter, no water appeared to be getting past a hardpan located at the bottom of the lysimeter. The lack of substantial infiltration at the porous concrete site was associated with lower hardness values suggesting that the water was not picking up dissolved material from the soils and may have been short-circuiting from the rock basin to the lysimeter without passing through a substantial soil layer. In contrast, the lysimeter installed at the Phase II porous asphalt suggested that infiltration was occurring although rates were slow. The progressively increasing hardness levels at the asphalt lysimeter and decreasing hardness at the concrete lysimeter support this argument.

The quality of water extracted from the two lysimeters was very different at the two sites and appeared to exhibit very different trends over time. Due to the limited data, caution is necessary in the interpretation of any apparent trends. The hardness of water extracted from the asphalt lysimeters was initially 17 mg/L but increased to 840 and 930 mg/L during the latter two events. The hardness of water from the concrete lysimeters decreased over time. Water from the first storm event at the concrete lysimeter had a hardness concentration of 55 mg/L. By the last event, hardness had dropped to 11 mg/L.

COD, DOC and nutrients were only analyzed in water from the concrete lysimeter since adequate volumes to perform all analyses could not be obtained from the asphalt lysimeter within the 48-hour sampling period. Both COD and DOC measured in water from the concrete lysimeter also declined from the levels measured during the first event but were generally consistent with concentrations measured at the Phase II parking lot reference site. The concentrations of nitrate-N in water from the concrete lysimeter was low (<0.9 mg/L in all cases) and also showed a tendency to decline over time.

The four trace metals analyzed in water from the two lysimeters did not all follow similar patterns. With the exception of total cadmium measured in water from the asphalt lysimeter (0.24 µg/L), concentrations of both total and dissolved cadmium were detected at concentrations below reporting limits at both sites during the three storms. Total and dissolved copper concentrations were similar at both sites although concentrations were more variable in water from the asphalt lysimeter. Lead was the only metal that showed evidence of substantial differences between sites. Dissolved lead in water from the asphalt lysimeter was always detected below reporting limits (0.066J to 0.074J µg/L). Dissolved lead measured in water from the concrete lysimeter was roughly an order of magnitude greater (0.64 to 2.2 µg/L). This large difference may be related to the differential infiltration properties at these two sites. Infiltrating water from both sites contained extremely low levels of total zinc (2.5 to 9J+ µg/L) and dissolved zinc (1.8 to 11J µg/L). Concentrations of zinc measured in water from the parking lot reference sites and effluent from the four filtration systems at the treatment train were consistently in excess of water quality criteria. Thus it appears the infiltration process at the asphalt site effectively reduced lead and zinc concentrations but only zinc was reduced in concentration at concrete site.

TREATMENT TRAIN

The program is designed to address the following questions:

1. *What is the total volume of stormwater processed by the CDS unit for the monitoring event and for the season?*

A total of 310,624 cubic feet (8,796,000 liters or 7.1 acre-feet) of stormwater was treated by the CDS unit during the 2006/2007 season. This represented 95.4 percent of the runoff from resulting from 4.5 inches of rain. With annual rainfall increasing to 7.7 inches during the 2007/2008 season, the CDS unit treated 696,695 cubic feet (19,728,000 liters or 16 acre-feet) of stormwater. This was 99.5 percent of the total runoff from the County Operations Center for the 2007/2008 storm season. The difference in the percent of stormwater treated in each wet season is related to differential frequencies of rainfall intensity. High intensity rain events cause flows to exceed the 7.0 cfs limit of the bypass weir.

2. *What are the mass and general characteristics of solids removed by the CDS unit at the end of the monitoring period?*

Visual estimates during the sump cleanout process indicated that the material consisted primarily of fine sediments. Of the roughly 94 cubic feet of material found in the CDS sump, floating materials were estimated at less than 1 cubic foot. Only 1.6 percent of the sump material was considered gross pollutants thus 98.4 of the sump material was classified as sediment.

The general physical characteristics of the solids were compared with results of sampling the CDS sump at the end of the 2005/2006 season. This year sediment removed from the sump was predominantly fine material consisting of 52.7 percent clay and 13.2 percent silt sized particles. This is in sharp contrast to material removed from the CDS sump in the first survey. At that time, sediment removed from the sump consisted of 97.3 percent sand and gravel. The reason for these large differences in sump sediment characteristics can be attributed to sediment discharged from the ME construction site both during and between storm events. The site required frequent dewatering starting in January 2008 in order to minimize uncontrolled discharges during storm events.

3. *What is the mass of each target pollutant in the sediment portion of the solids removed by the CDS unit?*

Sediments from the CDS sump contained 550 grams of phosphorous, 450 grams Kg of oil and grease, 74 grams of TKN, and 40 grams of ammonia-N. Both phosphorous and nitrogen (TKN) loads were well below levels measured in the 2005/2006 study despite the nearly 4.5 times increase in sediment load. Zinc remained the most abundant metal present in the sump sediments with 136 grams. Total masses of copper, lead and cadmium were estimated at 33, 28 and 0.2 grams, respectively.

4. *What are the volume and pollutant loads entering each filtration unit and the volume and pollutant loads after treatment.*

Water volumes and pollutant loads were assessed separately for the Phase I and II treatment train configurations. The volume of water entering, bypassing and being fully treated by the Phase I MFS2 was accurately quantified during eight events between January and April 2007. During this time a total of 112,142 cubic feet (3,175,507 liters) of stormwater entered the MFS unit after receiving initial treatment by the CDS unit. Sixty-eight percent of this water was effectively treated. The vendor installed a modified collection box and gate valve assembly designed allow the system to reach its rated capacity of 1.75 cfs but the actual capacity remained similar to observed during the Phase I monitoring conducted during the 2005/2006 wet season. Flow through the filters was limited to less than half the design capacity before water started discharging through the internal bypass.

Statistical analysis of the influent and treated effluent data from the MFS unit (MFS2) indicated that the system resulted in statistically significant reductions in solids (SSC and TSS), COD, total copper, total lead and total zinc. Statistically significant increases were noted for dissolved nutrients (orthophosphate-P, ammonia-N and nitrate-N). Closer graphical examination and linear regression of the effluent and influent data demonstrated that the Phase I MFS2 unit efficiently removed of total SSC, fine SSC, coarse SSC and TSS over the ranges encountered at the treatment train. Although removal of total copper, lead and zinc was statistically significant, only lead showed evidence of substantial improvements in the final effluent. The regression suggested that effluent concentrations were roughly 55% of influent concentrations. Given the strong tendency for lead to associate with fine particulates, it was not surprising to see effective treatment by a filtration BMP.

As with the low but statistically significant removal of total copper and zinc, the increases in soluble nutrients were minor (10-20 percent) and occurred at low concentrations. Neither the small increases in dissolved nutrients nor the small decreases in total metals should be considered characteristic of this BMP at ranges outside the relatively low loading rates experienced at this site.

5. Does the treated stormwater meet receiving water quality standards?

Final effluent from the treatment train was examined for the two configurations employed during the study. The Phase I configuration consisted of the CDS unit and one MFS unit (MFS2) with perlite media in the filter cartridges. During this period, the MFS unit was installed with an internal bypass to prevent exceeding the design flow capacity of the filter cartridges. Final effluent was compared against water quality standards for the treated stormwater only. Over the wet season, the MFS unit treated 68 percent of the water entering the unit therefore roughly 1/3 of the water passed through without treatment. Although this system was intended to treat all water up to a rate of 1.75 cfs, it was only able to treat roughly 0.6 cfs to 0.8 cfs before water would go through the internal bypass.

The Phase II treatment train configuration consisted of the CDS unit and four filtration units one of which (MFS2) was determined to be nonfunctioning upon a post-season survey conducted by the vendor. This was due to improper installation of the filter cartridges. The inspection determined that the antiflotation beams designed to hold the filters in place had not been securely attached.

Construction activities being performed during the Phase II monitoring clearly had an impact on sediment loading. Sediment in the Phase I final effluent was reduced to less than 17 mg/L. In contrast, sediment in Phase II final effluent from all functioning filter systems averaged 70 mg/L. The higher concentrations of solids in the Phase II filtration systems reflects the increased sediment loads from the reference area, runoff from the ME building construction site, and dewatering of the construction site between events.

All final effluent from functioning filtration systems met the available reference criteria for TSS, COD, total phosphorus, and nitrate during both the Phase I and II testing. Sediment in effluent from the MFS2 filtration unit matched the comparison criteria of 100 mg/L during one event but no filters were functioning in the unit.

There was no evidence of substantial removal of dissolved metals by the filtration units under both the Phase I and II treatment train configurations. Although dissolved metals were generally lower in effluent from Phase II filtration systems, the influent concentrations were also lower than previously encountered. Higher levels of solids dominated by the fine clay fraction (less than 2 microns) are likely to have impacted the partitioning of total and dissolved metals. At the same time, the increased loads of fine clay would also be expected to have had a substantial negative impact on the performance of the filtration media.

Concentrations of dissolved copper and zinc remained elevated and exceeded the water quality criteria used as benchmarks. The extremely low hardness of the final effluent (averages of 15-21 mg/L) during both Phase I and II resulted in very low water quality criteria for dissolved metals. Dissolved copper and zinc commonly exceeded the acute water quality criteria for effluent from both the Phase I and II treatment train configurations based upon these hardness levels. Total hardness in the San Diego River receiving waters are typically 400 mg/L or greater. If one were to very conservatively evaluate dissolved metal water quality exceedances of all effluent data at a hardness of 100 mg/L, none of the Phase II effluent (including effluent from the nonfunctional MFS2 site) would have exceeded the criteria. Seventy-five (75) percent of the dissolved copper and zinc measurements in the Phase I configuration would still have exceeded the water quality criteria.

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