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THE EFFECTIVENESS OF PERMANENT HIGHWAY RUNOFF CONTROLS: SEDIMENTATION/FILTRATION SYSTEMS

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16. Abstract

This study evaluates the performance of sedimentation/filtration systems that are the most common control for treating highway runoff in the Edwards Aquifer recharge zone. The study includes: 1) monitoring and evaluating the Seton Pond sedimentation/filtration facility in Austin, Texas, and 2) evaluating the factors that affect sedimentation in a prototype detention basin.

Results from the Seton Pond facility show that sedimentation/filtration is an excellent form of treatment for runoff captured in the system; however, the poor hydraulic performance of the sand filter reduces the facility's capture capacity and increases the quantity of untreated runoff that bypasses the system. Results from the prototype experiments show that detention time is more important than outlet design for achieving satisfactory removal of constituents in runoff. Treatment by sedimentation alone is comparable to sedimentation/filtration when adequate and consistent detention times are achieved.

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SUMMARY

Concern for the quality of highway and urban runoff recharging the Edwards Aquifer has prompted the state to adopt rules that require TxDOT to construct runoff treatment systems. The observed performance of these systems indicates a need for improved design guidelines and enhanced management practices. This study evaluates the performance of sedimentation/filtration systems, which are the most common control for treating stormwater runoff in the Austin, Texas, area. The study includes: 1) monitoring and evaluating the Seton Pond sedimentation/filtration facility in Austin, Texas and 2) evaluating the factors that affect sedimentation in a prototype detention basin.

Results from the Seton Pond facility show that sedimentation/filtration is an excellent form of treatment for runoff captured in the system; however, the poor hydraulic performance of the sand filter reduces the facility's capture capacity and increases the quantity of untreated runoff that bypasses the system. Frequent maintenance is required for proper hydraulic operation of the sand filter. Results from the prototype experiments show that detention time is more important than outlet design for achieving satisfactory removal of constituents in runoff. Treatment by sedimentation alone is comparable to sedimentation/filtration when adequate and consistent detention times are achieved.

1. INTRODUCTION

1.1. Background and Significance of Work

Concern for the environmental impact of highway runoff in the Edwards Aquifer recharge zone has prompted the state to adopt rules requiring treatment of highway and urban stormwater runoff. Moreover, a satisfactory state stormwater management program is required to obtain a National Pollutant Discharge Elimination System (NPDES) permit from the United States Environmental Protection Agency (USEPA). The management program consists of identifying structural and nonstructural runoff controls that reduce the impact of runoff constituents on the quality of receiving waters. Runoff controls constructed by the Texas Department of Transportation (TxDOT) and presently operating in the Austin area include sedimentation/filtration systems, vegetative controls, and hazardous material traps. The observed performance of the runoff control systems demonstrates a need for improved design guidelines and maintenance procedures.

The purpose of this research is to evaluate the effectiveness of sedimentation/filtration systems for the treatment of highway runoff. This evaluation will assist TxDOT in implementing a cost-effective and efficient program for managing stormwater runoff from highways. The observed removal efficiencies reported in this document provide a basis for determining the best management practice (BMP) for existing and future runoff control sites. Identifying BMPs will enable TxDOT not only to reduce the environmental impact of the constituents in highway runoff, but also to comply with NPDES permit requirements.

1.2. Objectives

The study consists of two parts: (1) monitoring and evaluating the performance of a sedimentation/filtration facility (Seton Pond) and (2) evaluating the effectiveness of sedimentation in a prototype-scale detention basin. The Seton Pond facility is an off-line facility that incorporates a dry extended detention basin and a horizontal bed (vertical flow) sand filter. Highway runoff from US 183 enters the pond and is discharged after treatment into a tributary of Walnut Creek. The objectives for the field analysis include:

- evaluation of the hydraulic performance of the facility,
- determination of the removal efficiencies for sedimentation and sedimentation/filtration, and
- recommendation of a maintenance schedule and maintenance procedures for the facility.

The experiments performed in a prototype-scale sedimentation basin at the Center for Research in Water Resources (CRWR) of The University of Texas at Austin included:

- sedimentation in a controlled environment,
- evaluation of the factors that affect removal of the constituents in highway runoff, and
- evaluation of sedimentation as an alternative to sedimentation/filtration.

The construction of the basin was funded by TxDOT in order to pilot test new runoff treatment technologies.

2. LITERATURE REVIEW

Each runoff treatment facility has unique features that distinguish one system from others. This review provides background information and presents a perspective on the performance capabilities of detention ponds and sand filters. A comprehensive review of literature pertaining to permanent runoff controls was compiled by Barrett et al. (1995a).

2.1. Extended Detention Ponds

Extended dry detention ponds can effectively and inexpensively treat highway runoff (Schueler 1987). The primary purpose of a dry detention pond is to control the peak flow associated with the runoff from a watershed. Reduction in the rate of flow can limit the frequency of occurrence of erosion, thereby reducing the sediment load to the receiving waters. The secondary purpose of the pond is to temporarily store runoff to allow the removal of particulate material by settling. The treatment efficiencies typically are low because the outlet structures are designed to control the peak discharge from the watershed, so there is a relatively short residence time in the control.

The length of detention time for a particular runoff event is dependent on the size and intensity of the storm. Reducing the peak flow may not be necessary for many small storms and a detention time of only 1 to 2 hours is achieved. The ideal detention time for pollutant removal is 24 hours, with a minimum of 6 to 12 hours (Schueler 1987). Storage of runoff for at least 24 hours may reduce the concentration of particulate materials by 90% or more. The detention pond should drain in 24 to 36 hours in order to sustain a grassy bottom cover (Stahre and Urbonas 1990). Outflow structures, which significantly reduce flow through a system, are required to achieve adequate detention times. Common outflow structures include fixed-orifice discharge pipes or vertical perforated risers.

Detention ponds are most effective in the removal of particulate constituents and the associated materials that are sorbed to the suspended solids (Schueler et al. 1992). Detention ponds are less effective in removing the soluble components of runoff, such as nitrate and some phosphorus species. Soluble constituents are more effectively removed in a wet pond containing algae and aquatic plants that take up soluble nutrients.

Dry extended detention ponds have the highest maintenance requirements of all pond runoff control systems (Schueler et al. 1992). Routine maintenance includes removing trash and debris, mowing, unclogging the outlet control device, and removing accumulated sediment from the floor of the pond. Yearly costs associated with pond maintenance are estimated at 3–5% of the construction costs. Schueler et al. (1992) also observed that poorly maintained ponds may be a nuisance to the surrounding community.

Dry detention ponds are effective substitutes for wet detention ponds where the removal of soluble constituents is not a concern (Dorman et al. 1996). Observed removal of total suspended solids (TSS's), BOD, total phosphorus, TKN, and trace metals were 80–90%, 20–30%, 20–30%, 20–30%, and 40–80%, respectively, after 12 hours of storage. Compared with wet ponds, dry ponds have the advantages of less volume and lower construction costs. However, these advantages are insignificant in circumstances where removal of soluble constituents is important. Biological processes and other reactions that occur in wet ponds enhance the removal of soluble constituents of the runoff (Dorman et al. 1996).

Dorman et al. (1988) observed low or negative removals for certain constituents in dry detention basins. The poor performance was attributed to insufficient time to settle out smaller particles and the resuspension of sediment that was removed from runoff from previous storms.

A summary of performance data for dry detention ponds in North Carolina, Maryland, Virginia, Texas, and Kansas is presented in Table 2-1. Direct comparison of these data is not possible given that the watershed area, drainage time, number of storms monitored, pond design, and removal efficiency techniques differed for each study. However, the information presented in Table 2-1 provides an example of the variability of removal performance by dry extended detention ponds.

Table 2-1 Removal Efficiencies for Seven Dry Detention Ponds (%) (after Stanley 1996)

Detention Pond	TSS	TOC	TN	NO3-N	TP	Pb	Zn
Lakeridge, Virginia	14	-	10	9	20	-	-10
London, Virginia	29	-	25	-	40	39	24
Stedwick, Maryland	70	-	24	-	13	62	57
Maple Run, Austin, Texas	30	30	35	52	18	29	-38
Oakhampton, Baltimore, Maryland	87	-	-	-10	26	-	-
Lawrence, Kansas	3	-3	-	20	19	66	65
Greenville, North Carolina	71	10	26	-2	14	55	26

Adequate removal of some constituents in highway runoff occurs in extended detention ponds; however, there are uncertainties in overall performance and design. Chronic clogging of the outlet structure affects long-term removal capacity. A clog causes runoff to remain in the pond and reduces the capacity of the pond to capture subsequent runoff events. Another problem with extended detention ponds is designing the capture volume and outlet structure to meet recommended detention times for acceptable pollutant removal. Ponds must provide a consistent and effective detention time for a wide variety of storm volumes to be an effective form of treatment. Sizing the capture volume outflow structure to prevent erosion of downstream channels is another important detail that complicates the design of ponds (Schueler et al. 1992).

2.2. Sand Filters

Sand filters are a relatively new technology for the treatment of stormwater runoff (Schueler et al. 1992). Sand filters consist of a horizontal bed of sand and a gravel underdrain containing a network of perforated drainage pipes. Runoff first passes through the sand media, where solids are removed. The treated runoff then flows through the underdrain system and discharges into receiving waters. Sand filters can be installed on-line or off-line. Off-line systems are more effective because the volume of runoff with the highest concentrations of constituents, the first flush, is captured, and the excess runoff is bypassed. On-line systems do not include a bypass feature; that is, the total volume from a runoff event enters the sand filter. The first flush can be displaced from the filter by the cleaner runoff occurring later in the runoff event (when the total volume exceeds the capture capacity of the filter).

Removal of particulates is achieved by sedimentation onto the surface of the sand filter and by trapping the particulate in the sand medium. Sand filters efficiently remove suspended solids and associated metals; however, organics, nutrients, and fecal coliform are removed to a lesser extent (Schueler et al. 1992). Nutrient removal can be enhanced by a cover crop that is planted on the surface of the bed. Sand filters are used extensively for runoff treatment only in Austin, Texas. Average removal efficiencies observed for three Austin-area filters were 85% for TSS's, 35% for nitrogen, 40% for dissolved phosphorus, 40% for fecal coliform, and 50–70% for trace metals (City of Austin 1990).

Cost and maintenance are two disadvantages associated with sand filters (Schueler et al. 1992). Construction costs range from $100 to $350 per cubic meter of runoff treated. While sand filters cost 2–3 times as much as infiltration trenches, they are cheaper to maintain over time. Sand filters also require frequent maintenance for satisfactory operation. The top 8–15 cm of sand and accumulated sediment must be removed from the sand filter when long drainage times begin to affect the capture volume of the system. The maintenance frequency has ranged from 1 month to 1 year, depending on the site (Schueler et al. 1992). Maintenance costs are estimated at 5% of the construction cost per year.

The Lake Jackson sedimentation/filtration facility that was constructed in 1983 in Tallahassee, Florida, collects runoff from a 6,700 ha urban watershed. The facility consists of a 1.8 ha sand filter within a 163,000 m^3 wet detention basin. After treatment by sedimentation and filtration, the runoff is pumped to an artificial marsh for nutrient removal (LaRock 1988). The system was efficient in removing solids, total phosphorus, and total nitrogen. The average removals were 97% for TSS's and approximately 60%

for phosphorus and total nitrogen during a 4-year period. Nitrate concentration increased, indicating possible nitrification.

The design and watershed size of the Lake Tohopekaliga site in Florida were similar to those of the Seton Pond facility in Austin, Texas. The watershed area consisted of mixed commercial and residential use and covered 49 ha. The system included a dry detention pond and a sand filter. A TSS removal of 81% and a total phosphorus removal of 85% were observed by sedimentation/filtration (Harper and Herr 1993). A reduction of approximately 33% in phosphorus concentration occurred in the filter, while the remainder was removed by settling and plant uptake (Harper and Herr 1993). Although the filter clogged with sediment within a few months of operation, the system functioned well enough to obtain performance data for six storms in the year that monitoring was conducted.

A Delaware sand filter best management practice (BMP) differs from the typical Austin filter in design (Bell et al. 1996). Rather than providing a wide filter bed, the Delaware filter includes a long, narrow filter chamber and an adjacent sedimentation chamber. Runoff enters the sedimentation chamber as sheet flow and collects until the chamber reaches capacity, at which point the runoff spills over into the filter chamber. A diagram of the Delaware filter is included in Appendix A.

The watershed for the Airpark site was a 0.69 ha commercial parking lot located adjacent to US Route 1 and south of the national airport in northern Virginia. The site was 95% impervious. Two filters were constructed to treat runoff from the site; however, the performance was monitored only for the south site. The system included a 22-m^2 sedimentation basin and a 22-m^2 sand filter. Twenty storms were sampled from April to September 1994 at the influent and effluent of the filtration system. Mass balance removal for the entire monitoring period indicated removal of TSS's and zinc was 80% and 90%, respectively. Most nitrogen and phosphorus species were removed in the range of 65–70%. The removal of nitrate was -63%. The hydraulic performance declined and runoff backed up into the parking lot early in the study. Apparently the flow restriction was caused by a woven silt fence that separated the filter medium from the outflow grate.

The material was replaced with a geotechnical fabric that offered a higher permeability. Another improvement made to the system was the installation of a perforated underdrain system.

Welborn and Veenhuis (1987) evaluated an on-line sand filter system that collects runoff from a 32 ha site consisting of approximately 50% impervious cover. The sand bed contained three layers: 46 cm of fine sand in the top layer, 30 cm of coarse sand in the intermediate layer, and 15 cm of gravel with a perforated underdrain in the bottom layer. The facility was designed to capture the first 1.33 cm of runoff. Additional runoff is discharged over an emergency spillway. A total of twenty-two storms were monitored over a 2-year period. Average discharge rates declined over the course of the monitoring period, even though the filter was cleaned twice during the study. While cleaning did improve the drainage rate, it remained lower than the rates observed at the beginning of the study. Peak and average discharges declined noticeably after larger storms.

Average removals for TSS's, BOD, total phosphorus, TOC, COD, and zinc that were reported by Welborn and Veenhuis (1987) ranged between 60% and 80%. The influent concentrations of organic nitrogen plus ammonia nitrogen ranged from 0.3 mg/L to 7.8 mg/L, and the effluent concentrations of organic nitrogen plus ammonia nitrogen ranged from 0.3 mg/L to 3.7 mg/L. The influent concentrations of nitrate plus nitrite nitrogen were 0.1 mg/L to 1.2 mg/L, and increased to 0.2 mg/L to 5.5 mg/L from the influent to the effluent. Apparently nitrification also occurred in the system.

2.3. Summary

The results of the previous studies indicate that dry extended detention ponds and sand filters are viable options for treating highway runoff. Yet while these systems are effective in removing particulate material, a comparison of the results from different studies indicates considerable variability in performance, especially with detention ponds. Dissolved constituents are not efficiently removed unless vegetation is grown in the system. Frequent maintenance is required for ponds and filters to ensure that they maintain proper hydraulic operation. Maintenance is more crucial for sand filters because accumulated suspended solids tend to clog the filter.

System characteristics, performance capabilities, and maintenance of detention ponds and sand filters reported in the literature provided a basis for comparing the data observed in this study for a combination detention pond/sand filter system. The following are specific objectives for this study:

- An evaluation of a sedimentation/filtration system will be conducted to provide hydraulic performance and removal efficiency data that can be compared with previous studies.
- The effect of hydraulic performance on capture volume will be quantified.
- The extent to which removal performance is affected by a decline in hydraulic performance will be determined.
- Maintenance requirements and design guidelines will be recommended for optimum sedimentation/filtration system performance.
- Extended detention will be investigated as an alternative to sedimentation/filtration.
- An investigation will be conducted to determine the effect of outlet design and residence time on pollutant removal in a dry extended detention basin.

3. FIELD MONITORING AND EVALUATION

3.1. Introduction

The Seton Pond sedimentation/filtration facility, constructed by the Texas Department of Transportation (TxDOT) and operated by the City of Austin, collects and treats stormwater runoff from a nearby watershed. The area of the watershed is 33.6 ha and is made up of a section of US Highway 183 extending from Capital of Texas Highway to Balcones Woods Drive, including the frontage roads and the adjacent commercial development. A site description, a hydraulic analysis, and a performance evaluation of the Seton Pond facility are discussed below. The objectives of the sedimentation/filtration study include the following:

1) Determination of the removal efficiency of several constituents commonly found in highway runoff
2) Evaluation of the capacity of the sedimentation/filtration facility to capture runoff
3) Determination of the effectiveness of sedimentation alone
4) Evaluation of the maintenance and operational requirements of a sedimentation/filtration facility

3.2. Site Description

The sedimentation/filtration system at the Seton Pond facility includes four major components: an influent channel, a hazardous materials trap (HMT), a sedimentation basin, and a sand filter. A plan view of the facility is shown in Figure 3-1. A picture of Seton Pond is presented in Figure 3-2.

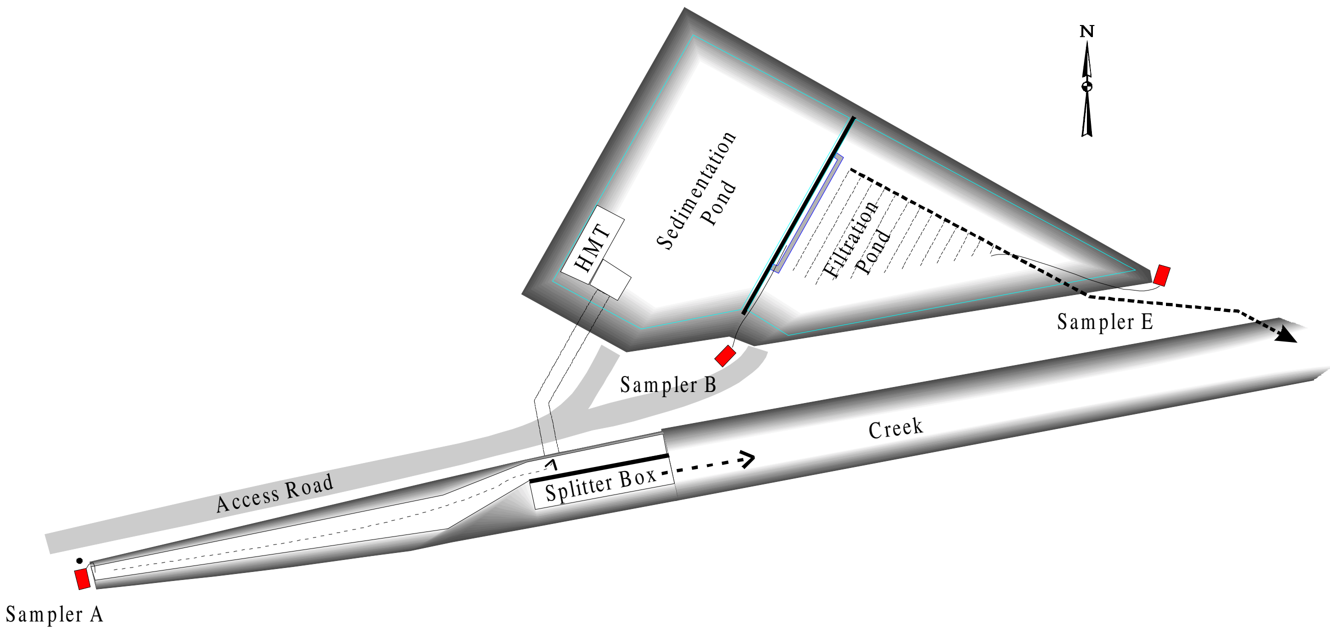


Figure 3-1 The Seton Pond Sedimentation/Filtration Facility: Plan View

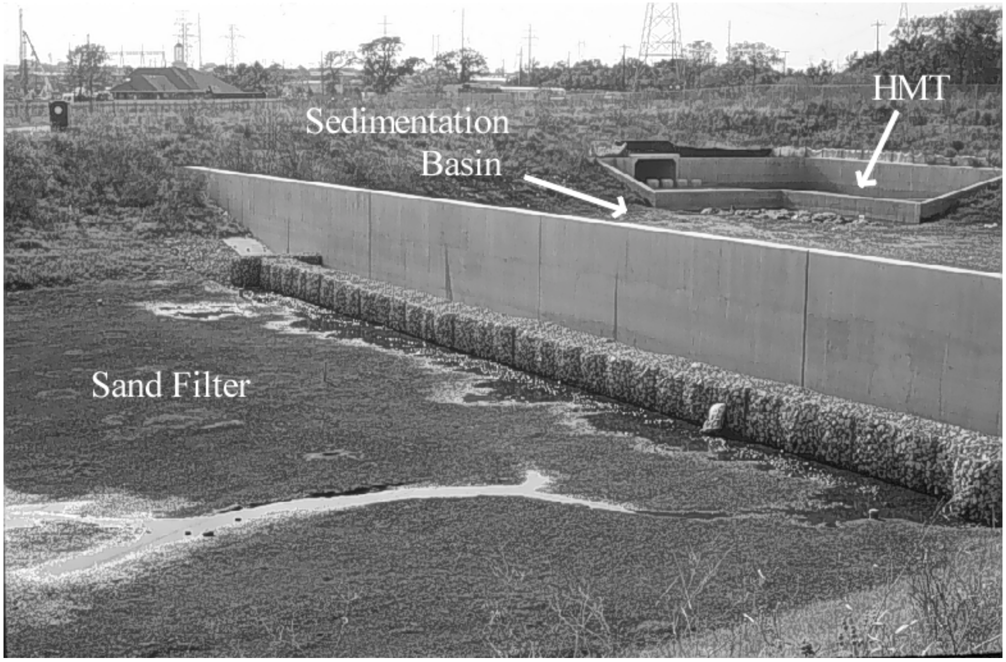


Figure 3-2 Seton Pond Sedimentation/Filtration Facility

3.2.1. Influent Channel

The influent channel delivers runoff from the watershed drainage system to the sedimentation basin. Runoff is collected and transported by the watershed drainage system to a single box culvert. The box culvert discharges the runoff into the Seton Pond influent channel pictured in Figure 3-3. The channel has a slope of 0.003. Runoff flow is diverted to the sedimentation basin by a broad crested weir at the end of the channel. The runoff flows through a second box culvert and empties into the sedimentation basin.

A splitter box is located at the end of the influent channel on the opposite side of the broad crested weir (see Figure 3-4). The splitter box is an off-line feature designed to bypass excess runoff. Runoff flows over the weir to the creek when the sedimentation basin is filled to capacity. The top of the weir is 1.1 m above the floor of the channel and 2.4 m above the bottom of the basin.

Figure 3-3 Influent Channel with Sampler Box and Rain Gauge

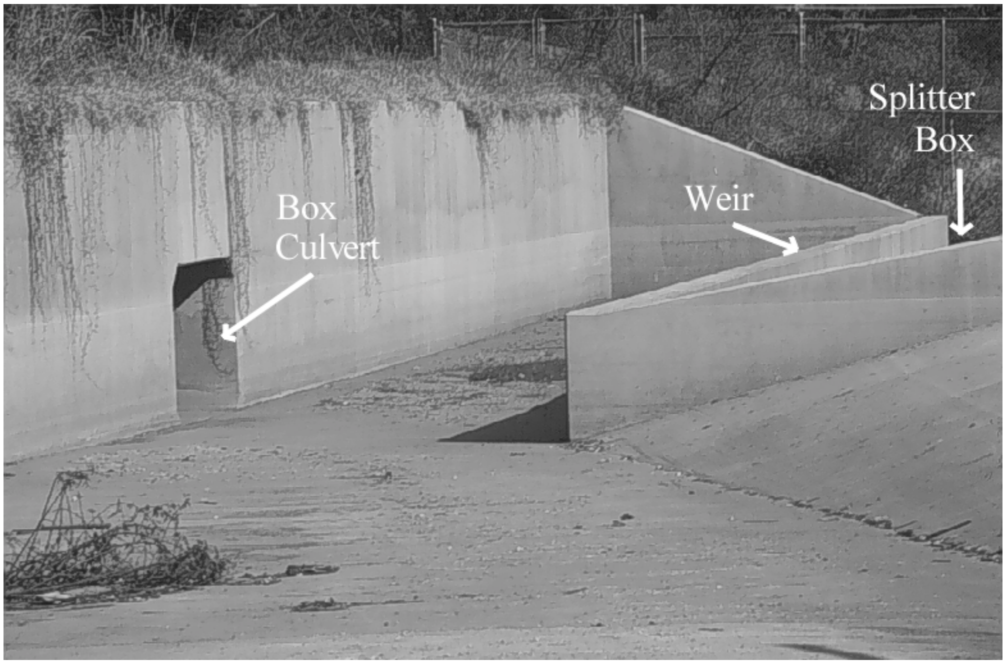


Figure 3-4 Influent Channel Splitter Box and Box Culvert

3.2.2. Hazardous Materials Trap

One major component of the sedimentation basin is the hazardous materials trap, or HMT. The HMT, located adjacent to the influent structure of the sedimentation basin, receives the first flow from the influent channel. The HMT is a 38-m^3 temporary storage basin that is designed to collect hazardous materials spilled on the highway. The hazardous liquid is stored in the HMT until personnel arrive at the facility to remove the material. The HMT is ineffective when the spill occurs during a storm event or during a time when the sedimentation basin and HMT are filled with runoff from a previous storm. Hazardous material will bypass the HMT and enter the sedimentation/filtration system under these two conditions. A picture of the HMT is presented in Figure 3-5.

Figure 3-5 Hazardous Materials Trap

3.2.3. Sedimentation Basin

The sedimentation basin, designed to capture the first 1.3 cm of runoff, has a capacity of 4,320 m^3. The basin is separated from the sand filter by a retaining wall that is 30 cm thick and 3 m high. The sedimentation basin is drained from a perforated riser pipe located at the center of the retaining wall. The pipe is corrugated metal having evenly spaced openings along its height. This structure drains a composite of runoff volume throughout the depth of the basin. Unlike other runoff controls, the sedimentation basin is off-line, i.e., runoff will bypass the system when the basin fills to capacity. Untreated runoff bypasses the system when the water depth in the basin reaches approximately 2.4 m. A picture of the sedimentation basin is displayed in Figure 3-2.

3.2.4. Sand Filter

Runoff from the sedimentation basin enters the sand filter through an 11 cm diameter hole at the base of the retaining wall and then through a rock gabion that distributes the flow and prevents erosion of the sand filter. The filter consists of three separate layers. The top layer contains 0.05–0.10 cm diameter washed sand at a depth of

45 cm. The second layer contains gravel that is separated from the sand layer by geotextile fabric. The gravel is 1.3–5.1 cm diameter washed gravel and serves as the underdrain medium. An impermeable, 30 cm clay liner, the third layer, was installed to prevent seepage into the groundwater. The area of the sand filter is approximately 825 m^2.

Thirteen perforated collection pipes (10 cm in diameter) are located in the gravel layer and span the width of the filter. These pipes collect the filter effluent and discharge the effluent into a 20 cm effluent pipe that runs the length of the filter bed, perpendicular to the perforated pipes; the effluent eventually empties into a creek. A picture of the Seton Pond sand filter is displayed in Figure 3-6.

3.3. Sampling Scheme

The removal efficiencies of runoff constituents by sedimentation and filtration were based on samples that were collected from the influent channel, the basin effluent, and the filter effluent.

Figure 3-6 Seton Pond Sand Filter

Automatic samplers were installed at three locations in the Seton Pond facility, namely, the influent channel (Sampler A), the sedimentation basin (Sampler B), and the sand filter (Sampler E). The specific sample locations are shown in Figure 3-2. The samplers at all three locations were ISCO 3700 samplers. The following lists sampling locations, sampling schemes, and sampling times:

- Sampler A: Samples were drawn in the first box culvert, approximately 2 m from the outlet. The sampler holds twenty-four 350 mL bottles, with each sample comprising four bottles. Samples were drawn at 15 minutes, 45 minutes, 75 minutes, 135 minutes, and 195 minutes after the flow depth in the channel reached a depth of 2.5 cm. A second program, which drew six samples at 60-minute intervals, was initiated if the storm exceeded the initial sampling period.
- Sampler B: Samples were drawn from an effluent pipe connected to the throttle hole in the retaining wall. Sampler B also held twenty-four 350 mL bottles, with each sample comprising four bottles. Samples were drawn at 5 minutes, 2 hours, 4 hours, 10 hours, and 16 hours after the sampler was activated.
- Sampler E: Samples were drawn from the 20 cm discharge pipe in the underdrain of the filter. The sampler held four 3,500 mL bottles, with each bottle representing a single sample. Samples were drawn at 24-hour intervals.

3.4. Flow Measurement and Hydraulic Analysis

An ISCO 3230 Bubbler Flow Meter was installed at each sampling location to measure and record flow at given time intervals. Flow measurements were used to assign a particular volume of runoff to each sample. The following sections describe the methods used to measure flow and designate influent, basin effluent, and filter effluent sample volumes for each storm.

3.4.1. Influent Channel

Flow Measurement

A flow meter was used to measure and record the flow in the influent channel. The bubbler was placed approximately 2 m from the end of the culvert. The flow meter was programmed to convert water depth to flow rate using Manning's equation. The parameters for the equation, width, slope, and roughness of the channel were also entered into the flow meter. The depth of water in the influent channel was converted to flow rate and recorded every 5 minutes.

The following is the equation describing rectangular open-channel flow in the influent channel:

$$Q_{in} = \frac{1}{n} hwR^{2/3} S^{1/2} \tag{3-1}$$

where

Q_{in}	=	the influent flow in the channel (m^3/s),
n	=	the channel roughness, 0.013,
h	=	measured height of flow (m),
w	=	width of the channel, 2.75 m,
R	=	hydraulic radius (m), and
S	=	the channel slope, 0.00078.

Influent Sample Volumes

The volumes assigned to the influent samples were based on time. For any sample *i*, the time at which that sample was taken was t_i and the sample times before and after were t_{i-1} and t_{i+1}, respectively. The time increment of flow assigned to *i* began at $\frac{t_{i-1}+t_i}{2}$ and ended at $\frac{t_i+t_{i+1}}{2}$. Flow was measured every 5 minutes during the time increment and converted to volume. The total volume of runoff assigned to a sample was the summation of the volume measured every 5 minutes from $\frac{t_{i-1}+t_i}{2}$ to $\frac{t_i+t_{i+1}}{2}$. An illustrated example of a time increment of flow assigned to an influent sample is presented in Figure 3-7..

Two exceptions to the previously defined time increment of flow were the first and last samples of the runoff event. The time increment for the first sample, t_1, began when flow was first detected in the channel and ended at time $\frac{t_1 + t_2}{2}$. The influent sampler was activated at a water depth of approximately 2.5 cm. The time increment for the final sample, t_f, began at $\frac{t_{i-1} + t_i}{2}$ and ended at either the time of last detectable flow or when a new runoff event entered the channel.

3.4.2. Sedimentation Basin

Volume Measurement

A flow meter was installed in the sedimentation basin for measuring and recording depth of water over time. The bubbler for the sedimentation basin was placed at the base of the retaining wall separating the basin from the sand filter. The depth of water in the basin initially was measured at 5-minute increments; this time interval was increased to 10 minutes as the drainage times increased.

An equation was developed for describing the volume of water as a function of water depth in the basin. The equation is:

$$V_{Sample} = -65.262\left(h^3\right) + 568.9\left(h^2\right) - 511\left(h\right) \qquad (3\text{-}2)$$

where

V_{Sample} = volume associated with basin sample (m^3), and
h = water depth in the basin (m).

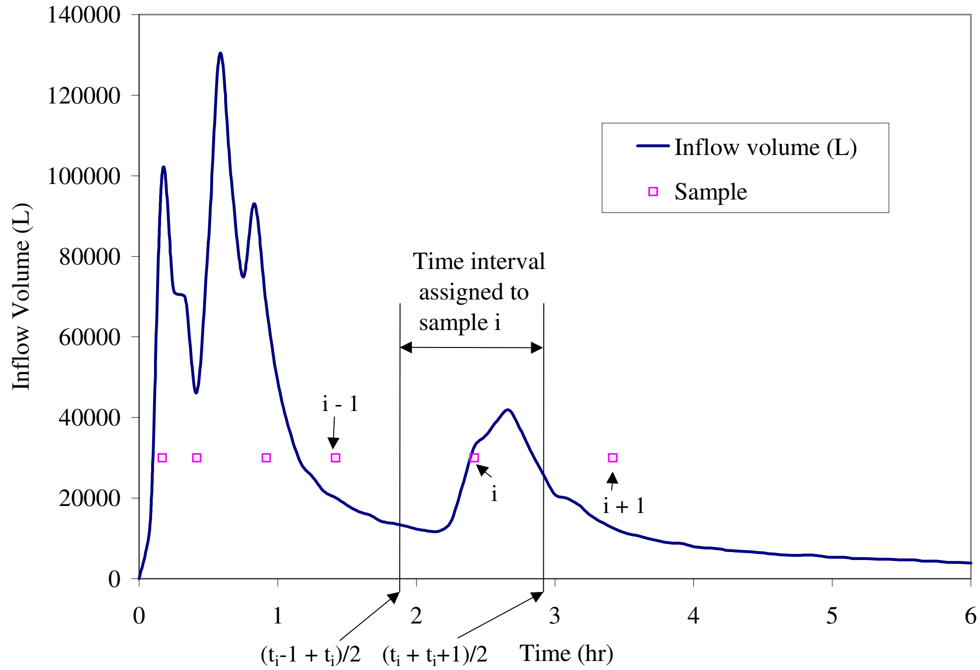


Figure 3-7 An Example of Flow Assigned to an Influent Sample

The total volume of runoff could be calculated by measuring the maximum water depth achieved during the rainfall event. Occasionally, the system was not drained completely and a subsequent runoff event refilled the basin. In these cases, both runoff events were considered part of one storm. The additional runoff volume from the second event was the difference in the volume at the time the event began and the volume at the subsequent maximum depth.

It was assumed that the effluent flow from the sedimentation basin was negligible during the time the basin was filling compared to the total volume of runoff collected in the basin. The effluent flow was negligible only under two conditions: 1) the basin was filled within 2 to 3 hours, and 2) the runoff depth was approximately 1.5 m or less, whereby the hydraulic head did not create significant effluent flow.

The effluent flow as the basin was filling was calculated in cases where the discharge rates were not negligible. Flow was calculated by deriving a relationship between basin height, h, and effluent flow, Q_{eff} , from the basin. The height-volume relationships for storms where effluent flow was not negligible are presented in Table 3-2. These relationships were developed by plotting the effluent flow as a function of depth in the basin. Least squares analyses defined the line of best fit. Exponential and polynomial equations provided the best representation of the data plotted.

Table 3-1 Effluent Flow versus Runoff Depth

Storm Date	Effluent Flow (Q_{eff}) versus Height (h) Equation	R^2 Value
4/22/96	$Q_{eff} = 0.1191*\exp(4.9768*h)$	0.991
8/22/96	$Q_{eff} = 0.0833*\exp(2.6345*h)$	0.975
8/29/96	$Q_{eff} = 29.243(h^4) – 152.8(h^3) + 289.27(h^2) – 230.71(h) + 74.096$	0.999
12/15/96	$Q_{eff} = 13.054(h^3) – 38.589(h^2) + 39.924(h) - 11.89$	0.999

The effluent flows for various depths were calculated using an analysis of basin and influent flow data. A flow balance on the sedimentation basin yields:

$$Q_{eff} = Q_{in} - \frac{\Delta V_{Basin}}{\Delta t} \quad (3\text{-}3)$$

where

Q_{in} = measured flow entering the sedimentation basin (L/s),

V_{Basin} = the volume of runoff in the basin at time *t* (L), and

t = time (s).

Effluent flow data were obtained by using two approaches. In the first approach, the effluent flow, Q_{eff}, was determined when $Q_{in} = 0$, at which times $Q_{eff} = -\frac{\Delta V_{Basin}}{\Delta t}$. The change in volume over time was determined by calculating change in depth over 1-hour intervals during a draining period. The difference in the volume at the beginning and the end of the interval was divided by the time interval to yield Q_{eff} for that depth.

The second approach was based on the premise that when $\frac{\Delta V_{Basin}}{\Delta t} = 0$, $Q_{eff} = Q_{in}$. This condition occurred in the transition from filling to draining and was signified by a gradual peak on the basin hydrograph. A gradual peak was when the maximum depth was sustained for approximately 30 minutes or more, and steady state conditions could be assumed. At steady state, $\frac{\Delta V_{Basin}}{\Delta t} = 0$, therefore $Q_{eff} = Q_{in}$, the flow recorded at the influent channel.

A least squares analysis was used to determine a best fit for the data obtained from the two approaches. An equation was derived describing Q_{eff} as a function of height (Table 3-1) and was used to calculate the effluent flow during the filling of the basin. A typical curve for Q_{eff} versus height is presented in Figure 3-8.

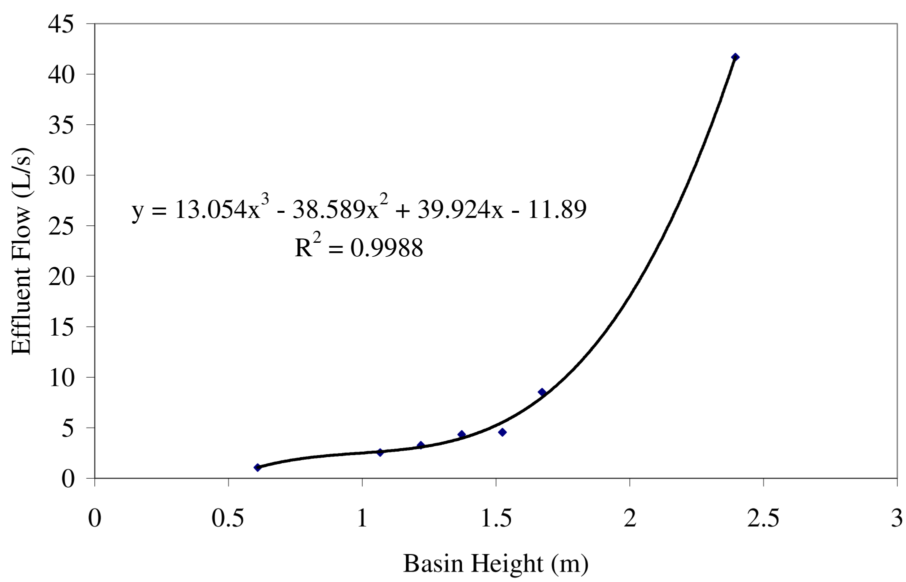


Figure 3-8 Basin Effluent Flow versus Basin Height

Basin Sample Volumes

The runoff volume assigned to a sample in the basin was calculated in a similar manner. For a sample taken at time t_i, the basin volume at $\frac{t_{i-1}+t_i}{2}$ and $\frac{t_i+t_{i+1}}{2}$ were calculated. The runoff volume assigned to sample *i* was the difference of the two volumes, or the volume of runoff that drained from the basin from time $\frac{t_{i-1}+t_i}{2}$ to time $\frac{t_i+t_{i+1}}{2}$. The volume assigned to sample i, is described by the following equation:

$$V_i = V\left(\frac{t_{i-1}+t_i}{2}\right) - V\left(\frac{t_i+t_{i+1}}{2}\right) \qquad (3\text{-}4)$$

An illustrated example of a volume assignment to a basin sample is presented below in Figure 3-9.

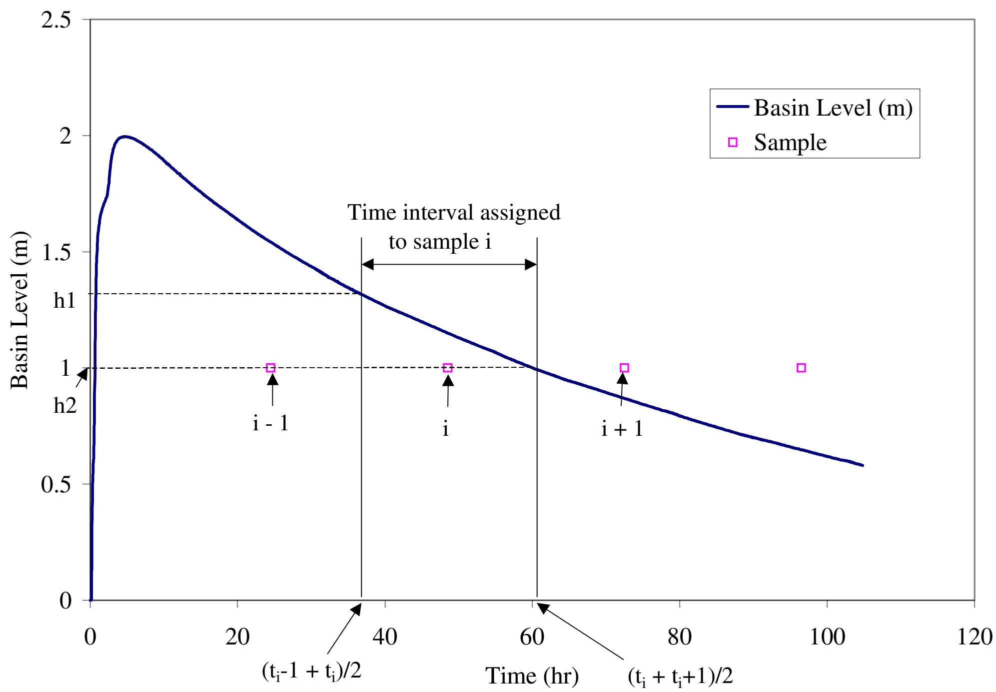


Figure 3-9 An Example of Volume Assigned to a Basin Sample

The time increment for the first sample of a storm event began at the maximum level obtained in the initial filling of the basin. The time increment for the final sample ended when the basin was completely drained or when the basin was nearly drained and a new runoff event refilled the basin.

The time increment for a basin sample had to be adjusted under certain circumstances. If the basin refilled between $\frac{t_{i-1}+t_i}{2}$ and t_i, then the volume of Q_{eff} leaving the basin during refilling was assigned to sample *i*, and the time increment for sample $i-1$ ended when refilling began. However, if the basin refilled between t_i and $\frac{t_i+t_{i+1}}{2}$, then the volume was assigned to sample $i+1$, and the time increment for sample *i* ended when refilling began. The time increment was adjusted because a sample taken during or after refilling of the basin had constituent concentrations more representative of the new volume of runoff entering the basin than a sample taken before refilling.

3.4.3. Sand Filter

Originally, the volume in the sand filter was to be calculated by the same method as the volume in the sedimentation basin. However, the filter exceeded the design drainage time of 24 hours and required several days or weeks to drain. Consequently, runoff from separate rainfall events mixed in the filter, and it became impossible to distinguish between runoff generated from different events. Therefore, flow measurement data for separate rainfall events was discarded. Instead, a method was developed for determining the average constituent concentration in the effluent from the sand filter and applying the concentration to the total volume of runoff passing through the filter.

3.4.4. Volume Consistency

Three major factors affected the consistency of the volume measured at the influent and the sedimentation basin: 1) the accuracy of Manning's equation to describe the flow in the influent channel, 2) the accuracy of the volume/water depth relationship that was used to calculate the volume in the basin, and 3) the bypass of runoff when the depth in the basin was at the maximum level.

Channel versus Basin Volume Calculation

The source of inaccuracy in the influent flow measurement came from the conditions governing the use of the Manning's equation, which describes uniform, open-channel flow (Roberson and Crowe 1990). The runoff flow observed in the influent channel was not uniform; therefore, the inflow volume was adjusted.

The equation for basin volume as a function of depth was developed from a plan view of the facility. The calculated basin volume was compared with the calculated channel volume for each storm monitored in the study. The basin volume was approximately half of the channel volume for each storm.

A volume correction was necessary to achieve continuity. The equation for the volume in the basin was assumed to be a more accurate account of the total runoff than Manning's equation describing the flow rate in the influent channel. The slope of the influent channel was adjusted to 0.00078 to make the volume calculated at the channel and the basin consistent. This slope resulted in less than 11% difference in runoff volume between the channel and the basin.

The volume of runoff often exceeded the capture capacity of the sedimentation basin in the case of a large rainfall event and caused runoff to bypass the facility. Therefore, the flow measured at the inflow overestimated the actual volume of runoff captured by the basin. The difference in volume required that the recorded inflow volume be adjusted. A hydrograph was produced that showed inflow and water depth in the basin over time. During the time interval when the water depth in the basin was maintained at a level of 2.4 m, which is the maximum water depth in the basin, the influent rate of flow would bypass the system rather than enter the treatment facility. Therefore, the flow during that period had to be subtracted from the total influent volume measured for the event.

3.5. Removal Efficiency

The removal efficiency of the sedimentation/filtration facility was determined for each constituent analyzed. Methods of sample analysis, mass loads, and removal efficiency calculations are presented in this section. The mass loads were found at the influent channel, the basin effluent, and the final effluent. Removal efficiencies were calculated for the sedimentation alone and for a combination of sedimentation and filtration. The removal efficiencies were based on ten runoff events.

3.5.1. Sample Analysis

Samples were analyzed for the same constituents at the influent channel, sedimentation basin, and sand filter sampling locations. A list of the constituents analyzed, methods of analysis, holding times, and sample preservatives is presented in Table 3-2.

Table 3-2 Laboratory Analysis Methods

Constituent	Method Identification	Holding Times	Preservative
TSS	Std. Methods 18^{th} ed. 2540 B	7 days	None
Turbidity	Std. Methods 18^{th} ed. 2130 B	24 hours	None
COD	Std Methods 18^{th} ed. 5220 D	3 months	H_2SO_4
TOC	Std Methods 18^{th} ed. 5310 B	28 days	H_2SO_4
Nitrate	Std Methods 18^{th} ed. 4500-NO_3-D	24 hours	None
TKN	EPA 351.4	28 days	H_2SO_4
Phosphorus	EPA 365.3	28 days	H_2SO_4
Metals	ICP Method 6010	6 months	HNO_3

3.5.2. Influent Loading

The mass loading for each constituent was calculated at the influent to determine the composition of the highway runoff before treatment. Each influent sample was assigned to a fraction of the total runoff event. The loadings corresponding to each sample volume were summed to produce the total loading for the event. The following equation was used to calculate mass loading at the influent:

$$M = \left(\sum_{i=1}^{n} C_i V_i \right) * \frac{g}{1000mg} \qquad (3\text{-}5)$$

where

M = mass loading (g),

C_i = concentration of sample i (mg/L),

V_i = volume associated with sample i (L), and

n = total number of samples for storm i.

Because the runoff event outlasted the total sample time of the influent sampler in some cases, a fraction of the runoff volume was not sampled. In this situation, the average of the event mean concentrations (EMCs) for the previous runoff events was calculated and used to represent the unsampled volume. The load contained in the unsampled volume was added to the loading contained in the sampled volume to give the total influent load for that event.

3.5.3. Sedimentation Basin Loading and Removal

The calculations of mass loading at the effluent of the sedimentation basin were similar to the calculations for the influent loading. Sample volumes were calculated using Equation 3-4, and the total effluent loading from the sedimentation basin was calculated using Equation 3-5. The following is an equation for determining removal efficiency by sedimentation:

$$R = \left(1 - \frac{\sum_{i=1}^{n} \left(M_{Basin} \right)_i}{\sum_{i=1}^{n} \left(M_{Influent} \right)_i} \right) * 100\% \qquad (3\text{-}6)$$

where

R	=	removal efficiency by sedimentation (%),
$(M_{Basin})_i$	=	basin effluent mass loading for storm i (g),
$(M_{Influent})_i$	=	influent mass loading for storm i (g), and
n	=	total number of storms monitored.

In some cases, the draining time for a single runoff event outlasted the sampling period. Sample concentrations were estimated for the time beyond the sampling period to account for the unsampled volume. Plotting constituent concentrations as a function of time for each individual event and performing a least squares analysis to determine the line of best fit developed an equation. The equation then was used to forecast concentrations for the fraction of runoff that remained unsampled. Estimated concentrations were projected every 24 hours until the runoff for that event had drained from the basin. Exponential decay was the most accurate representation of concentration over time. This method was determined to be accurate only in describing the concentration particulate material over time. Therefore, the concentrations of soluble constituents were not estimated using exponential equations.

3.5.4. Filtration Loading and Removal

The mass loading of the constituents in the final discharge was initially measured by assigning runoff volumes to designated sample concentrations. However, a flow-weighted average effluent concentration could not be determined owing to poor drainage of the filter. Therefore, the constituent concentrations in the final effluent were averaged over the 10-month monitoring period. The outflow rate was assumed to remain relatively constant because of the slow rate at which the filter drained. Accordingly, the outflow rate was independent of filter depth and time; in addition, it was assumed that each sample represented an equal volume of runoff. TSS concentrations in the final effluent were consistent over the duration of the monitoring period (Figure 3-10). The y-axis was scaled to the average influent concentration of TSS's. The consistency of the TSS data also supported the decision to average the constituent concentrations in the final effluent. Filter effluent was sampled at 24-hour intervals during the monitoring period. The final effluent concentrations for each constituent plotted over time are presented in Appendix B.

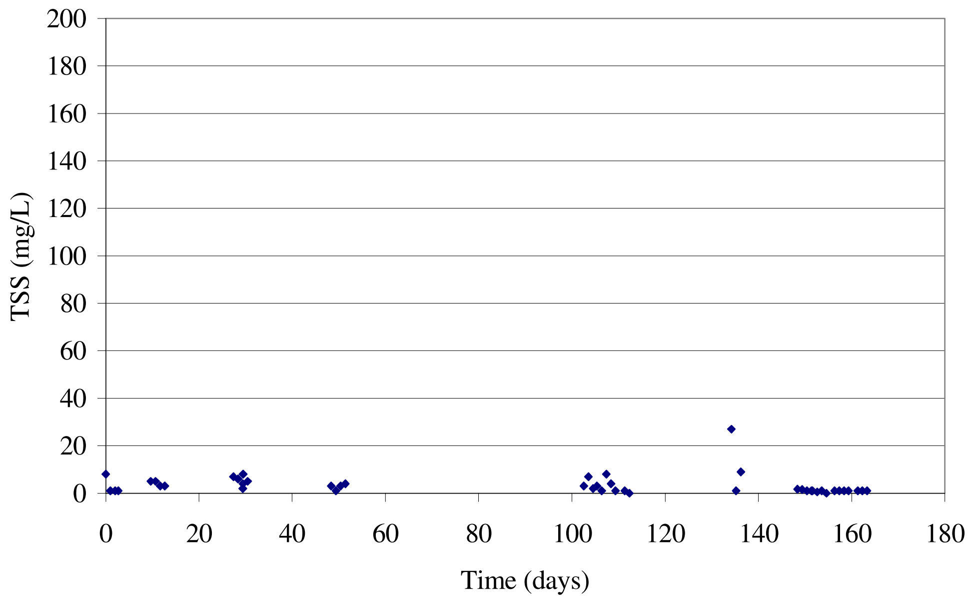


Figure 3-10 TSS Concentration in the Filter Effluent versus Time

3.6. Results

3.6.1. Hydraulic Results and Performance

The total flow for a single runoff event measured at the influent channel must equal the total volume captured in the sedimentation basin plus any runoff that bypasses the system and any water that evaporates from the surface of the basin. Evaporation was assumed to be negligible for this study. A flow balance was performed to determine the consistency between the volume measured at the influent channel and the volume measured in the sedimentation basin. The results of the flow balance for the ten storms monitored in the study are presented in Table 3-3. The influent volume in Table 3-3 does not include the runoff that bypassed the system.

Table 3-3 Influent and Basin Volume Comparison (Bypass Excluded)

Storm Date	Influent Volume (m^3)	Pond Volume (m^3)	% Difference
11/17/95	3,901	3,659	-6.2
12/8/95	577	548	-5.1
12/17/95	610	608	-0.3
2/29/96	1,294	1,270	-1.8
4/22/96	961	1,062	+10.6
6/22/96	695	729	+4.9
8/23/96	7,495	7,564	+0.9
8/29/96	6,358	5,672	-10.8
10/27/96	1,157	1,279	+10.6
12/16/96	4,950	4,448	-10.1
Total	**27,997**	**26,838**	**-4.1**

The data presented in Table 3-3 show that most of the runoff passing through the influent channel was accounted for in the basin. None of the events showed a difference of greater than 11%. The smallest percent difference, 0.3%, occurred on 12/17/95.

The facility had been in operation for approximately 1 year prior to the monitoring period, and extensive commercial construction activities in the contributing watershed had covered the sand filter with a layer of sediment. This layer prevented the system from draining between storm events, so a clean-out cap for the sand filter underdrain was removed to empty the pond. The cap was left off for the entire first year of monitoring, and data were collected on the efficiency of the sedimentation basin alone. The first six storm events that were analyzed were treated only by sedimentation. The drainage times for these six events ranged from 4 to more than 7 days.

Although facility maintenance was the responsibility of the City of Austin, nothing was done to improve the conditions of the sand filter (despite repeated requests). In August of 1996, staff from the Center for Research in Water Resources (CRWR) cleaned the filter and attempted to restore the system to design operating conditions. With the clean-out cap replaced, drainage through the sand filter improved; however, the system never completely drained within the 48 hours. Examples of the pond drainage times from August of 1996 to the conclusion of the study are presented in Figure 3-11. The data show a substantial increase in drainage time during this period. The storm on 8/25/96 required only 4 days to drain to the same depth that the storm on 4/5/97 drained to in over 2 weeks. The final four events in Table 3-3 were treated by the combined system and required 7 to more than 14 days to drain.

During the time of the study, the filter was usually the limiting factor in the drainage time. The depth of water in the basin and the depth of water in the filter remained the same throughout the entire drainage period, indicating that the potential discharge from the sedimentation basin was greater than the discharge from the filter. Consequently, the filter flow regulated the effluent flow rate from the basin in addition to the facility.

There were instances when the basin effluent pipe clogged and limited the effluent flow rate from the basin. A period when the water depth in the pond was higher than the water depth in the filter was evidence of a clog. The plot of the event on 4/5/97 is an example. Maintenance was performed to remove sediment in the pond effluent pipe at a depth of approximately 1.5 m. The drainage rate was limited by the obstruction in the pipe prior to that point. After the obstruction was removed, the drainage rate temporarily increased for a 24-hour period and leveled off again. The rate leveled off because the depth of water in the basin reached the depth in the sand filter, and the filter media once again governed the drainage rate.

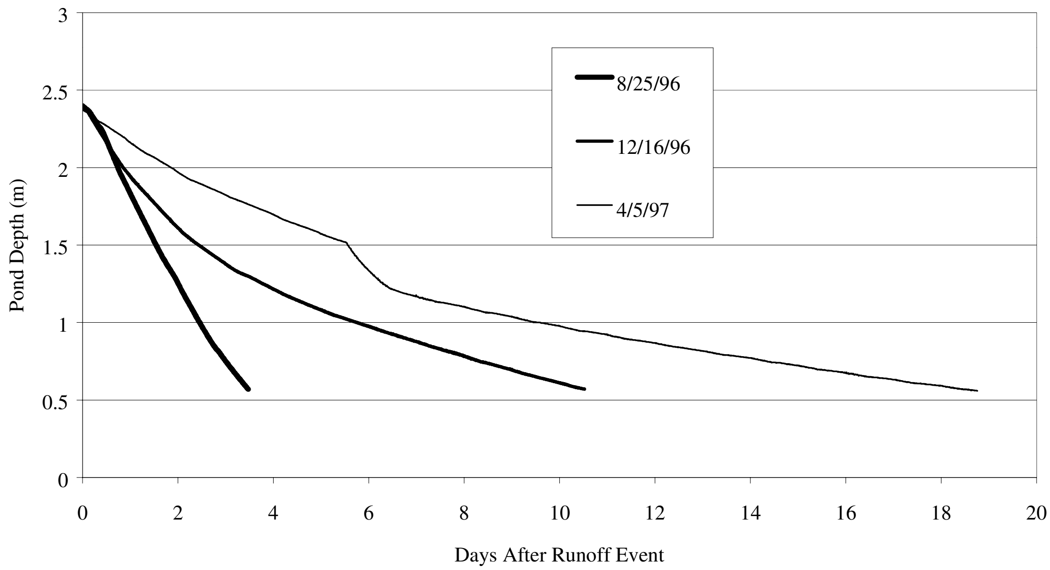


Figure 3-11 Drainage Patterns for the Seton Pond Sedimentation Basin

The decrease in basin drainage rate caused a decline in the quantity of runoff that was collected from the watershed. Runoff remained in the sedimentation basin for extended periods because the flow through the filter was decreasing with time and, thus, limiting the effluent flow rate of the basin. Runoff that remained in the basin reduced the maximum capacity of the basin for capturing subsequent runoff events. Consequently, the basin captured a smaller percentage of a subsequent runoff event than it would have caught under proper drainage conditions. A larger percentage of runoff bypasses the facility as a result. This compromises the effectiveness of the facility and increases the constituent loading to the receiving waters.

The influent and pond hydrograph for the storm on 8/23/96 is presented in Figure 3-12. The basin is filled to capacity at a depth of approximately 2.4 m. At this depth, any additional runoff that enters the influent channel will bypass the system as long as the flow rate in the channel is greater than the effluent flow rate of the basin. The level of the basin exceeded the maximum level during the second and third runoff events on 8/23/96, with runoff bypassing the system. Less runoff would have bypassed had the volume captured from the first event drained more rapidly. Similarly, less runoff from the third event would have bypassed the facility had the volume captured from the second event drained more rapidly. Approximately 20% of the total runoff from the watershed bypassed the facility over the entire 18-month monitoring period. The impact of bypassed runoff on the overall treatment efficiency of the system is discussed in Section 3.7.2.

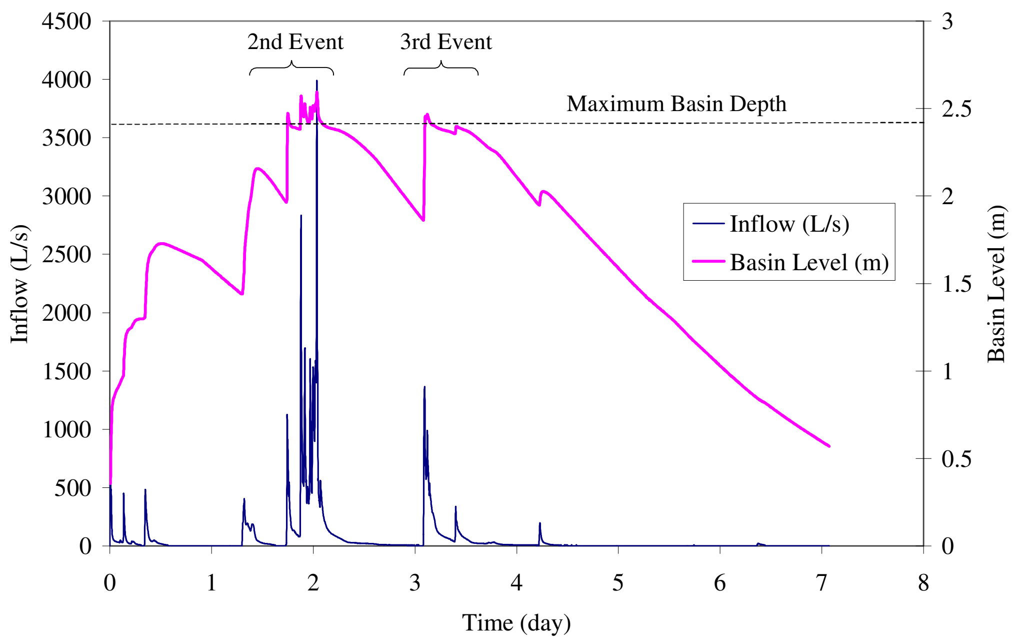


Figure 3-12 A Runoff Event that Exceeds the Basin Capture Volume

3.6.2. Sedimentation Removal Efficiency

A total of ten storms between 11/95 and 12/96 were selected for analysis of removal efficiency through sedimentation. The monitoring of storm events continued through 6/97; however, events after 12/96 were not evaluated owing to the poor hydraulic performance of the system. Runoff remained in the basin and filter from 2/97 until the end of the monitoring period, rendering it impossible to distinguish between runoff events. The criteria for storm selection were sampling accuracy, availability of flow data, and availability of constituent concentration data. The loading and removal efficiency results for each runoff constituent are presented in Table 3-4. The results were based on a flow-weighted average of the ten storms in Table 3-3. The percent removal that is shown in Table 3-4 represents the removal efficiency for various runoff constituents that entered the sedimentation basin. Untreated runoff that bypassed the system was not included in the loading of a constituent and percent removal calculations.

The average nitrate-nitrogen concentration increased through the system; however, because removal was based on load and not on concentration, the removal was positive. Load was calculated by multiplying the sample concentration by the volume measured at the sample location. The removal efficiency reflects the difference between influent and effluent concentration if the volume measured at the influent and effluent are the same. However, there was a difference between the influent channel volume and the basin volume (Table 3-3). The total influent volume was only 4.1% larger than the total basin volume; however, this difference was large enough to change the nitrate-nitrogen removal efficiency from negative to positive.

Table 3-4 Mass Balance Results for the Sedimentation Basin (Bypass Excluded)

Constituent	Avg. Influent Conc. (mg/L)	Influent Load (kg)	Avg. Effluent Conc. (mg/L)	Effluent Load (kg)	Removal (%)
TSS	204	5,705	24.0	644	89
Turbidity	53.0	750	26.3	358	52
COD	90.6	2,474	32.4	846	66
TOC	32.0	692	12.6	262	62
Nitrate	1.24	20.6	1.28	19.9	3
TKN	1.59	33.8	1.24	24.8	26
Phosphorus	0.356	7.96	0.181	3.92	51
Zinc	0.138	1.80	0.028	0.349	81
Iron	3.25	70.2	0.81	17.2	75

Of the ten storms evaluated in Table 3-4, the first six were treated by sedimentation alone, while the final four were treated by the combined system. The storm events treated by sedimentation alone drained in 4 to >7 days. The storm events that were treated by the combined system drained in 7 to >14 days. The removal efficiencies for prefilter sedimentation and postfilter sedimentation are shown in Appendix D. The removal of all constituents, except TKN, in the sedimentation basin was greater for postfilter sedimentation.

The removal efficiencies of runoff constituents in the basin were reduced when the constituent load of the bypassed runoff was included in the mass balance of the basin. A comparison of the total measured inflow and basin volume recorded during the study indicated that 80% of the total runoff collected from the watershed actually entered the system and received treatment. The remaining 20% of the flow bypassed the system. The quality of the bypassed runoff was not determined easily. Because a sampler was not installed at the splitter box, the constituent concentrations in the bypassed runoff had to be estimated using the concentrations at the influent channel. The average influent concentrations listed in Table 3-4 were assumed for the bypassed runoff. In reality, the constituent concentrations of the bypassed runoff are probably less than the EMCs for a given runoff event. The basin captures the volume of runoff containing the highest pollutant concentrations, the first flush, and the less concentrated runoff bypasses the system. The estimated concentrations of the bypassed runoff were not adjusted, however, because of the lack of data to prove the concentrations were less than the EMCs for that runoff event. The constituent loads and removal efficiencies were recalculated, factoring in the untreated volume of bypassed runoff. The results are presented in Table 3-5.

A comparison of Table 3-4 and Table 3-5 shows that bypassed runoff reduces the treatment efficiency of the system. A clogged filter not only increases the quantity of runoff that bypasses the system; it also extends the detention time of the runoff that is captured and allows more time for settling. The additional detention time for the captured runoff may compensate for the runoff bypassing the system untreated. The sedimentation basin underwent a dramatic increase in drainage time over the first 4 months of filter operation (8/25/96 to 12/16/96; see Figure 3-11). The extended drainage time might be justified if the treatment efficiency is significantly greater on 12/16/96 than on 8/25/96. The results for these individual storms, presented in Appendix D, reveal negligible improvement. The removal efficiency of TSS's was 91% on 8/25 and 92% on 12/16. The negligible improvement in removal efficiency means that the drainage through the clean filter provided sufficient detention time for settling in the sedimentation basin. Additional detention time in the basin provided negligible improvement and served only to increase the quantity of runoff that bypassed the system. The settling behavior of constituents in runoff over time provides a possible reason for the negligible improvement in removal efficiency.

Table 3-5 Mass Balance Results for the Sedimentation Basin (Including Bypass)

Constituent	Watershed Load (kg)	Bypass + Basin Effluent Load (kg)	Removal (%)
TSS	7,132	2,070	71
Turbidity	937	546	42
COD	3,092	1,464	53
TOC	865	435	50
Nitrate	25.7	25.1	2
TKN	42.2	33.3	21
Phosphorus	9.95	5.91	41
Zinc	4.81	1.32	64
Iron	87.8	34.8	60

The removal of highway runoff constituents in the sedimentation basin over time is presented in Figure 3-13 through Figure 3-21. The graphs were developed using sample concentrations obtained from the entire 18-month monitoring period. Time zero on each plot represents the time when the sedimentation basin began to accept runoff. A majority of the data points is located within the first 2 days of the runoff events because, at the beginning of the study, runoff events drained faster and samples were taken at shorter intervals.

The observed data on most constituents indicate a clear increasing trend in fraction removed over time. An exponential growth equation provided the best representation of the data plotted. The following equation was used:

$$F = a(1 - \exp(-kt)) \tag{3-7}$$

where

F = fraction of constituent removed (mg/mg),

a = upper limit of fraction removed (mg/mg),

k = rate constant (1/days), and

t = time after runoff event (days).

A least squares analysis was performed on the data by adjusting the variables *a* and *k*. The y-axis scale in the figures was adjusted depending on the range of removal data observed for the particular constituent.

The removal efficiencies for most constituents showed a definite increase over time, while a few constituent removal efficiencies showed no clear relationship over time. Removal of solids, COD, phosphorus, and metals increased over time. Approximately 85–90% of TSS's was removed in the first 24 hours of detention (see Figure 3-13). The increase in removal of TSS's was negligible after the first 24 hours. Zinc and iron experienced high removal in the first 36–48 hours. The greatest removal of the organic constituents, COD and TOC, occurred within the first 3–4 days of detention. Nitrate and TKN did not display a clear relationship between fraction removed and detention time, so a least squares analysis was not performed.

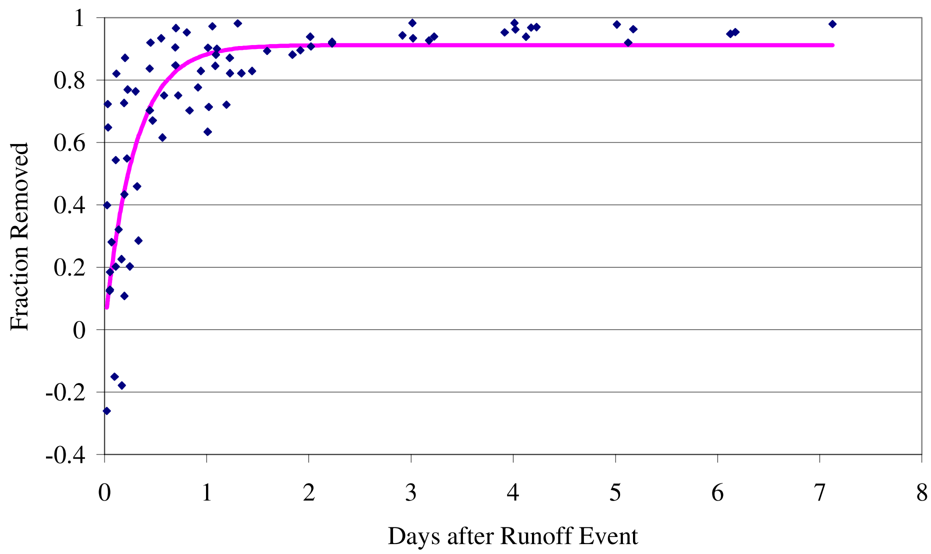


Figure 3-13 Fraction of TSS's Removed over Time

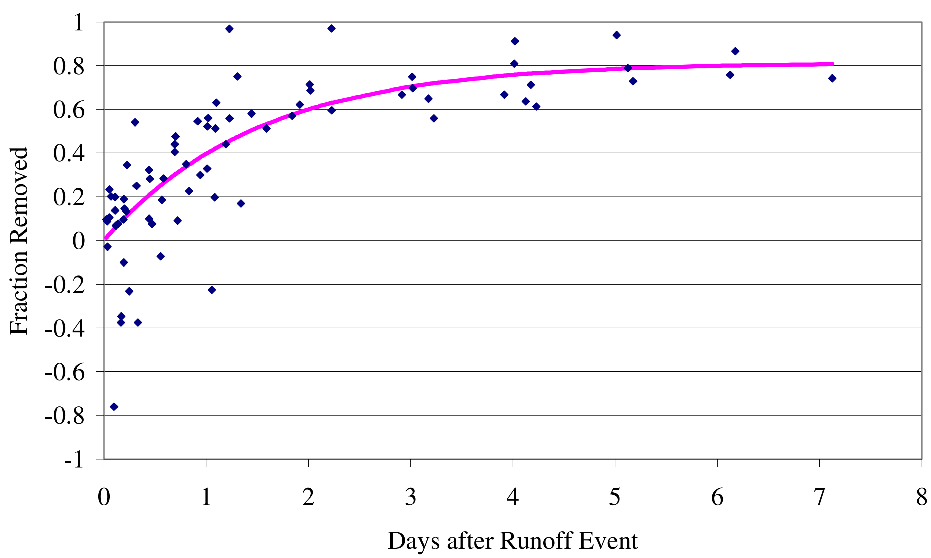


Figure 3-14 Fraction of Turbidity Removed over Time

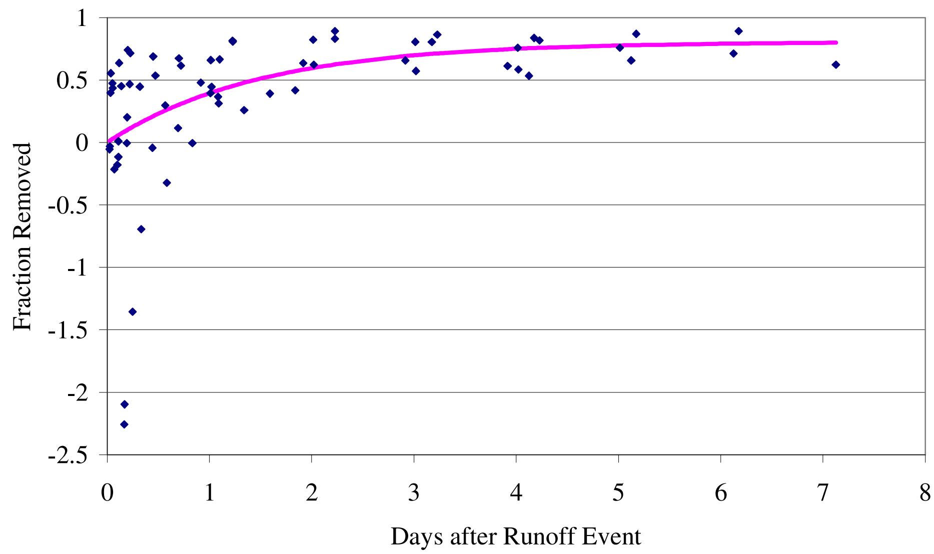


Figure 3-15 Fraction of COD Removed over Time

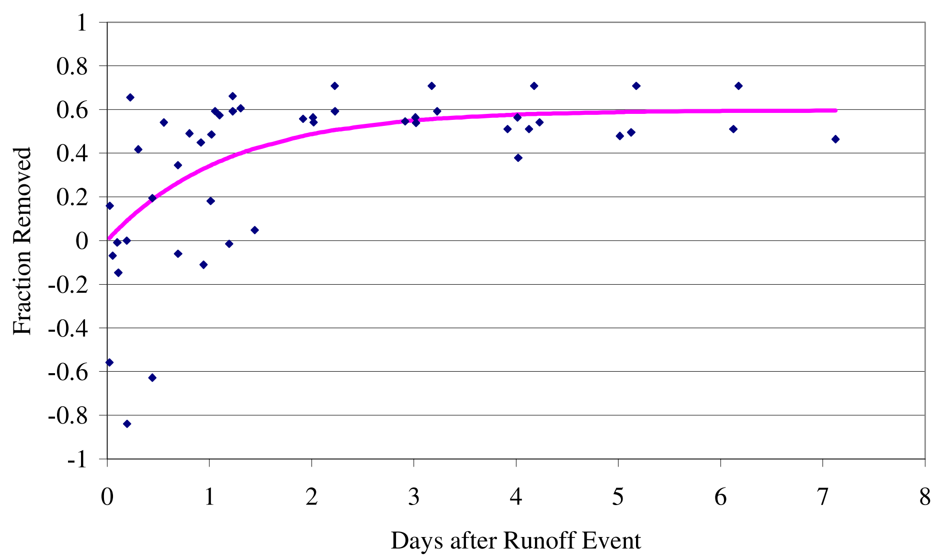


Figure 3-16 Fraction of TOC Removed over Time

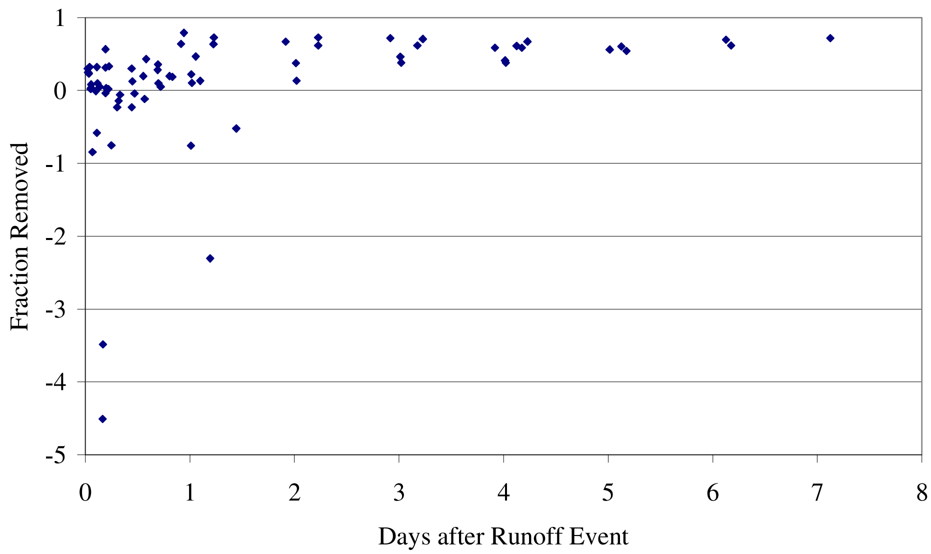


Figure 3-17 Fraction of Nitrate Removed over Time

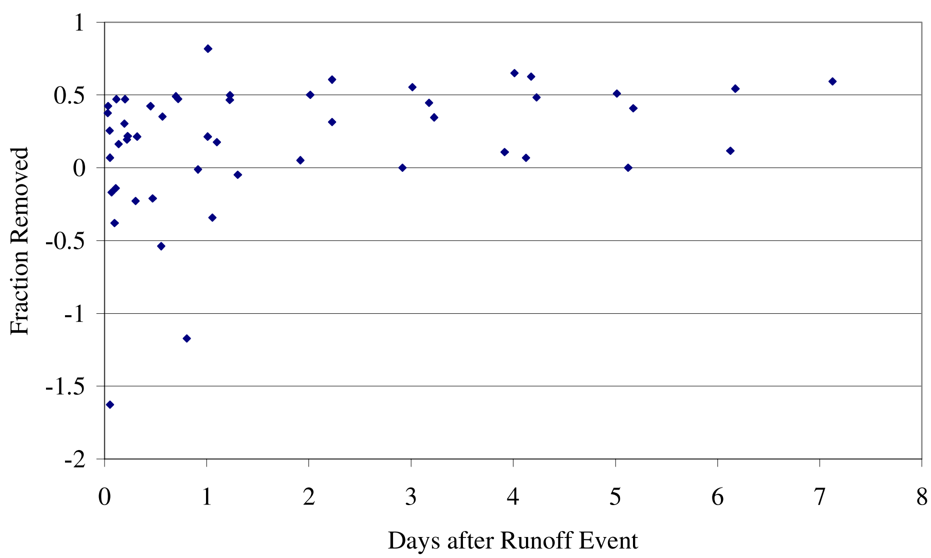


Figure 3-18 Fraction of TKN Removed over Time

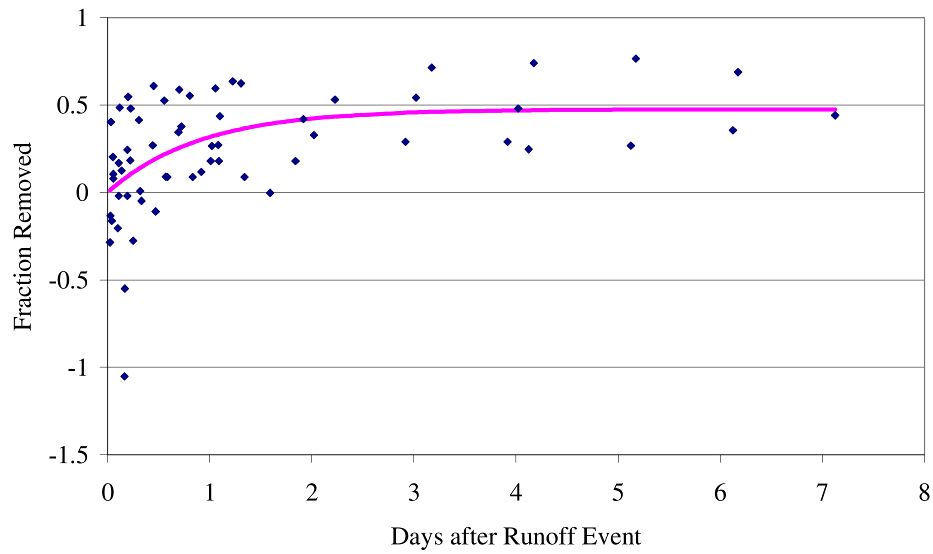


Figure 3-19 Fraction of Phosphorus Removed over Time

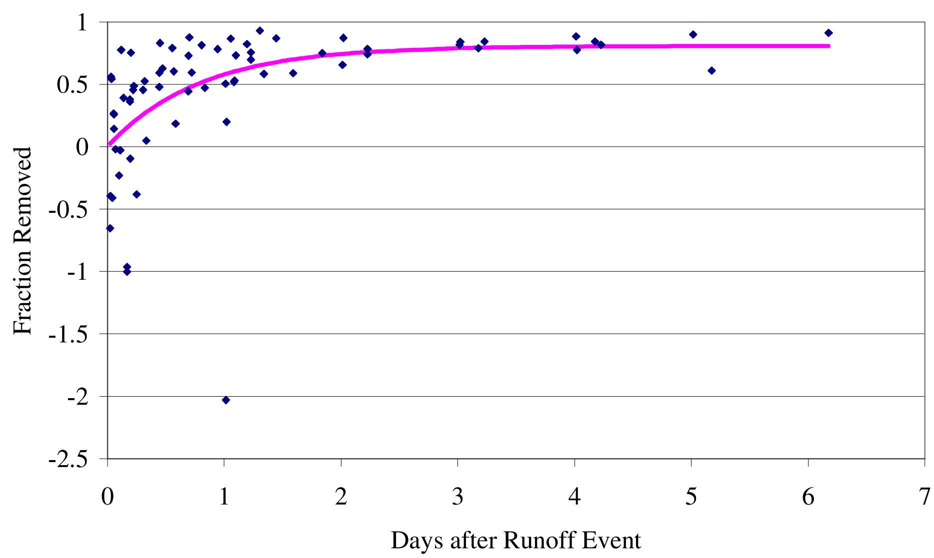


Figure 3-20 Fraction of Iron Removed over Time

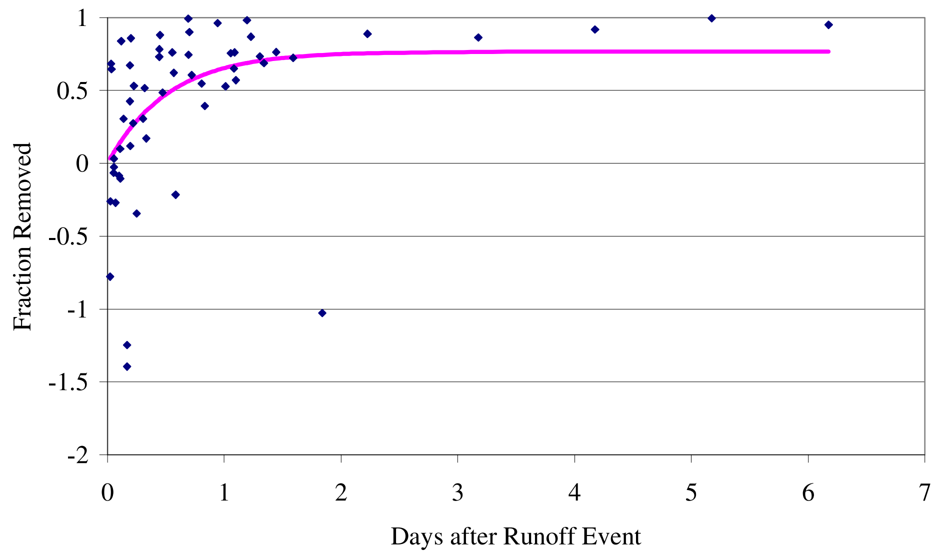


Figure 3-21 Fraction of Zinc Removed over Time

3.6.3. Overall Removal Efficiency (Sedimentation and Filtration)

The treatment of highway runoff constituents in the combined sedimentation/filtration system was monitored for approximately 10 months. The filter was put back on-line in 8/96, with the study then ending in 6/97. The mass balance for the sedimentation/filtration system is summarized in Table 3-6. The results pertain only to the runoff that entered the system — not to the runoff that bypassed. The mass load in the final effluent discharge was determined by multiplying the total volume for all the runoff events monitored by the mean effluent concentration from the filter. Because volume was not measured in the filter, the volume measured in the sedimentation basin was used instead. The mass load in the final effluent discharge was compared with the mass load in the runoff in the influent channel to determine an overall system removal efficiency. A plot of effluent concentration obtained from the filter over time for each constituent is presented in Appendix B.

Table 3-6 Results for the Sedimentation/Filtration System (Excluding Bypass)

Constituent	Influent EMC (mg/L)	Influent Load (kg)	Effluent EMC (mg/L)	Effluent Load (kg)	Removal (%)
TSS	204	5,705	3.50	94.0	98
Turbidity	53.0	750	4.60	62.6	92
COD	90.6	2,474	11.0	286	88
TOC	32.0	692	12.6	261	62
Nitrate	1.24	20.6	0.474	7.40	64
TKN	1.59	33.8	0.591	11.9	65
Phosphorus	0.356	7.96	0.126	2.72	66
Zinc	0.143	3.85	0.008	0.214	94
Iron	3.25	70.2	0.175	3.71	95

The results presented in Table 3-7 include removal efficiencies for the constituents in the total runoff drained from the watershed. The total includes the runoff that enters the system plus the runoff that bypasses the system. The actual mean constituent concentrations of the bypassed runoff were impossible to determine with the available data. The average influent concentrations listed in Table 3-4 were assumed for the bypassed runoff. The reason the bypassed runoff was included in the mass balance was to determine the total load to the receiving waters.

3.7. Discussion

3.7.1. Sedimentation

Constituent removal by sedimentation depends on whether the constituent is in the particulate or soluble form. Typically, TSS's are easily removed because they exist in the particulate form. Because nutrients such as nitrogen have a significant soluble fraction in highway runoff, they cannot therefore be effectively removed by settling. In the following sections, the results for the runoff captured and treated at the Seton Pond facility will be compared with previous field and laboratory experiments; differences in constituent removal will also be discussed.

Solids

Approximately 90% of the TSS load was removed in the Seton Pond sedimentation basin. Studies conducted on two similar extended detention ponds, the National Urban Runoff Program study at the Stedwick Pond in Maryland and the Occoquan Watershed Monitoring Laboratory study at the London Commons Pond in Virginia, showed approximately 65% TSS removal (Schueler 1987). The estimated average detention time for these two ponds was 6–12 hours. While the detention time for the sedimentation basin was difficult to estimate, in most cases runoff remained in the basin for more than 3–4 days. Ideally, a detention pond should have a detention time between 6 and 24 hours (Schueler 1987). The Seton Pond did not function as the ideal pond because its effluent flow was limited by the flow through the sand filter.

Table 3-7 Results for the Sedimentation/Filtration System (Including Bypass)

Constituent	Watershed Load (kg)	Bypass + Final Effluent Load (kg)	Removal (%)
TSS's	7,132	1,520	79
Turbidity	937	250	73
COD	3,092	905	71
TOC	865	434	50
Nitrate	25.7	12.5	51
TKN	42.2	20.3	52
Phosphorus	9.95	4.71	53
Zinc	4.81	1.18	76
Iron	87.8	21.3	76

Whipple and Hunter (1981) conducted column experiments with runoff collected from various locations in New Jersey. They found that 60–70% of the TSS load settled out within the first 6 hours of detention, and a maximum of 80–90% settled out within the first 48 hours of detention. The Seton Pond sedimentation basin removed between 50% and 90% of TSS's in the first 6–48 hours (see Figure 3-13). An overall removal efficiency of 90% for the Seton Pond basin appears to be reasonable, given that 80–90%

removal was achieved for 48-hour detention in the column experiments and that runoff in the Seton Pond basin frequently required more than 3 or 4 days to drain.

Organics

Organics were not as easily removed as TSS's in the Seton Pond basin. Percent removal for COD and TOC was 66% and 62%, respectively. The maximum removal of organics was 40–50% after 32–48 hours of detention in the column experiments (Whipple and Hunter 1981). In the Seton Pond basin, a removal of 50% to 60% COD and 40% to 50% TOC was achieved in 32–48 hours. The removal rate of COD is characterized by a sharp increase within the first 6 hours of detention, and then by a gradual increase to approximately 50% after 48 hours (Whipple and Hunter 1981). This trend would be expected, given that oxygen demand versus time is represented by exponential decay. In addition, COD has a soluble fraction that limits the peak removal. The trend shown by the data presented in Figure 3-15 is similar to the trend described by Whipple and Hunter (1981). The results shown in Figure 3-15 indicate that removal percentages level off after approximately 3 days. An overall percent removal of 66% for COD seems attainable, given that the Seton Pond basin often required more than 3 days to drain.

Nutrients

Nitrogen and phosphorus are nutrients typically found in highway runoff. Sedimentation is not the preferred treatment method for nitrogen because a significant fraction is in the soluble form. Peak removal of total nitrogen is typically 40% after 48 hours of detention (Schueler 1987). Nitrogen was monitored by analyzing two constituents, TKN and nitrate. TKN removal by sedimentation versus time does not show a clear relationship (Figure 3-18). The runoff event on 3/26/97 had unusually low TKN removal over the course of the 6-day draining period. The basin effluent samples taken for that event show that the fraction removed never exceeded 0.12. The removal of TKN was approximately 50–60% after 48 hours if the storm on 3/26 is disregarded.

Nitrate is a soluble species that generally remains in runoff after treatment by sedimentation. Many studies have shown an increase in nitrate after treatment. Nitrification occurring within the basin is the most likely reason for the increase. Nitrate removal by sedimentation was only 3% and, as anticipated, there was no trend in removal over time (Figure 3-17). In a similar study, a pond in Greenville, North Carolina, removed 3% nitrate (Stanley 1996).

Phosphorus may be dissolved and in particulate form. The concentration of soluble phosphorus in urban runoff makes up more than one-half of all total phosphorus. Particulate phosphorus usually settles out after an adequate detention time, and a portion of the dissolved phosphorus adsorbs to particulate matter, which eventually settles. Resuspension of particulates may be associated with low removal of phosphorus. Accordingly, erratic removal of phosphorus may be expected. The plot of fraction of phosphorus removed versus time presented in Figure 3-19reflects this phenomenon. Approximately 50% of the total phosphorus removal occurred in the Seton Pond basin. The results of column experiments performed by Whipple and Hunter (1981) indicate a maximum upper limit for total phosphorus removal after 48 hours of 40% to 50%. A maximum upper limit of 50% removal of total phosphorus after 4 days of detention is indicated by the data presented in Figure 3-19.

Metals

Zinc and iron may be in the particulate and soluble forms in highway runoff. According to Schueler (1987), approximately 70% of the zinc in urban runoff is dissolved. Settling and adsorption to settleable particles account for the removal of zinc. The results of the column experiments indicate that the maximum zinc removal is 40–50% after 48 hours (Whipple and Hunter 1981). The observed removal of zinc after sedimentation was approximately 80% in the Seton Pond. Removals of 60% and 26%, respectively, were reported at the Stedwick and Greenville sites (Schueler 1987). The high removal efficiency at the Seton Pond facility may be attributed to the long detention times.

Approximately 75% removal of iron was observed during the course of the monitoring period at the Seton Pond basin. The plot of the fraction of iron removed over time (Figure 3-20) is similar to the plot for zinc. Removals of zinc and iron in the first 2-3 days were significant and approached a maximum limit of 75% to 80%.

3.7.2. Overall Removal of Constituents in Highway Runoff

The overall removal at Seton Pond includes sedimentation and filtration. Removal of constituents involves sedimentation of particulates on the surface of the filter and trapping constituents in the sand medium. Sand filters generally exhibit high removal for solids and metals, but moderate removal for organics and nutrients. Organics and nutrients are primarily soluble and pass through the filter with little or no removal. Metals also are soluble; however, metals can be adsorbed to negatively charged solid and organic particles. Therefore, soluble metals are removed from solution by sorption on particulates that are trapped on or in the filter.

Removal efficiencies observed at the Seton Pond facility and at four Austin-area runoff facilities that were monitored during 1984–89 are presented in Table 3-8. The Highwood, Barton Creek Square Mall (BCSM), and Jollyville facilities are systems where sedimentation and filtration occur in one basin (City of Austin 1990). The Brodie Oaks facility has separate basins for sedimentation and filtration. All the facilities are on-line except for the Jollyville system, and all facilities were designed to capture the first 1.3 cm of runoff except Brodie Oaks, which captured 4.3 cm of runoff. It should also be noted that approximately 65% of the runoff collected in the Brodie Oaks sedimentation basin was used for irrigation and did not enter the filtration basin.

The removal efficiencies reflect only the runoff that entered the system and then received treatment. Thus, these data may be compared with the data observed at the Seton Pond facility. The removal efficiencies for Highwood and BCSM exclude those storms that exceeded the capture capacity of the systems. Water losses other than evaporation and saturation losses were considered to be a portion of the outflow in order to have consistency between outflow volume and inflow volume.

Table 3-8 Comparison of Systems Located in Austin, Texas (Percent Removal)

Constituent	Highwood	BCSM	Jollyville	Brodie Oaks	Seton Pond
TSS	86	75	87	86	98
COD	29	40	67	82	88
TOC	43	38	61	87	62
Nitrate	-18	-42	-82	-38	64
TKN	40	60	62	81	65
Zinc	40	74	81	84	94
Iron	57	65	86	71	95

Table 3-8 compares removal efficiencies for various constituents in highway runoff. These data indicate that the Seton Pond facility was more efficient than the other facilities in the removal of TSS's, COD, nitrate, zinc, and iron. However, the removal of TOC and TKN observed in the Seton Pond facility was comparable to the removals reported for the other facilities.

The effectiveness of the Seton Pond facility can be attributed to two main factors: detention time and the layer of sediment that accumulated on the surface of the sand filter. A longer detention time allows more particulate matter to settle out in the sedimentation basin. The average detention time in the Seton Pond facility ranged from 4 to more than 14 days, compared with 20 to 26 hours for other Austin-area facilities. The layer of fine particles on the top of the sand filter provides more filtering than would be achieved with sand alone. The layer also may accumulate organic material, which increases the cation exchange capacity of the filter and provides additional adsorption sites for dissolved metals (USEPA 1981). Accumulation of organic material is evident by the increase in removal of COD from the basin effluent to the filter effluent. The extended detention time and the layer of fine particles may explain the increase in the removal of particulate and soluble zinc and iron; however, the increase in the removal of nitrate, a soluble constituent, remains unexplained.

One theory for the increased nitrate removal relates to a transformation that occurred in the filter basin during a long portion of the monitoring period. Runoff remained in the filter basin for increasingly longer periods of time as the permeability of the filter declined. The first rainfall event of 1997 occurred in early February, and from that date until the conclusion of the study, the sand filter failed to drain completely. Runoff remained in the filter basin for the last 5 months of the monitoring period. Consequently, the filter basin began to develop the characteristics of a wet pond. Algae blooms that covered the entire water surface appeared at certain times of the year. Rooted aquatic plants grew from the filter and lined the surface of the bed. The filter basin also provided a habitat for a variety of insects and frogs.

A comparison of sedimentation and filtration indicates a substantial difference in nutrient removal. Nitrate removal increased from 3% to 64%, and TKN removal increased from 26% to 65% after treatment by filtration. Approximately 66% of the total phosphorus was removed beyond the upper removal limit of 40% to 50% that was suggested by Schueler. These levels of nutrient removal are not typical of sand filters treating highway runoff. One possible explanation for these observations is the removal of nitrogen and phosphorus by plant uptake. Nitrogen and phosphorus are nutrients that are required for plant growth and maintenance; however, only soluble forms can be utilized. The highway runoff is a source of soluble nutrients for the plants. Plant uptake could be the reason for the improvement of nutrient removal in the sand filter. Plants also can take up metals in addition to nitrogen and phosphorus. Plant uptake could also be a reason for the increased removal of zinc and iron.

A decision must be made regarding the rehabilitation of the pond to a sand filter or its continued operation as a wet pond. If the facility is restored to function as a filter, the drainage time would decrease and the amount of runoff captured by the facility would increase. An increase in capture volume means a larger volume of runoff could be treated. However, if the facility is transformed to a wet pond, superior nutrient removal as a result of plant uptake could be achieved. Nitrate also may be removed by denitrification if the pond becomes anaerobic. In addition to improved nutrient removal, the wet pond also would require less maintenance to continue operations. Removal of the sediment layer that accumulated on the surface of the sand filter would not be necessary.

Major uncertainties about the wet pond may make the sand filter a better option. The annual rainfall in Austin may not be sufficient to support a wet pond. Rainfall in the watershed area may keep the pond full during the winter and spring; however, rain is scarce and the pond could dry up during the summer months. The aquatic vegetation, which is so important for nutrient removal, would die as a result of a lack of water. Odors produced when the pond dried up may also be a nuisance to the surrounding community.

The extent of the capture volume and the impact on removal efficiency are not clear. Approximately 20% of the total runoff volume bypassed the system during the period of time that the system was monitored. The percentage of runoff bypassing the system continued to increase as the permeability of the filter decreased. The TSS removal in the sedimentation basin for the runoff event at the beginning of filter operation was approximately the same as the runoff event captured by the system 4 months later. The increased detention time for this period had no effect on removal by sedimentation. The increased detention time also did not affect the removal by filtration. The TSS concentrations in the effluent from the filter remained relatively constant from the start of the filter operation to the end of the study. Thus, longer drainage times caused by the clogging filter will only reduce the amount of runoff that is captured and will not improve the treatment of the runoff entering the facility. Soluble constituents may possibly be removed to a greater extent after longer detention. This benefit would likely be insignificant compared to the impact of the pollutants in the untreated runoff that bypassed the system. This evidence suggests that maintaining the sand filter is a more effective option than its continued operation as a wet pond.

3.7.3. Maintenance Requirements

Routine maintenance is required to achieve maximum efficiency and to sustain an aesthetically pleasing facility. General maintenance requirements include mowing the grass and collecting and removing trash and debris from the site. The area was neglected frequently during the monitoring period, with the result that tall grass and trash accumulated on the site. The runoff control structure required regular maintenance to maximize the performance of the system. Currently the City of Austin maintenance activities include: "removal of accumulated materials from detention ponds, sedimentation basins, and sand filters; regrading of detention ponds to improve drainage; and restoration of filter underdrain systems to provide regulated stormwater discharges" (Walker 1997). Additional recommended maintenance includes routine cleaning of the influent channel and the HMT to remove accumulated sediment, and occasional inspection of the basin and filter effluent discharge pipes to locate any blockage.

Maintaining efficient operation involves proper maintenance as necessary. Sedimentation/filtration systems may require different time intervals between maintenance work, given the different characteristics of each system. For example, the Seton Pond facility is prone to frequent clogging. The annual mass loading on the facility was calculated as 3,500 kg/yr, based on the average TSS influent concentration and the total yearly runoff captured. This load translates to 3.3 kg/yr per m^2 of sand filter bed. Removal of accumulated sediment from the sand filter every 6 months is recommended. The effluent discharge pipe of the sedimentation basin also should be inspected and cleaned of any blockage during routine maintenance. The HMT and influent channel need to be cleaned of sediment at least once per year.

The above maintenance schedule is specific to the Seton Pond facility. Other sites may require more or less frequent maintenance depending on the sediment load on the system. Some factors that contribute to the quantity of sediment load include the size of the watershed area, the amount of construction in the watershed, the presence of unlined channels, and the storm frequency in the area. The Seton Pond site drains a large watershed (34 ha), and during the monitoring period commercial construction projects were in progress in the watershed. The EMC of TSS's for a typical runoff event in the Austin area is approximately 200 mg/L (Barrett et al. 1995b). Runoff events having an EMC of TSS's of more than 300 mg/L are an indication that there may be a construction site on the watershed. On 12/8/95 and 12/17/95 the TSS concentrations were 321 mg/L and 533 mg/L, respectively. These elevated TSS concentrations contribute to the rapid clogging of the sand filter.

A major consideration in maintaining sedimentation/filtration facilities is the cost of maintenance. The operating budget for pond maintenance and restoration for fiscal year 1997 for the City of Austin was approximately $351,000. The City of Austin planned to restore thirty-five ponds during 1997. Thus, the annual cost for the restoration of a sedimentation/filtration pond is roughly $10,000 per pond. The eventual goal is to allot $4,000 per pond, a value that would fluctuate depending on the maintenance needs of each pond (Walker 1997).

4. PROTOTYPE EXPERIMENTS

4.1. Introduction

Several experiments were conducted to study the effectiveness of sedimentation as a method of treating highway runoff. The prototype-scale sedimentation basin at the Center for Research in Water Resources (CRWR) was used for all experiments. The objectives of the experiments were the following:

1) Determine the effectiveness of sedimentation in removing constituents present in highway stormwater runoff.
2) Compare the effect of outlet structure design on removal efficiency.
3) Evaluate the effects of detention time on pollutant removal efficiency.

4.2. Experimental Design

The experiments were performed in a prototype-scale runoff control testing facility at CRWR. The facility consists of a 38-m^3 storage tank, a three-stage water filtration system, a mixing tank, two experimental collection basins, and a sump area for reclaiming water used in the experiments. A plan view of the facility is presented in Figure 4-1.

4.2.1. Water Storage and Filtration

Prior to mixing, the recycled water from the storage tank was filtered to remove suspended solids and dissolved compounds remaining in the water from the previous experiment. Originally, the water was pumped through a three-stage filtration system consisting of sand, activated carbon, and ion exchange resin. The filtered water was then discharged to a 19 m^3 mixing tank. The filtration system was used for the first three experimental runs. The recycled water was replaced by nonchlorinated well water after problems were encountered with the filtration system. (The filtration system was unable to remove small, suspended particles in the recycled water, which could alter the particle-size distribution of the runoff.)

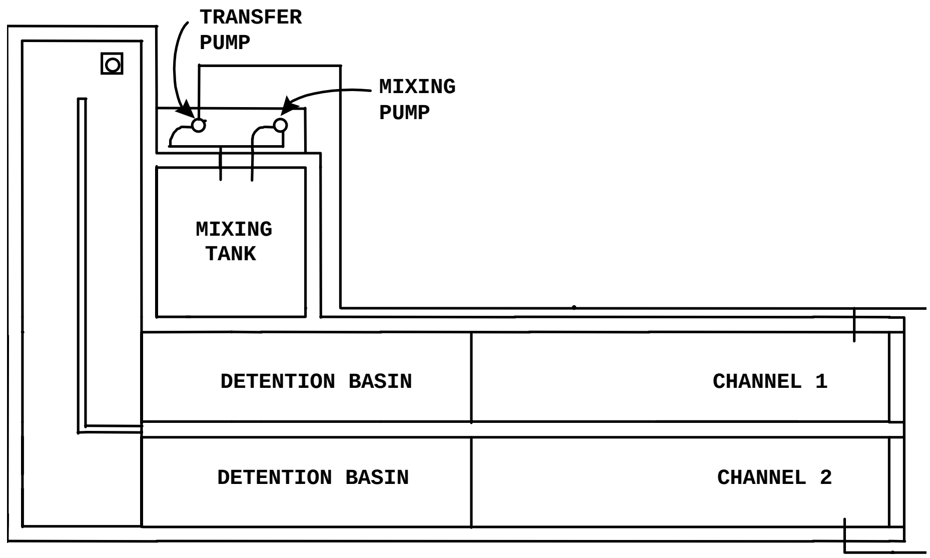


Figure 4-1 Runoff Control Facility Plan View

4.2.2. Distribution System

The distribution system includes a mixing tank, a piping network, and two centrifugal pumps. The mixing pump circulates water through the mixing tank by drawing water from a perforated pipe along the bottom of the tank and discharging the water through a discharge pipe located 0.5 m from the top of the tank. After mixing, water is distributed from the tank to the channels by the transfer pump that also draws at the bottom of the mixing tank. Water is discharged from the distribution pipe at the head of each channel.

4.2.3. Sedimentation Channel

Sedimentation was tested in Channel 1 of the prototype sedimentation basin. The channel was designed to represent a section of a sedimentation pond. Excess runoff that was not used during the experiments was diverted to Channel 2. The sedimentation basin includes an 8.7 m entrance ramp with several flow dissipaters located along the length. The channel is 1.8 m wide and has a bottom area of 8.7 m^2. At the opposite end of the basin is a 1.2 m retaining wall with a 2.5 cm opening at the bottom left corner for drainage. An effluent pipe with a control valve is attached to the opening in order to regulate the effluent flow rate and the drainage time of the basin. A sampling trough is located at the end of the effluent pipe to create a sufficient depth for sample collection. From the trough the effluent was collected in the sump area and was returned to the storage tank via a sump pump. A cross section of Channel 1 is shown in Figure 4-2.

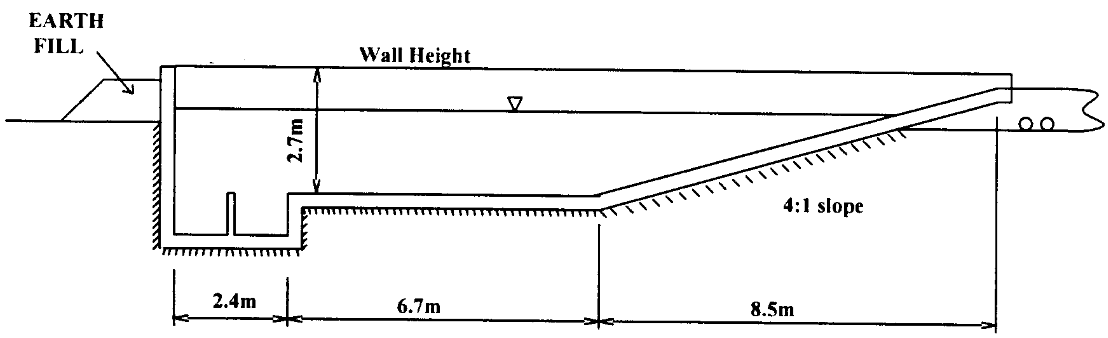


Figure 4-2 Runoff Control Facility Cross Section

4.2.4. Skimmer Design

The outflow device used for the second set of experiments consisted of three major components: a skimmer, a 1 inch (2.54 cm) drainage hose, and a float. The skimmer has openings on the top and underside so that the effluent valve, not the skimmer, limits effluent flow from the basin. A 1.3 m long flexible plastic drainage hose is attached to the skimmer and is connected to the opening at the bottom of the retaining wall. The length of the hose is sufficient to skim the surface even at the maximum experiment depth. The flotation material is Styrofoam and is attached around one-half of the skimmer. The Styrofoam was placed on one side to allow the intake component to float horizontally, maximizing the flow of water into the skimmer. A diagram of the skimmer configuration in the basin is illustrated in Figure 4-3.

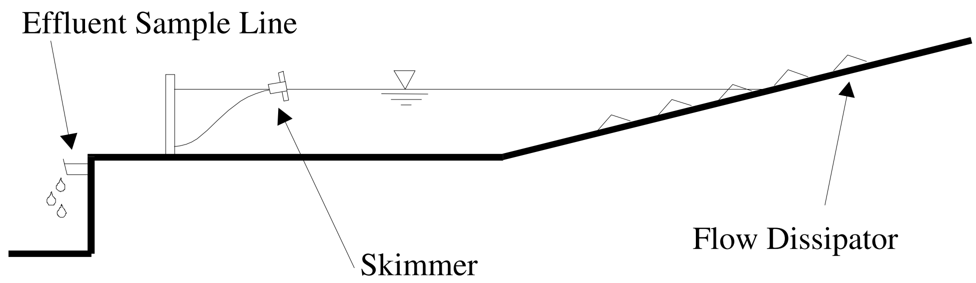


Figure 4-3 Sedimentation Basin with Skimmer Attachment

4.3. Materials

Dulay (1996) developed a synthetic highway runoff. The highway runoff "cocktail" was a mixture of actual sediment (collected from a highway runoff treatment basin), clay, and metal nitrates. These ingredients were added to simulate the highway stormwater runoff characteristics found in the Austin area (Dulay 1996). Highway runoff sediment was added to provide solids, organics, metals, and nutrients to the simulated runoff. However, the sediment alone did not produce an accurate representation of actual highway runoff. The addition of Gleason, Velvacast kaolin, and coarse clays was necessary to maintain a particle-size distribution comparable to that observed in highway runoff. Sodium carbonate was also added to enhance the particle-size distribution. Metal nitrates (zinc, lead, and iron) were added as a source of these metals, along with nitrate in concentrations comparable to those found in highway runoff. Constituents in the highway runoff cocktail that are necessary, postdilution concentrations were reported by Dulay (1996). The mass of each constituent required to achieve the dilution concentrations when added to the mixing tank is presented in Table 4-1.

4.4. Sampling Scheme

Samples of the influent and effluent of the channel were collected and analyzed to determine the removal efficiencies of the constituents by sedimentation. Four influent grab samples, 350 mL each, were taken over the duration of the discharge into the channel. The samples were blended into one composite sample representing the volume of water in the basin (approximately 8,600 liters). Sample collection was based on the depth of the runoff in the basin during filling. The total volume was divided into four equal volumes of water; samples were taken at a height that represented the discharge of one-half of each quarter of the total volume into the basin. Influent samples were collected when the basin was 0.125, 0.375, 0.625, and 0.875 of the volume when full.

Four 3,000 mL effluent samples were collected at 80, 250, 445, and 735 minutes after the maximum water depth was attained. Sample times were programmed into the automatic sampler based on the estimated time of drainage. Each sample represented one-fourth of the total simulated storm sample volume. Samples were collected when one-half of each quarter volume was discharged, e.g., the time of the first sample approximated the time that the first 1,075 liters, or the midpoint of the first one-fourth of the total volume, were discharged.

Table 4-1 Synthetic Runoff Constituents and Concentrations

Constituent Added	Necessary Post-Dilution Concentration (mg/L)	Mass Required for Dilution (g)
Detention pond sediment	500	9,080
Gleason clay	40	800
Velvacast kaolin	60	1,200
Coarse clay	20	400
$Pb(NO_3)_2$	0.16	3.03
$Cu(NO_3)_2$ $3H_20$	0.113	2.16
$Fe(NO_3)_2$ $9H_20$	1.8	34.25
$Zn(NO_3)_2$ $6H_20$	0.91	17.22
Na_2CO_3	0.9	17.04

4.5. Volume Measurement

An ISCO 3230 Bubbler Flow Meter was installed in the channel to measure and record water depth in the channel at 5-minute intervals. Water depth data over time were downloaded from the flow meter using a laptop computer running the Flowlink 3.21 software. A relationship for volume as a function of water depth in the basin was developed to determine when to sample. The following is an equation for volume as a function of water depth based on the geometry of the channel basin:

$$V_{Basin} = l(w)(z) + \frac{1}{2}\frac{(z)(z)(w)}{s} \tag{4-1}$$

where

V_{Basin}	=	volume of runoff in the sedimentation basin (m^3),
l	=	length of the base of the basin (m),
w	=	width of basin (m),
h	=	water depth in the basin (m), and
s	=	slope of the channel entrance ramp (m).

4.6. Experimental Procedure

Two sets of experiments were performed. In the first set, the sedimentation basin was drained through an orifice that was installed at the bottom of the retaining wall. In the second set, the skimmer was attached to the outlet structure and the basin was drained from the water surface. The steps involved in each set of experiments were identical and are listed below.

Day 1:

1) Download previous data recorded on the flow meter.
2) Prepare the highway cocktail in a 30 L bucket with approximately 11 L of water and mix for 30 minutes.

3) Fill the mixing tank with filtered water or well water and start the circulation pump.
4) Add the highway runoff cocktail into the mixing tank and mix for at least 30 minutes.
5) Start the transfer pump and open the valve to Channel 2 to flush out the distribution pipe.
6) When the distribution pipe is running clean, open the valve to Channel 1 to begin filling the basin.
7) Monitor the flow meter and collect influent grab samples from the discharge pipe into Channel 1 at water depths of 0.16 m, 0.37 m, 0.54 m, and 0.70 m. The depths correspond to the filling midpoints of successive runoff volumes equal to one-fourth of the total volume.
8) Blend the four grab samples into one composite influent sample.
9) Close the valve on the discharge pipe into Channel 1 at a water depth of 0.78 m (corresponding to 8,600 L), turn off mixing pump, and start the automatic sampler.
10) Allow the mixing tank to drain completely before deactivating the transfer pump.
11) Prepare the influent samples for analysis.

Day 2:

1) Download the flow meter data from the experiment.
2) Collect and prepare the effluent samples for analysis.

The conditions in the sedimentation basin were maintained to simulate a sedimentation pond in the field to the greatest extent possible. The basin was cleaned prior to the first experiment but was allowed to accumulate sediment throughout the experimental period to simulate actual sedimentation ponds.

4.7. Removal Efficiency Calculation

Calculations of the removal efficiencies for the constituents in the simulated highway runoff require three steps: 1) testing the influent and effluent samples for constituent concentrations; 2) determining the flow-weighted average effluent concentrations; and 3) performing a mass balance on the sedimentation basin. The sample analysis was conducted at the CRWR laboratory at the J. J. Pickle Research Campus at The University of Texas at Austin. The constituents examined and the sample analysis methods used are shown in Table 3-2.

A mass balance was performed based on the characteristics of the influent and effluent samples. Ideally, the timer on the automatic sampler was programmed to draw samples at the midpoint of each quarter volume of runoff that flowed out of the sedimentation channel. However, because the drainage times for each experiment were not identical, the volume of runoff assigned to each effluent sample was calculated using a modification of the volume/water depth equation. The following equation was used for determining the runoff volume associated with each effluent sample:

$$V_i = \left(lwh_i + \frac{1}{2}\frac{h_i^2 w}{s} \right) - \left(lwh_{i+1} + \frac{1}{2}\frac{h_{i+1}^2 w}{s} \right) \tag{4-2}$$

where

V_i = volume designated to sample i (m^3),

h_i = water depth at the start of the volume associated with sample i (m), and

h_{i+1} = water depth at the start of the volume associated with sample $i+1$ (m).

The influent and effluent loads were calculated by multiplying the total runoff volume for the experimental run by the influent and flow-weighted average effluent concentrations, respectively. The cumulative mass loading was determined to calculate the removal efficiency. The following equation was used to calculate the removal efficiency of a constituent:

$$R = \left(1 - \frac{\sum_{i=1}^{n} (C_{eff})_i V_i}{\sum_{i=1}^{n} (C_{\inf})_i V_i} \right) * 100\% \tag{4-3}$$

where

R = percent removal for the experiment,
$(C_{eff})_i$ = flow-weighted effluent concentration for experimental run i (mg/L),
$(C_{inf})_I$ = influent concentration for experimental run i (mg/L),
V_i = volume for experimental run i (L),
i = experimental run number, and
n = total number of runs in the experiment.

4.8. Results

4.8.1. Bottom-Drained Experiments

A total of seven bottom-drained experimental runs were performed, of which five were included in the sedimentation study. The sampling scheme, drainage time, and total runoff volume remained constant for most of the runs. Experimental Run 2 was discarded because the required filling height was exceeded; Run 3 was discarded because the flow measurement data were downloaded incorrectly. The other five runs — Runs 1, 4, 5, 6, and 7 — were sampled accurately and were included in the analysis. The drainage times for Runs 1, 4, 6, and 7 were similar. The drainage time for Run 5 was changed to evaluate the effect of extended detention time on sedimentation.

Hydraulic Performance

The drainage patterns for the four experiments used in the bottom-drained sedimentation analysis are presented in Figure 4-4. The drainage times were relatively consistent at 18 to 22 hours. The increase in drainage time observed over time was a result of outlet structure clogging. Clogging was caused by sediment, algae, and plant material that accumulated in the narrow opening of the effluent control valve. Significant clogging of the valve was experienced in Run 5. Discharge ceased shortly after the experiment was initiated. The valve was cleaned the following day, and the basin began draining again. Consequently, the data observed in Run 5 was used to test extended detention. The valve position was changed slightly during cleaning, and the drainage times of Runs 6 and 7 increased. This small difference did not significantly affect the effluent sampling scheme. Approximately one-fourth of the total volume was still assigned to each sample.

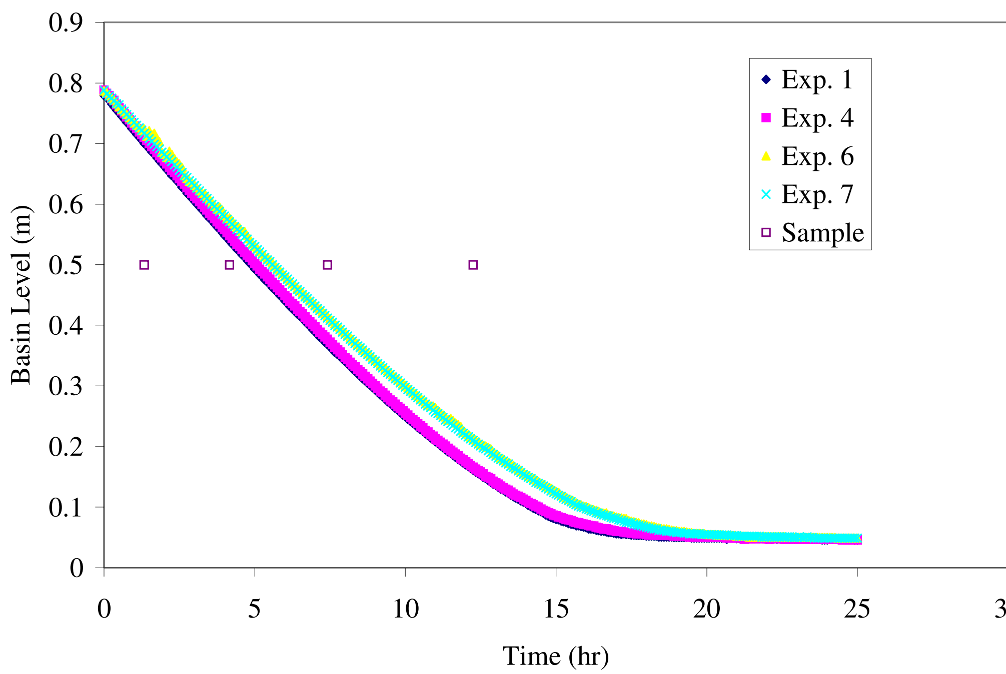


Figure 4-4 Bottom-Drained Experiment Drainage Patterns

Removal Efficiency

The mass balance results for the bottom-drained experiment are shown in Table 4-2. The loadings for all constituents except turbidity were based on four experimental runs. Because the influent turbidity concentration for Run 6 was not available, that run was not included. The results presented in Table 4-2 show that bottom-drained sedimentation is a viable option for the treatment of the synthetic highway runoff. Almost all the constituents were removed to some extent. Nitrate was the only constituent that increased in concentration after treatment, indicating that nitrification occurred. Sedimentation was most effective in removing COD and TSS's. The removal efficiencies for COD and TSS's were 73% and 70%, respectively. Nutrient removal efficiencies were less because a substantial fraction of nitrogen and phosphorus are soluble and are not removed by sedimentation.

Table 4-2 Mass Balance Results for the Bottom-Drained Experiment

Constituent	Avg. Influent Conc. (mg/L)	Influent Load (g)	Avg. Effluent Conc. (mg/L)	Effluent Load (g)	Removal (%)
TSS	300	10,413	90	3,128	70
Turbidity	131	4,551	85	2,954	35
COD	23	782	6.0	209	73
TOC	19	659	12	419	36
Nitrate	0.27	9.48	0.30	10.6	-11
TKN	1.37	47.6	0.88	30.5	36
Phosphorus	0.31	10.8	0.14	4.92	54
Zinc	0.21	7.35	0.10	3.49	53

The TSS's are the best representation of particulate removal: concentration and time during the four runs are consistent. The data representing the percent TSS's remaining in the runoff over time that are presented in Figure 4-5 indicate that 60–70% of the removal of TSS's occurred during the first 4 hours. After that time, the percent remaining begins to level off as the percentage of smaller particulate material in suspension increases. The percent of TSS's remaining decreased to between 10% and 25% by the end of the sampling period. A longer detention time was necessary to determine any additional removal by TSS's.

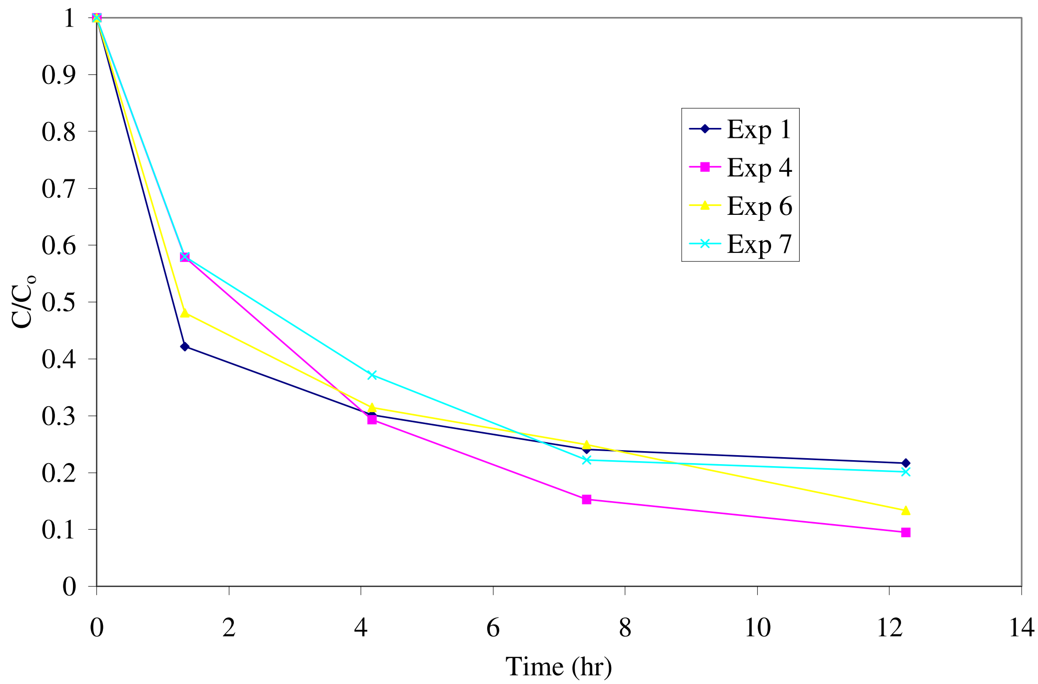


Figure 4-5 Fraction of TSS's Remaining over Time for the Bottom-Drained Experiment

The effect of detention time on removal efficiency was evaluated in Run 5. The runoff in Run 5 was detained with no drainage for approximately 24 hours. Drainage was initiated, and the automatic sampler was activated at the end of the 24-hour period. The results of the mass balance for this experiment are shown in Table 4-3.

The extended detention time improved the removal of TSS's from 70% to 96%. Turbidity removal increased from 35% to 85%, while the removal for nitrate and TKN increased to 3% and 58%, respectively. Phosphorus removal also increased from 54% to 87%. However, COD and zinc remained relatively unchanged and TOC removal decreased from 36% to 23%. Overall, it was evident that extending the detention time improved the water quality.

Table 4-3 Mass Balance Results for the 24-Hr Detention Experiment

Constituent	Avg. Influent Conc. (mg/L)	Influent Load (g)	Avg. Effluent Conc. (mg/L)	Effluent Load (g)	Removal (%)
TSS	270	1,796	11	75	96
Turbidity	164	1,091	25	167	85
COD	33	219	9	63	71
TOC	22	147	17	114	23
Nitrate	0.46	3.06	0.45	2.98	3
TKN	1.00	6.62	0.42	2.77	58
Phosphorus	0.23	1.53	0.03	0.20	87
Zinc	0.114	0.758	0.060	0.398	48

4.8.2. Surface-Drained Experiments

The purpose of investigating surface-drained sedimentation was an evaluation of the improvement in removal that could be achieved over bottom-drained sedimentation. It was predicted that the surface of the runoff basin would contain the cleanest portion of the total volume during the draining period. At time zero, when the basin was completely full of runoff, the composition of particles was assumed to be uniform throughout the entire volume. Samples were taken at two depths, x and y, from the surface of the water and $x < y$. After a certain time, t, Sample x should contain particles with a settling velocity $\leq \frac{x}{t}$, and Sample y should contain particles with a settling velocity $\leq \frac{y}{t}$ (Lawler 1997). Because $\frac{y}{t} > \frac{x}{t}$, Sample y contains particles having a larger fraction of settling velocities. Because it was assumed that the particles with a given settling velocity were uniformly mixed throughout the basin at time zero, then Samples x and y should have the same concentration of particles for any given settling velocity $\leq \frac{x}{t}$. However, because Sample y also contains particles with settling velocities $> \frac{x}{t}$, but $\leq \frac{y}{t}$, then Sample y contains more total particles. A concentration gradient develops that is decreasing in the upward vertical direction over time. Therefore, by skimming water from the surface, the cleanest water should be removed, and the removal efficiency can be improved.

Surface-drained sedimentation was tested in three experimental runs, Runs 8, 9, and 10. The percent removal for each constituent was based on the loadings for all three experimental runs. In each run, the basin was drained using a skimmer (Figure 4-3). The cocktail used was the same as that used in the bottom-drained experiment.

Hydraulic Performance

No problems were encountered with the skimmer during draining; however, there was difficulty initiating draining. The skimmer did not submerge and begin draining immediately as the basin filled with runoff. Air was trapped in the skimmer hose, retarding the flow to the effluent pipe. The skimmer was not submerged properly even at the maximum basin depth. The hose had to be positioned manually to release the trapped air before the draining process could begin.

The drainage patterns for Runs 8, 9, and 10 are shown in Figure 4-6. The goal for this experiment also was a drainage time in the range of 18–22 hours. In a trial run with clean water, it was discovered that with the same valve setting, the basin drained slower with the skimmer than without skimmer. The effluent valve was opened to increase the flow to compensate. Some valve adjustments were still being made during the experimental phase (Figure 4-6). The drainage times ranged from 16–23 hours. The sampling scheme used to obtain an accurate volume associated with each sample was not adjusted, though this range was larger than those observed in the previous set of experiments.

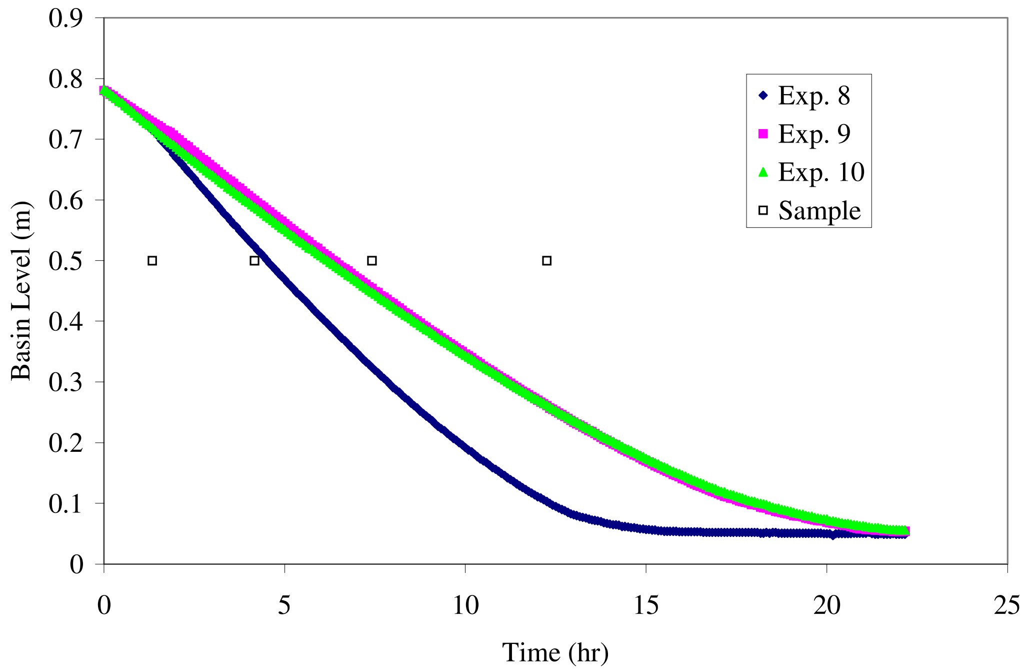


Figure 4-6 Surface-Drained Experiment Drainage Patterns

Removal Efficiency

The mass balance results for the three surface-drained experiments are presented in Table 4-4. The results indicate that surface-drained sedimentation was effective in treating simulated highway runoff. Surface-drained treatment efficiencies were slightly greater than bottom-drained efficiencies in the removal of some constituents. TOC was an exception. TOC removal increased from 36% to 56%. Surface draining was shown to be less effective for COD and zinc. COD decreased from 73% to 41% and zinc decreased from 53% to 33%. Phosphorus removal remained the same. The only constituent to increase in concentration after sedimentation was nitrate. Surface-drained sedimentation did not outperform sedimentation with extended detention times. Overall, constituent removal efficiencies with extended detention were greater than removal efficiencies with surface draining. TOC was the only constituent with a greater removal by surface draining.

Table 4-4 Mass Balance Results for the Surface-Drained Experiment

Constituent	Avg. Influent Conc. (mg/L)	Influent Load (g)	Avg. Effluent Conc.(mg/L)	Effluent Load (g)	Removal (%)
TSS	260	6,722	63.2	1,636	76
Turbidity	162	4,191	93.0	2,406	43
COD	28.7	742	16.9	439	41
TOC	28.3	734	12.4	322	56
Nitrate	0.30	7.85	0.32	8.32	-6
TKN	0.97	25.2	0.57	14.8	41
Phosphorus	0.30	7.77	0.14	3.59	54
Zinc	0.22	5.61	0.15	3.77	33

This experiment also showed a clear relationship between TSS concentration and time. A plot of percent TSS's remaining versus time is presented in Figure 4-7. The data indicate that most of the removal by sedimentation occurred within the first 1.5 hours. The percent TSS's remaining decreased to approximately 30–40% after 2 hours, and the rate of removal began to level off in a linear fashion. The linear trend continued to the end of the sampling period, approximately 12 hours after draining was initiated. TSS's had decreased to approximately 10–20% of the influent concentration after 12 hours.

The suspended solids concentration initially decreased at a faster rate for the surface experiment as compared with the bottom experiment. Removal of TSS's by 60–70% was observed in 2 hours in the surface experiment and in about 4 hours in the bottom experiment. The percentage of TSS's remaining is almost equal after approximately 7.5 hours. Therefore, the difference in removal may be attributable to surface-drained sedimentation that resulted in a lower concentration of TSS's within the first few hours of settling.

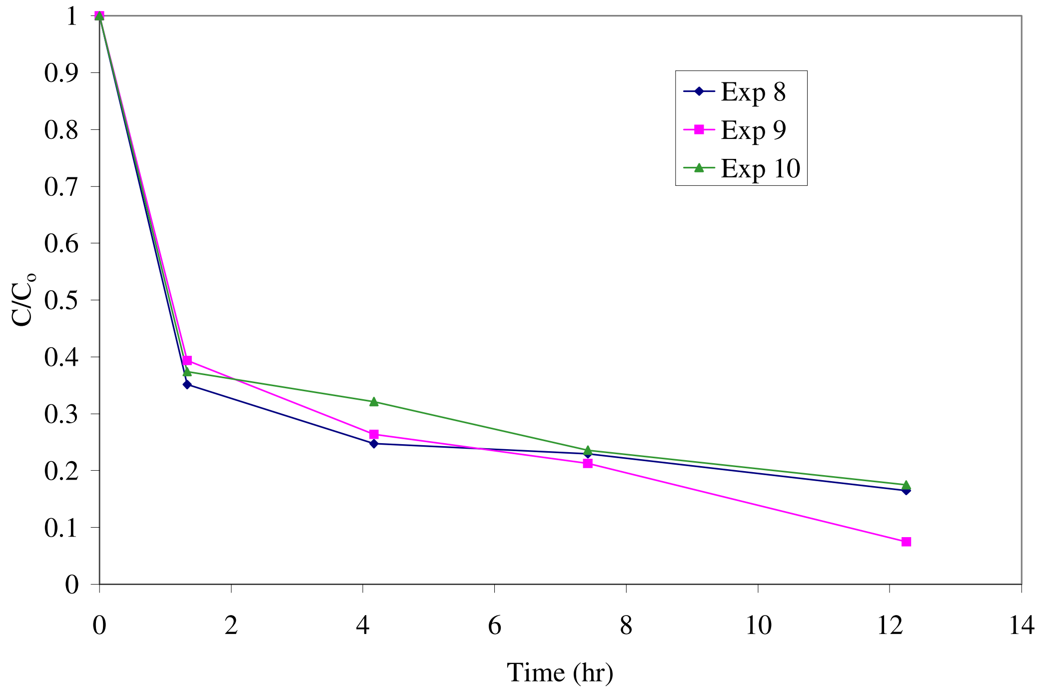


Figure 4-7 Fraction of TSS's Remaining over Time for the Surface-Drained Experiment

4.9. Discussion

The objective in conducting the prototype experiments was to evaluate the sedimentation process in a controlled environment, separate from filtration. Variables such as storm volume, drainage time, storm frequency, influent constituent concentrations, and particle-size distribution were controlled. Studying only the sedimentation basin allowed for the accurate evaluation of the hydraulic and constituent removal performance of the basin.

4.9.1. Overall Effectiveness of Sedimentation

A total of eight experimental runs were evaluated in the sedimentation study. The overall results indicate that sedimentation results in excellent removal of TSS's, good removal of phosphorus, moderate to good removal of organics and zinc, and poor to moderate removal of nitrogen constituents. In general, the removal efficiencies were highest for the constituents having the largest fraction of particulate material. Removal of TSS's, the only constituent comprised of all particulate material, was 70% or greater. Approximately 50% removal of phosphorus was observed in both surface and bottom draining. Approximately half of the total phosphorus in highway runoff is in the particulate form (Schueler 1987). Nitrogen and organic constituent removals were typically lower because much of the constituent is dissolved in the runoff. Oxygen supply and microbial population also affect removal of organics.

4.9.2. Comparison of Surface Draining and Bottom Draining

The results from the prototype experiments indicate that the improvement from bottom-drained to surface-drained sedimentation was marginal. Removals of TSS's, turbidity, and TKN were slightly superior in the surface-drained basin. Nitrate removal also improved; however, the removal remained negative. The removal efficiency improvements were relatively small, increasing by approximately 5–6 percentage points. TOC was the only constituent that exhibited much higher removal with the surface-drained experiments. The phosphorus removal for both experiments was 54%. The removal of COD and zinc was significantly less in surface-drained sedimentation. Removal of COD decreased from 73% to 41% and removal of zinc decreased from 53% to 33% in the bottom-drained experiments, compared with the surface-drained experiments.

The large discrepancy in COD and zinc removals is difficult to explain. The average influent concentrations for both experiments were similar (Table 4-2 and Table 4-4). The magnitude of COD removal is generally difficult to predict because removal involves two mechanisms, settling and microbial degradation (Dorman et al. 1988). Thus, COD removal is affected by a number of factors, such as detention time, microbial population, and dissolved oxygen concentration; laboratory or analytical errors are other possibilities. Several effluent COD concentrations were below detection limit in three of the four bottom-drained experiments. Zinc samples were tested at two different laboratory facilities. Most of the bottom-drained samples were analyzed at CRWR, while the Lower Colorado River Authority analyzed all the surface-drained samples.

The results of this study indicate that performance efficiency of surface-draining outlet structures was not sufficient to justify replacing bottom-draining outlet structures. Possible mechanical problems and maintenance requirements associated with a skimmer device must also be considered. A mechanical outlet structure, such as a skimmer, makes the sedimentation pond outlet more susceptible to malfunctions. The small increase in removal efficiency likely would not be worth the extra maintenance requirements.

4.9.3. Effect of Delayed Draining on Removal Efficiency

The results from experimental Run 5 indicate that delaying drainage for 24 hours improves removal considerably. Extending the detention time resulted in excellent removal of solids, COD, and phosphorus. Removal of TKN and zinc was good, while removal of nitrate was poor.

The removal efficiency for phosphorus, at 87%, was unusually high. One possible explanation for this result is the source of the constituent used in the synthetic highway runoff. Phosphorus was associated with the sediment collected from the floor of an actual sedimentation pond. The phosphorus component of the sediment represents only the fraction that settled out of the runoff. The dissolved fractions passed through the system. Thus, the synthetic runoff contained an uncharacteristically high fraction of particulate material that resulted in an unusually high removal rate for sedimentation.

Extending the basin detention time resulted in effective removal of particulate material. Unlike the dissimilarity of phosphorus in the synthetic runoff to the phosphorus in the actual runoff, TSS concentrations and particle-size distribution in the synthetic runoff were similar to TSS's in actual runoff (Dulay 1996). A plot of percent TSS's remaining over time for each of the four effluent samples collected is presented in Figure 4-8. Data for each of the three types of experiments are included. Delaying drainage for 24 hours reduced TSS concentrations in the effluent, especially for the first three samples. TSS removal was approximately 90% at 20–24 hours. The maximum limit for TSS removal was approached. Therefore, extending the drainage time so that a majority of the volume remains in the basin for at least 20 hours will result in greater removal efficiency.

After 24 hours, C/C_o remains relatively constant. This indicates that extending the drainage time too far will not substantially improve the removal of TSS's.

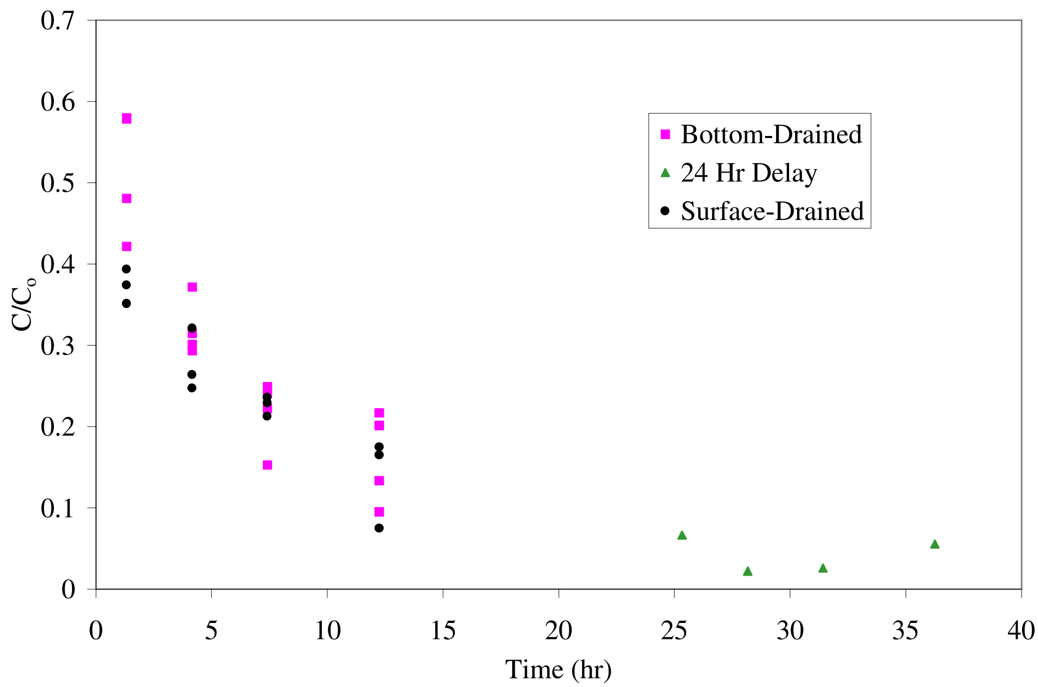


Figure 4-8 Comparison of TSS Removal for Different Drainage Characteristics

The results observed in Run 5 indicate that extended detention significantly reduces the concentration of pollutants in the synthetic runoff. The removal efficiency data observed for the prototype sedimentation basin produced results comparable to those for the Seton Pond sedimentation/filtration system. TSS removal was 96% for the prototype basin, compared with 98% for the Seton Pond facility. The removal of soluble constituents was one area where extended detention did not result in increased removal. Only 3% of the nitrates were removed in the prototype basin. This value is low compared with the removal at the Seton Pond facility; however, low nitrate removal is typical for most sedimentation/filtration systems. Overall, the extended detention basin was very effective for particulate removal. Extended dry detention ponds are recommended where soluble pollutant treatment is not a major concern.

5. SUMMARY AND CONCLUSIONS

5.1. Seton Pond Field Study

The Seton Pond runoff control facility was constructed by the Texas Department of Transportation (TxDOT) in Austin, Texas, to capture and treat runoff from US Highway 183. Runoff was treated to reduce the impact of pollutants on Walnut Creek. The performance of the sedimentation/filtration facility was monitored over a period of 18 months. Hydraulic performance, removal of constituents, and maintenance requirements were determined. Recommendations for improving the performance of the facility were developed.

The removal of constituents observed for the Seton Pond facility was higher than removals reported for other sedimentation/filtration systems in the area. Removal of solids, zinc, and iron was excellent, and removal of nutrients and organics was good. However, these results are not representative of the total runoff draining from the watershed. When bypassed runoff is taken into account in the system mass balance, the removal efficiency is decreased.

Several possibilities for the superior performance exhibited at Seton Pond were identified. The most important factor was increased detention time. A longer detention time allowed a greater fraction of particulate matter and constituents that are adsorbed to the particulate matter to settle out. Particulates that escaped the sedimentation basin accumulated on the surface of and in the sand filter. One possible reason for unusually high nutrient removal was the rooted plants growing in the sand filter. The plants took up soluble nutrients for growth and maintenance requirements. Two mechanisms predicted for the removal of dissolved metals were adsorption to particles that settled out and adsorption to organic materials accumulating in the sand filter. The accumulation of organic materials could increase the cation exchange capacity of the filter medium, thus improving metal adsorption.

The removal of constituents at the Seton Pond sedimentation basin was superior to typical removal efficiencies for sedimentation ponds. Removal of TSS's, zinc, and iron was excellent, and the removal of organics and phosphorus was good. Removal of TKN was moderate, and removal of nitrate was poor. The superior performance at the Seton Pond sedimentation basin was attributed to the exceptionally long drainage times observed during the course of the study. As the drainage times increased, an improvement in removal efficiency was observed. The sedimentation basin required more time to drain when filter operation resumed. The storm events receiving no filtration drained in 4 to more than 7 days. The storm events that were filtered drained in 7 to more than 14 days. With the exception of TKN, the removal of all constituents in the sedimentation basin was greater when the filter was operational.

The overall hydraulic performance of the sedimentation/filtration system was poor. The design drainage time was 24–48 hours. However, the drainage time ranged from 7 days to more than 14 days during the monitoring period. The increasing drainage time adversely affected the capture volume of the sedimentation basin. Therefore, a large portion of the runoff bypassed the system. Approximately 20% of the total volume of runoff from the watershed bypassed the Seton Pond facility during the monitoring period.

Maintenance is essential for proper hydraulic operation and optimum constituent removal. Lack of maintenance resulted in chronic clogging of the sand filter, which dramatically reduced the drainage rate of the runoff. Longer drainage times decreased the capture volume of the sedimentation basin and caused untreated runoff to bypass the facility. The calculated TSS loading on the sand filter was 3.3 kg/yr per m^2 of filter area. At this rate, maintenance on the sand filter bed was required at least two times per year.

The extended detention time provided by the clean sand filter was adequate for treating highway runoff. The clogging of the sand filter caused the drainage time to increase by a week or more. This additional detention time was not necessary and provided no substantial improvement in particulate removal by sedimentation or filtration. Longer detention times only caused more runoff to bypass. Detention time increased to such an extent that the sand filter was transformed into a wet pond. The wet pond provided better nutrient removal for runoff that entered the basin; however, the capture volume was reduced. A smaller volume of runoff was receiving improved treatment, but the increase in untreated bypassed runoff negated the improvement. Therefore, the increase in untreated bypass was of greater concern than the soluble nutrient effluent concentration.

5.2. Prototype Sedimentation Analysis

Draining from the surface of the prototype basin provided slightly improved removal for most of the constituents. However, the improvement was not sufficiently substantial to recommend one outlet design over the other. The TSS removal was excellent for both types of draining, nutrient removal was poor to good, and organic and trace metal removal was moderate to good. The results showed that some constituents were removed to a greater extent in the bottom-drained system. The removal efficiencies for COD and zinc were considerably greater in the bottom-drained experiments.

Surface-draining outlet structures, such as the skimmer, were not reliable for draining a sedimentation basin. In the lab experiments, the problems encountered initiating draining could be compounded at a field site. Because surface draining only improved removal slightly, if at all, and required the use of an unreliable outlet structure, we concluded that surface draining provides no advantage over bottom draining.

Detaining the runoff 24 hours prior to draining significantly improved the removal efficiencies of most constituents. Approximately 95% of suspended solids were removed, removal of organics and metals was good, and removal of nutrients was poor to excellent. (Nutrient removals may have been high because of an unusually high particulate fraction in the synthetic runoff). Overall, the results from the 24-hour detention experiment showed removal efficiencies comparable to sedimentation/filtration systems.

Dry extended detention ponds are a reasonable alternative to sedimentation/filtration systems under two conditions: 1) the area does not require significant removal of soluble pollutants, and 2) a majority of the captured runoff is detained for at least 20–24 hours. Ponds may show slightly less removal than sand filters; however, ponds are cheaper than filters and, moreover, do not need to be maintained as frequently.

5.3. Recommendations

5.3.1. General

- Sedimentation/filtration systems are recommended in urban areas having high impervious cover and where a large quantity of runoff is generated and the space in which to build a runoff control is limited.
- Regular maintenance is required to maintain desirable drainage rates and maintain the maximum capture volume.
- Factors that can affect the maintenance frequency are the watershed size, the presence of construction or unlined channels on the watershed, and the storm frequency in the region. These factors should all be carefully considered in the design of new sedimentation/filtration systems.
- In areas where soluble nutrients are a concern, a grass layer can be planted on the filter bed to enhance nutrient removal. It is not recommended that the filter be neglected in order to develop wet pond conditions. If soluble nutrients are still a problem, then the runoff control design must be reevaluated for that particular area.
- Dry extended detention ponds should be considered as a feasible alternative to sand filters. Detention ponds are cheaper to construct and maintain and can provide comparable treatment when designed to fully drain in 72–96 hours.
- A pond should be installed with a simple outlet structure that provides adequate detention time and that is not prone to clogging. Skimmers are not necessary for achieving adequate removal of constituents in runoff.

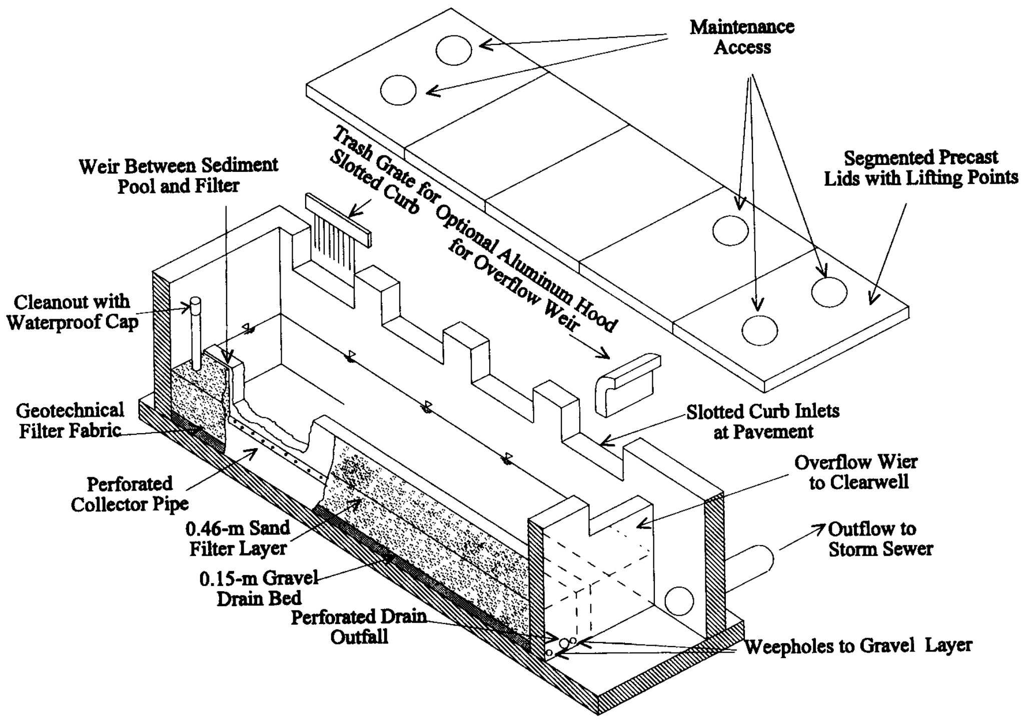
5.3.2. Site Specific

- Regular maintenance is required to continue operations as a sedimentation/filtration system.

- Biannual maintenance should be performed and should include removing the top layer of sand and accumulated sediment from the surface of the filter bed. Sediment also should be removed from the sedimentation basin, the hazardous materials trap (HMT), and the influent channel if necessary.
- Monthly maintenance is necessary to sustain an aesthetically pleasing facility. This maintenance includes mowing and collecting debris. The outflow structures also need to be inspected for clogging during these maintenance visits.

APPENDIX A

Delaware Sand Filter

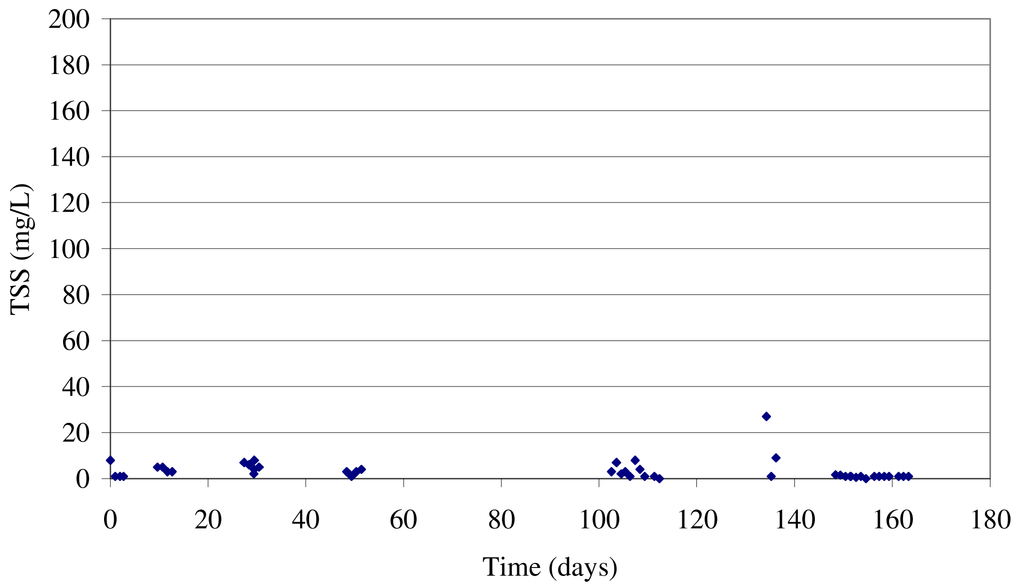


Delaware Sand Filter

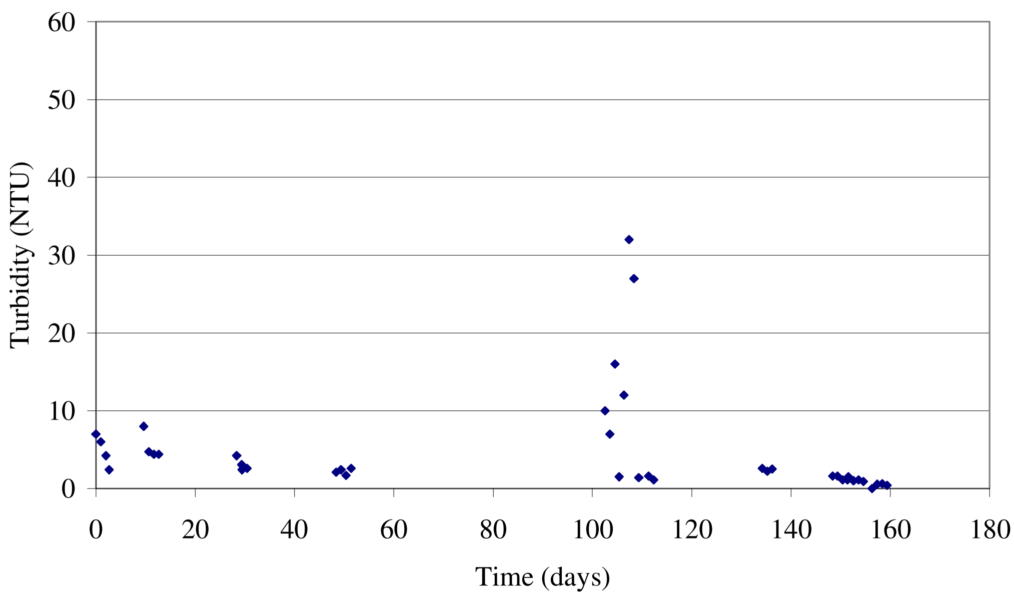
APPENDIX B

Constituent Concentrations in the Filter Effluent Plotted over Time

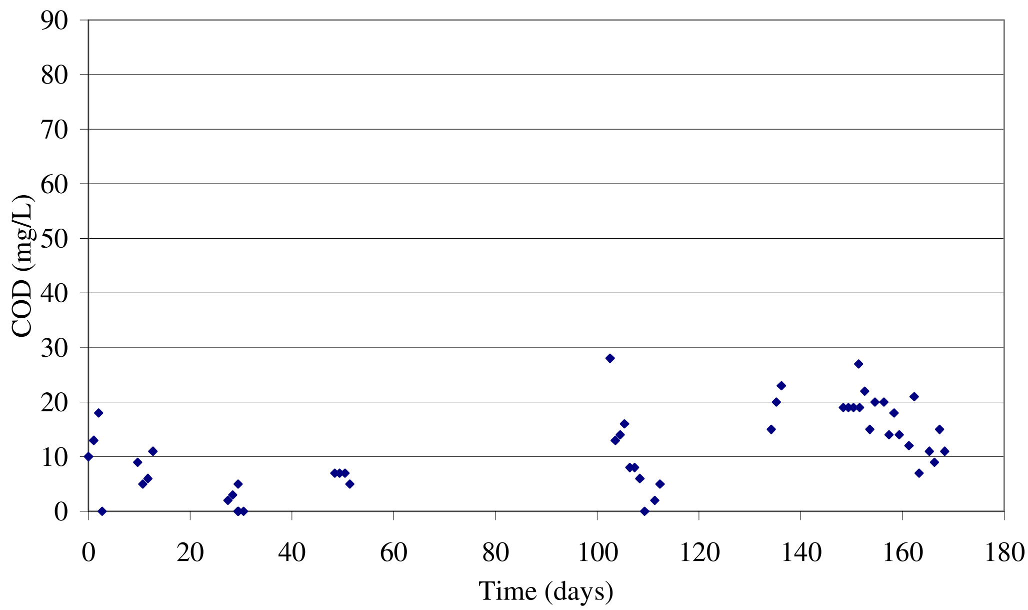
TSS vs. Time



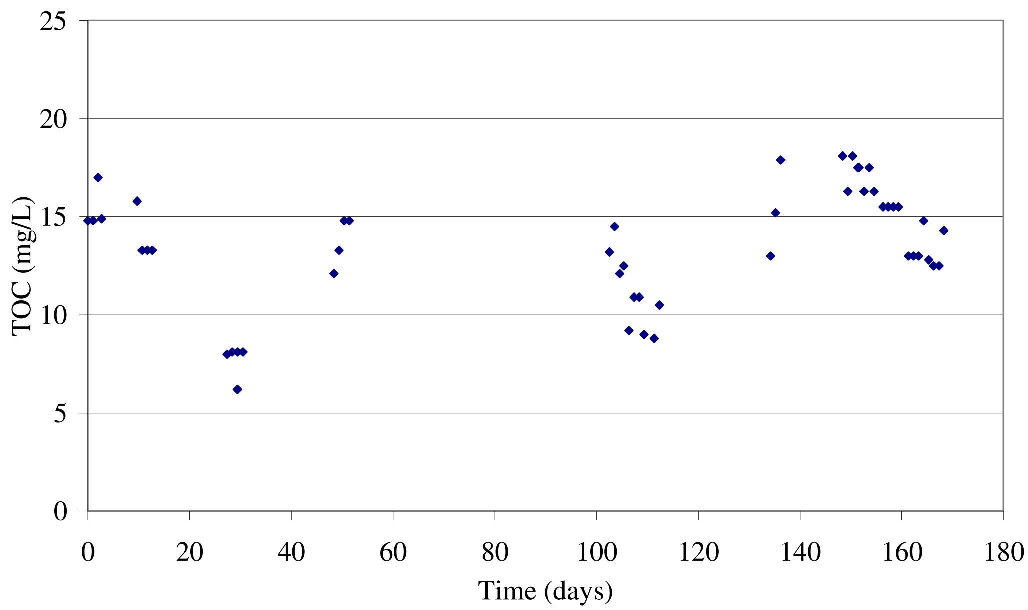
Turbidity vs. Time



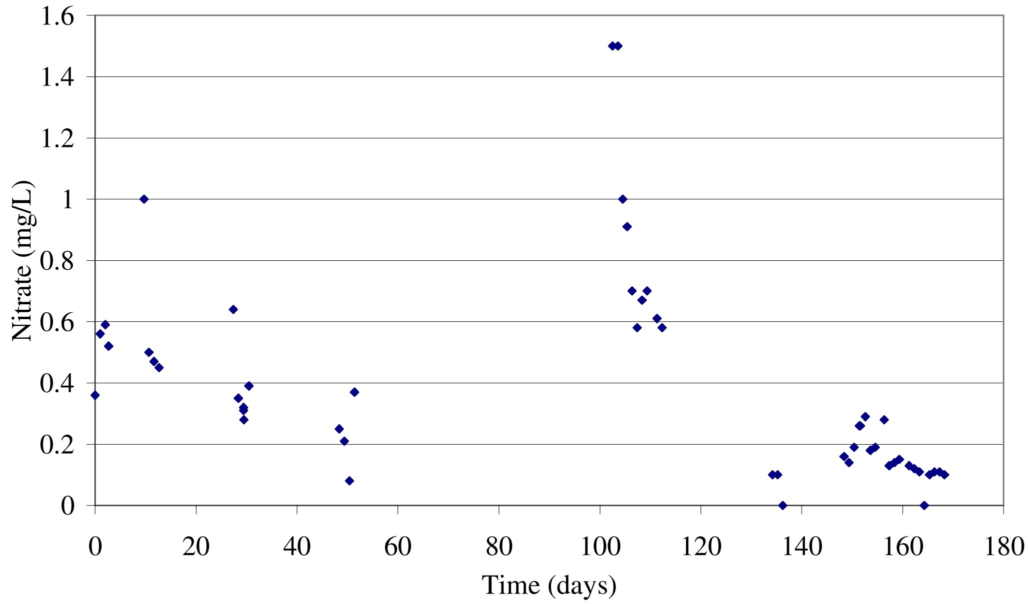
COD vs. Time



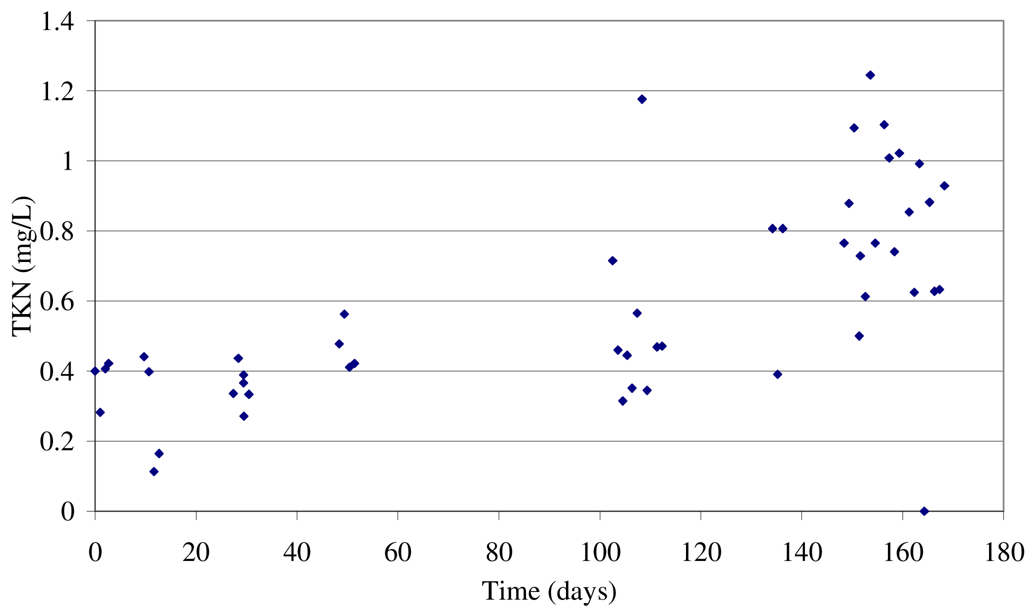
TOC vs. Time



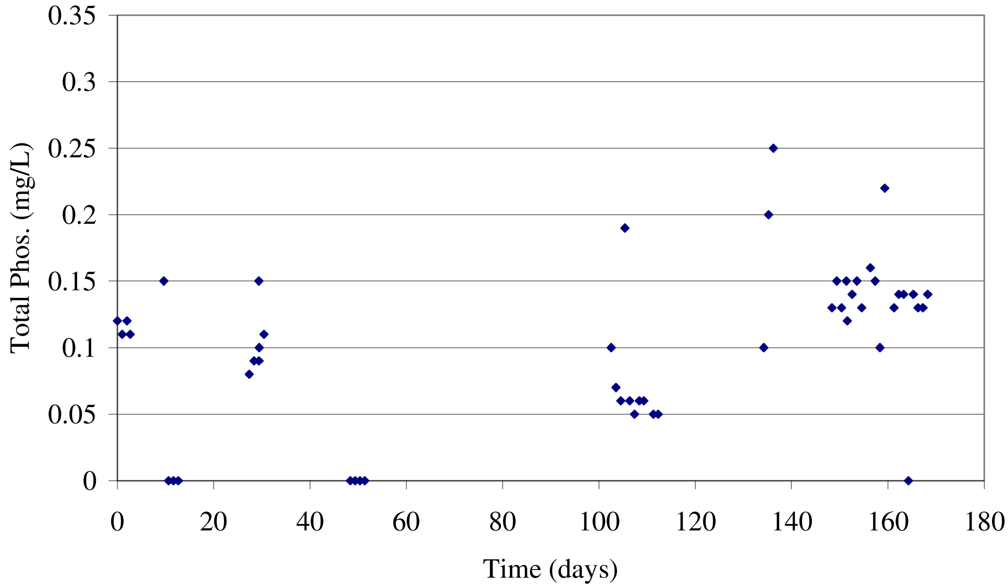
Nitrate vs. Time



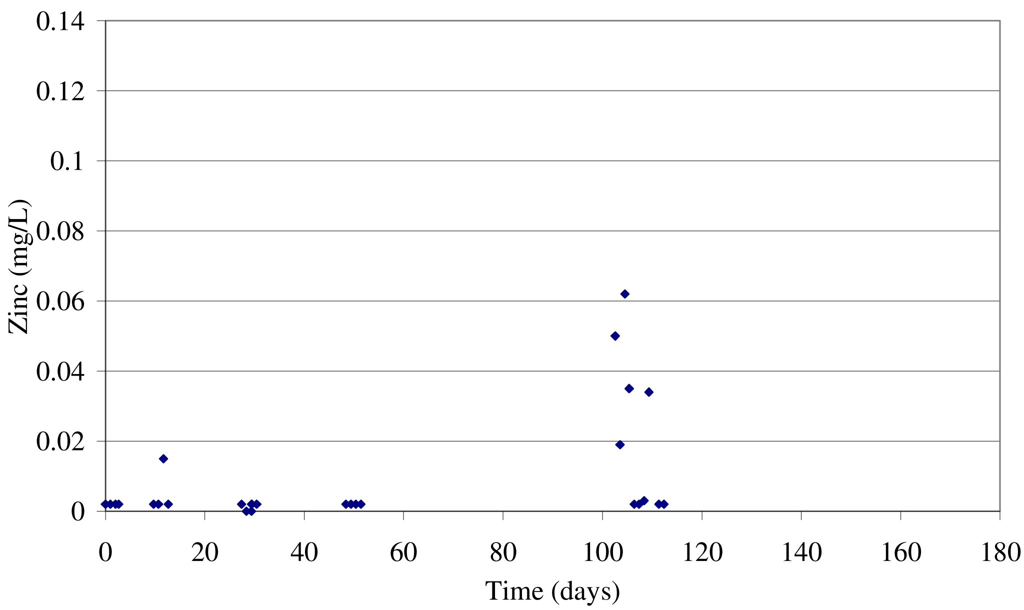
TKN vs. Time



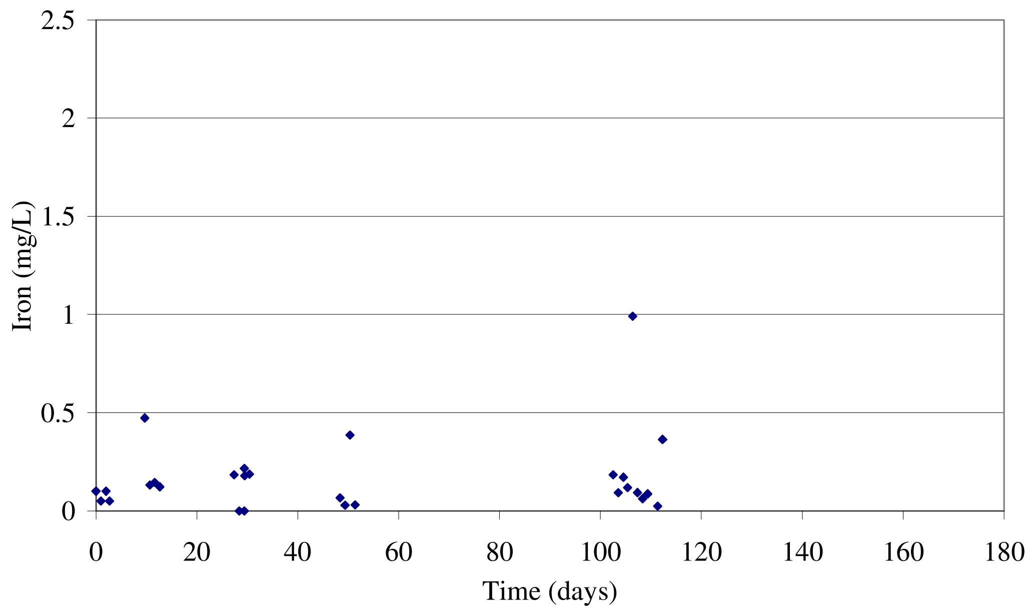
Total Phos. vs. Time



Zinc vs. Time



Iron vs. Time



APPENDIX C

Raw Data for the Seton Pond Facility

Summary of Constituent Concentrations in the Influent Channel

(* = unsampled volume)

Sample	Sample	Sample	Cum.	TSS	Turbidity	COD	TOC	Nitrate	TKN	Total	Zinc	Iron
No.	Date and Time	Volume	Volume							Phos.		
		Liters	Liters	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Storm 3												
1	11/17/95 12:15	46465	46465	101	43	134	NA	1.20	NA	0.34	0.124	3.189
2	11/17/95 12:20	41396	87861	143	46	134	NA	1.05	NA	0.36	0.183	3.946
3	11/17/95 12:50	227256	315117	151	49	104	NA	0.63	NA	0.33	0.142	3.302
4	11/17/95 13:20	653044	968161	219	52	86	NA	0.31	NA	0.34	0.145	3.210
5	11/17/95 14:20	1670206	2638366	69	31	13	NA	0.14	NA	0.18	0.042	1.268
6	11/17/95 15:20	1262159	3900525	20	28	27	NA	0.22	NA	0.18	0.001	0.135
Storm 4												
1	12/8/95	40000	40000	802	102	481	NA	3.60	4.000	1.00	0.792	15.266
2	12/9/95	40000	80000	730	106	947	NA	3.10	3.500	1.01	0.551	9.701
3	12/10/95	272000	352000	371	66	116	NA	1.20	1.430	0.47	0.170	5.219
4	12/11/95	178000	530000	125	72	105	NA	1.45	1.130	0.42	0.079	4.330
5	12/12/95	46600	576600	19	33	44	NA	1.90	0.850	0.29	0.027	0.135
6	12/13/95	700	577300	4	18	39	NA	1.65	0.650	0.27	0.145	0.768
Storm 5												
1	12/17/95	305000	305000	465	51	152	NA	0.88	1.130	0.37	0.250	4.688
2	12/17/95	305000	610000	602	52	117	NA	0.65	0.950	0.60	0.366	6.547
Storm 6												
1	2/29/96 10:35	13909	13909	332	140	237	NA	3.40	2.150	0.75	0.167	4.028
2	2/29/96 10:39	91908	105818	407	140	134	NA	2.25	2.050	0.96	0.345	5.867
3	2/29/96 11:09	98785	204603	197	92	117	NA	1.50	1.360	0.42	0.238	3.101
4	2/29/96 11:39	186630	391233	156	59	109	NA	1.50	1.320	0.52	0.214	3.833
5	2/29/96 12:39	380454	771687	311	54	123	NA	0.80	0.650	0.61	0.236	4.677
6	2/29/96 13:39	521910	1293596	102	49	52	NA	0.93	0.900	0.00	0.072	1.928

Summary of Constituent Concentrations in the Influent Channel (continued)

Sample No.	Sample Date and Time	Sample Volume Liters	Cum. Volume Liters	TSS mg/L	Turbidity NTU	COD mg/L	TOC mg/L	Nitrate mg/L	TKN mg/L	Total Phos. mg/L	Zinc mg/L	Iron mg/L
Storm 11												
1	4/22/96 9:25	1104	1104	275	96	231	74.8	1.75	NA	0.65	0.129	2.332
2	4/22/96 9:29	11436	12540	369	104	168	66.7	1.85	NA	0.63	0.278	2.921
3	4/22/96 9:59	253358	265898	399	51	101	31.4	1.01	NA	0.54	0.223	3.461
4	4/22/96 10:29	146317	412215	93	46	83	21.9	2.40	NA	0.35	0.096	1.747
5	4/22/96 11:29	246963	659178	265	54	76	32.1	0.86	NA	0.39	0.097	2.757
6	4/22/96 12:29	134579	793757	27	31	58	17.5	1.40	NA	0.29	0.050	0.589
7	4/22/96 13:29	59088	852845	28	24	43	18.7	1.72	NA	0.26	0.047	0.534
8	4/22/96 14:29	49709	902554	52	29	81	32.1	3.29	NA	0.29	0.064	0.998
9	4/22/96 15:29	46900	949454	128	96	107	46.1	2.50	NA	0.35	0.121	2.107
10	4/22/96 16:29	11085	960539	94	88	103	36.4	2.48	NA	0.32	0.095	2.009
11	4/22/96 17:29	0	960539	19	24	72	27.2	2.20	NA	0.26	0.076	0.545
12	4/22/96 18:29	0	960539	9	17	45	18.5	0.82	NA	0.25	0.067	0.352
Storm 15		421404	421404	270	54	108	28.7	1.06	1.223	0.40	0.172	3.634
1	6/23/96 14:29	65358	486763	342	96	142	57.0	1.00	5.253	0.51	0.291	6.177
2	6/23/96 14:33	40178	526941	332	68	119	41.9	1.85	3.139	0.43	0.219	4.525
3	6/23/96 15:03	74889	601830	36	25	53	22.0	4.87	2.120	0.22	0.028	0.984
4	6/23/96 15:33	30297	632126	32	27	70	26.8	1.80	2.772	0.26	0.011	0.482
5	6/23/96 16:33	41432	673559	18	8	45	16.9	1.49	2.999	0.22	0.147	0.107
6	6/23/96 17:33	21413	694972	16	5	31	20.3	5.60	2.079	0.22	0.001	0.122
Storm 19	*	5942951	5942951	262	53	106	29.5	1.16	1.419	0.39	0.169	3.559
1	8/22/96 10:06	152868	6095818	29	27	139	45.8	2.20	17.986	0.32	0.051	2.138
2	8/22/96 10:20	178660	6274478	52	41	270	53.7	3.00	2.071	0.45	0.160	3.728
3	8/22/96 10:50	48926	6323404	40	43	75	34.4	2.70	1.908	0.33	0.039	1.609
4	8/22/96 11:20	50802	6374206	15	23	64	26.5	4.70	2.152	0.28	0.001	0.680
5	8/22/96 12:20	64556	6438762	52	6	28	14.6	4.20	1.293	0.24	0.001	0.118
6	8/22/96 13:20	256187	6694949	84	80	142	66.0	6.80	2.317	0.54	0.180	5.248
7	8/22/96 14:30	48766	6743715	22	37	38	17.7	0.83	2.224	0.31	0.013	1.011
8	8/22/96 15:29	59710	6803425	54	76	111	43.6	1.40	1.779	0.33	0.038	1.816
9	8/22/96 16:29	25010	6828435	71	88	116	41.8	10.00	2.064	0.38	0.070	3.043
10	8/22/96 17:29	5156	6833592	20	31	82	33.9	1.40	1.710	0.32	0.018	0.976
11	8/22/96 18:29	404836	7238428	48	64	81	42.3	0.90	2.190	0.40	0.121	4.564
12	8/22/96 19:29	256498	7494926	21	29	37	21.2	0.79	1.791	0.26	0.001	1.611

Summary of Constituent Concentrations in the Influent Channel (continued)

Sample No.	Sample Date and Time	Sample Volume	Cum. Volume	TSS	Turbidity	COD	TOC	Nitrate	TKN	Total Phos.	Zinc	Iron
		Liters	Liters	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Storm 21	*	5055439	5055439	255	53	106	30.0	1.16	1.511	0.39	0.175	3.548
1	8/29/96 11:57	332621	5388060	8	47	126	55.6	3.50	2.861	0.51	0.001	1.561
2	8/29/96 12:56	141927	5529987	60	47	41	12.0	0.74	1.440	0.29	0.015	2.186
3	8/29/96 13:56	49237	5579224	8	17	22	8.0	2.30	0.914	0.18	0.001	0.605
4	8/29/96 14:56	35325	5614549	1	5	17	8.0	1.95	0.812	0.15	0.001	0.202
5	8/29/96 15:56	535976	6150526	46	40	31	9.9	1.30	1.259	0.25	0.041	2.884
6	8/29/96 16:56	207732	6358258	26	32	32	9.8	3.50	0.934	0.19	0.001	1.561
Storm 24	*	44081	44081	250	53	105	29.8	1.23		0.39		3.511
1	10/27/96 14:06	327620	371701	248	168	136	60.2	0.55	2.842	0.47	0.100	4.800
2	10/27/96 15:05	86436	458136	73	64	49	23.3	0.67	1.083	0.26	<0.05	1.200
3	10/27/96 16:05	355128	813264	80	63	62	40.6	0.55	2.256	0.31	0.100	3.100
4	10/27/96 17:05	74869	888133	24	30	19	14.7	0.52	NA	0.18	<0.002	0.900
5	10/27/96 18:05	50802	938935	21	29	17	14.7	0.50	0.204	0.15	<0.002	0.600
6	10/27/96 19:05	90504	1029439	16	21	14	16.8	0.42	0.641	0.14	<0.002	0.500
7	10/28/96 10:54	53145	1082583	182	176	130	60.2	1.30	2.301	0.37	0.200	5.300
8	10/28/96 11:08	25948	1108531	200	204	100	58.2	1.19	2.175	0.37	0.100	4.700
9	10/28/96 11:38	20791	1129322	85	120	82	42.9	1.10	1.624	0.29	0.100	3.100
10	10/28/96 12:08	13909	1143232	72	120	68	32.1	1.05	1.433	0.23	0.100	2.800
11	10/28/96 13:08	13287	1156519	41	57	53	29.9	1.00	1.117	0.20	<0.002	2.000
12	10/28/96 14:08	0	1156519	25	54	46	23.5	0.98	1.343	0.19	<0.002	1.700
Storm 28	*	3397176	3397176	236	57	102	37.0	1.30	1.591		0.171	3.460
1	12/15/96 4:30	132079	3529255	137	34	129	74.8	2.90	2.338	NA	0.182	3.675
2	12/15/96 4:44	347783	3877038	483	60	144	73.3	1.20	1.921	NA	0.411	8.535
3	12/15/96 5:14	571458	4448496	126	35	17	15.1	0.42	0.752	NA	0.094	3.111
4	12/15/96 5:44	501589	4950085	156	57	23	12.6	0.21	0.615	NA	0.059	5.422
5	12/15/96 6:44	0	4950085	65	25	8	10.8	0.24	0.445	NA	0.013	1.907
6	12/15/96 7:44	0	4950085	43	22	5	12.3	0.26	0.714	NA	0.025	1.450

Summary of Constituent Concentrations in the Sedimentation Basin Effluent

Sample	Sample	Sample	Cum.	TSS	Turbidity	COD	TOC	Nitrate	TKN	Total	Zinc	Iron
No.	Date and Time	Volume	Volume							Phos.		
		Liters	Liters	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Storm 3												
1	11/17/95 0:00			65	48	123	NA	1.35	NA	0.45	0.130	2.795
2	11/17/95 0:00			99	47	117	NA	1.10	NA	0.34	0.122	2.741
3	11/17/95 0:00			67	43	89	NA	0.43	NA	0.28	0.073	1.930
4	11/17/96 0:00			60	48	64	NA	0.26	NA	0.23	0.045	1.328
5	11/17/95 0:00	723268	723268	21	25	50	NA	0.14	NA	0.20	0.066	1.138
6	11/17/95 0:00	715774	1439042	25	27	38	NA	0.20	NA	0.20	0.033	0.739
7	11/17/95 0:00	329787	1768829	13	28	24	NA	NA	NA	0.16	0.019	0.672
8	11/17/95 0:00	295521	2064349	10	17	26	NA	NA	NA	0.18	0.013	0.656
9	11/17/95 0:00	496835	2561184	15	29	28	NA	NA	NA	0.20	0.017	0.583
10	11/17/95 0:00	320458	2881642	9	17	23	NA	NA	NA	0.22	0.015	0.575
11	11/17/95 0:00	777283	3658925	10	15	22	NA	NA	NA	0.18	0.110	0.350
Storm 4												
1	12/8/95 12:48			281	63	100	NA	1.60	1.200	0.41	0.213	4.063
2	12/8/95 12:53			280	63	107	NA	1.50	1.500	0.46	0.205	4.105
3	12/8/95 14:52	27057	27057	218	65	104	NA	1.55	1.350	0.45	0.139	3.374
4	12/8/95 16:52	83112	110169	145	61	101	NA	1.60	1.300	0.42	0.145	3.018
5	12/8/95 22:52	73008	183177	106	65	88	NA	1.70	1.950	0.57	0.103	2.063
6	12/9/95 4:52	101527	284704	80	64	73	NA	1.55	0.850	0.32	0.079	2.249
7		141932	426637	11	48	45	NA	1.58	0.230	0.13	0.019	0.723
8		94755	521391	5	40	27	NA	1.58	0.078	0.06	0.005	0.268
9		26324	547715	5	33	16	NA	1.58	0.026	0.03	0.001	0.099
Storm 5												
1	12/17/95 8:13			148	47	81	NA	0.58	0.650	0.29	0.098	2.471
2	12/17/95 8:18			188	53	60	NA	0.59	0.599	0.29	0.109	2.568
3	12/17/95 10:17	7358	7358	96	48	49	NA	0.69	0.550	0.25	0.050	1.265
4	12/17/95 12:17	81235	88594	69	44	35	NA	0.74	0.550	0.22	0.044	1.382
5	12/17/95 18:17	100122	188716	43	37	42	NA	0.67	0.600	0.19	0.037	0.946
6	12/18/95 0:17	69008	257723	18	27	44	NA	0.69	0.530	0.20	0.031	0.697
7		170152	427875	5	11	20	NA	0.66	0.462	0.10	0.001	0.107
8		99154	527030	5	5	10	NA	0.66	0.395	0.06	0.001	0.018
9		81135	608165	5	2	5	NA	0.66	0.338	0.03	0.001	0.003

Summary of Constituent Concentrations in the Sedimentation Basin Effluent (continued)

Sample	Sample	Sample	Cum.	TSS	Turbidity	COD	TOC	Nitrate	TKN	Total	Zinc	Iron
No.	Date and Time	Volume	Volume							Phos.		
		Liters	Liters	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Storm 6												
1	2/29/96 12:31			146	50	114	NA	2.10	1.190	0.00	0.221	3.472
2	2/29/96 13:31			162	54	93	NA	1.80	1.160	0.37	0.192	3.502
3	2/29/96 15:30	35801	35801	115	51	75	NA	1.18	0.710	0.37	0.100	2.114
4	2/29/96 18:30	234530	270330	110	47	52	NA	1.30	0.800	0.36	0.084	1.617
5	3/1/96 0:30	325860	596190	78	51	66	NA	1.27	0.660	0.33	0.066	1.349
6	3/1/96 11:07	258234	854424	74	42	57	NA	2.00	0.800	0.30	0.082	1.682
7		149707	1004131	30	36	29	NA	1.61	0.472	0.24	0.023	0.593
8		110368	1114499	13	29	16	NA	1.61	0.326	0.19	0.009	0.270
9		103865	1218364	6	24	9	NA	1.61	0.226	0.15	0.003	0.123
10		51541	1269906	3	20	5	NA	1.61	0.156	0.12	0.001	0.056
Storm 11												
1	4/22/96 10:14			262	44	87	44.7	1.05	NA	0.51	0.217	3.669
2	4/22/96 10:18			125	44	85	24.1	1.13	NA	0.45	0.154	3.093
3	4/22/96 12:18			95	39	92	32.9	1.02	NA	0.33	0.110	2.279
4	4/22/96 14:18	86734	86734	57	44	83	28.7	1.03	NA	0.30	0.040	1.414
5	4/22/96 20:18	269547	356281	34	33	86	23.1	1.05	NA	0.29	0.033	1.154
6	4/23/96 2:18	152078	508360	20	29	73	18.8	1.08	NA	0.26	0.001	1.235
7		553667	1062027	5	15	61	2.1	1.06	NA	0.11	0.001	0.206
Storm 15												
1	6/22/96 17:07			198	55	NA	55.8	0.74	NA	NA	0.138	3.489
2	6/22/96 23:07	112083	112083	66	45	NA	49.4	2.10	NA	NA	0.034	1.298
3	6/23/96 5:07	90476	202559	34	28	NA	32.2	1.10	NA	NA	0.040	0.864
4	6/23/96 11:07	84599	287157	38	35	NA	33.7	0.36	NA	NA	0.006	0.695
5	6/23/96 17:07	29908	317065	62	28	NA	30.8	5.64	NA	NA	0.003	0.570
6	6/23/96 23:07	186711	503776	38	21	NA	28.9	2.60	NA	NA	0.037	0.420
7		225283	729060	12	11	NA	15.7	2.09	NA	NA	0.019	0.079

Summary of Constituent Concentrations in the Sedimentation Basin Effluent (continued)

Sample No.	Sample Date and Time	Sample Volume Liters	Cum. Volume Liters	TSS mg/L	Turbidity NTU	COD mg/L	TOC mg/L	Nitrate mg/L	TKN mg/L	Total Phos. mg/L	Zinc mg/L	Iron mg/L
Storm 19												
1	8/23/96 10:55	667624	667624	25	19	67	17.4	>10	1.421	0.22	0.001	1.105
2	8/23/96 22:55	593117	1260741	37	42	61	13.9	0.93	1.490	0.18	0.001	1.105
3	8/24/96 10:55	1695014	2955755	34	30	35	11.9	0.44	1.189	0.17	0.001	1.332
4	8/24/96 22:55	593786	3549540	38	24	35	11.4	0.91	1.473	0.17	0.001	0.746
5	8/25/96 10:55	579672	4129212	9	16	35	9.4	0.57	1.692	0.16	0.001	0.485
6	8/25/96 22:55	564867	4694079	18	19	27	11.6	6.40	0.666	0.17	0.001	0.718
7	8/26/96 10:59	620797	5314876	9	NA	25	5.3	0.52	1.149	0.14	0.001	0.121
8	8/26/96 22:59	18403	5333279	10	NA	28	5.3	1.20	1.015	0.17	0.001	0.224
9	8/27/96 10:59	1135961	6469240	8	NA	38	7.6	0.34	1.128	0.14	0.001	0.220
10	8/27/96 22:59	446458	6915698	3	NA	42	7.6	0.26	1.933	0.16	0.001	0.145
11	8/28/96 10:59	387386	7303084	4	NA	32	7.8	NA	0.982	0.13	0.001	0.094
12	8/28/96 22:59	260652	7563736	7	NA	31	14.1	NA	0.982	0.15	0.001	0.695
Storm 21												
1	8/29/96 23:59	751397	751397	32	32	28	12.0	2.90	2.137	0.19	0.001	NA
2	8/30/96 11:59	470316	1221713	60	52	30	10.1	0.83	1.949	0.23	0.001	1.491
3	8/30/96 23:59	585713	1807426	39	NA*	20	12.0	1.30	1.507	0.20	0.001	1.334
4	8/31/96 11:59	703595	2511020	25	*NA	30	9.9	1.05	1.640	0.15	0.001	0.855
5	8/31/96 23:59	207998	2719018	46	64	26	7.8	0.77	1.405	0.15	0.001	1.069
6	9/1/96 11:59	667324	3386342	27	23	20	7.8	0.83	2.442	0.14	0.001	0.569
7	9/1/96 23:59	562457	3948798	11	*NA	16	7.8	1.10	1.705	0.15	0.001	0.634
8	9/2/96 11:59	514566	4463364	10	15	17	5.3	10.00	1.998	0.17	0.001	0.821
9	9/2/96 23:59	392089	4855454	6	13	28	5.7	0.78	1.348	0.13	0.001	1.086
10	9/3/96 11:59	361477	5216931	10	20	25	12.5	1.10	1.121	0.07	0.001	0.145
11	9/3/96 23:59	208979	5425910	1	6	15	7.8	2.55	4.795	0.29	0.001	0.326
12	9/4/96 11:59	245754	5671664	5	6	25	10.2	0.86	0.416	0.15	0.001	0.381
Storm 24												
1	10/27/96 14:34			NA	NA	97	47.3	0.44	1.845	0.38	0.100	4.400
2	10/28/96 14:33	401760	401760	37	42	44	21.2	0.58	1.584	0.24	0.100	2.500
3	10/29/96 14:33	126780	528540	12	30	30	18.9	0.56	1.726	0.22	<0.0	0.400
4	10/30/96 14:33	499803	1028343	9	29	34	19.0	0.40	1.068	0.15	<0.0	0.500
5	10/31/96 14:33	250689	1279032	5	9	33	25.6	0.40	0.986	0.17	<0.05	0.700

Summary of Constituent Concentrations in the Sedimentation Basin Effluent (continued)

Sample No.	Sample Date and Time	Sample Volume Liters	Cum. Volume Liters	TSS mg/L	Turbidity NTU	COD mg/L	TOC mg/L	Nitrate mg/L	TKN mg/L	Total Phos. mg/L	Zinc mg/L	Iron mg/L
Storm 28												
1	12/16/96 10:05	1571388	1571388	41	24	17	14.5	0.31	0.723	NA	0.001	1.203
2	12/17/96 10:03	607401	2178789	18	22	15	14.5	0.31	0.568	NA	0.028	1.029
3	12/18/96 10:03	527501	2706290	14	24	12	14.5	0.33	0.941	NA	0.001	0.630
4	12/19/96 10:03	1741801	4448091	7	21	16	16.3	0.37	0.743	NA	0.001	0.733

Summary of Constituent Concentrations in the Filter Effluent

Sample	TSS	Turbidity	COD	TOC	Nitrate	TKN	Total	Zinc	Iron
Date and Time							Phos.		
	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
10/29/96 1:31	8.0	7.0	10	14.8	0.36	0.400	0.12	0.002	0.100
10/30/96 1:31	1.0	6.0	13	14.8	0.56	0.282	0.11	0.002	0.050
10/31/96 1:31	1.0	4.2	18	17.0	0.59	0.406	0.12	0.002	0.100
10/31/96 17:58	1.0	2.4	0	14.9	0.52	0.422	0.11	0.002	0.050
11/7/96 17:36	5.0	8.0	9	15.8	1.00	0.441	0.15	0.002	0.473
11/8/96 17:35	5.0	4.7	5	13.3	0.50	0.398	NA	0.002	0.132
11/9/96 17:35	3.0	4.4	6	13.3	0.47	0.113	NA	0.015	0.145
11/10/96 17:35	3.0	4.4	11	13.3	0.45	0.165	NA	0.002	0.123
11/25/96 11:12	7.0	NA	2	8.0	0.64	0.336	0.08	0.002	0.184
11/26/96 11:12	6.0	4.2	3	8.1	0.35	0.437	0.09	NA	NA
11/27/96 11:12	2.0	3.1	0	6.2	0.32	0.366	0.15	NA	NA
11/27/96 12:27	4.0	3.0	5	6.2	0.31	0.389	0.09	0.002	0.216
11/27/96 13:28	8.0	2.4	0	8.1	0.28	0.271	0.10	0.002	0.179
11/28/96 13:28	5.0	2.6	0	8.1	0.39	0.334	0.11	0.002	0.188
12/16/96 10:52	3.0	2.1	7	12.1	0.25	0.478	NA	0.002	0.066
12/17/96 10:51	1.0	2.4	7	13.3	0.21	0.563	NA	0.002	0.029
12/18/96 10:51	3.0	1.7	7	14.8	0.08	0.411	NA	0.002	0.386
12/19/96 10:51	4.0	2.6	5	14.8	0.37	0.422	NA	0.002	0.031
2/8/97 15:24	3.0	10.0	28	13.2	1.50	0.715	0.10	0.050	0.184
2/9/97 15:24	7.0	7.0	13	14.5	1.50	0.460	0.07	0.019	0.092
2/10/97 15:24	2.0	16.0	14	12.1	1.00	0.315	0.06	0.062	0.172
2/11/97 11:23	3.0	1.5	16	12.5	0.91	0.445	0.19	0.035	0.119
2/12/97 11:23	1.0	12.0	8	9.2	0.70	0.351	0.06	0.002	0.991
2/13/97 11:23	8.0	32.0	8	10.9	0.58	0.565	0.05	0.002	0.093
2/14/97 11:23	4.0	27.0	6	10.9	0.67	1.176	0.06	0.003	0.062
2/15/97 10:04	1.0	1.4	0	9.0	0.70	0.345	0.06	0.034	0.087
2/17/97 10:04	1.0	1.6	2	8.8	0.61	0.469	0.05	0.002	0.024
2/18/97 10:04	NA	1.1	5	10.5	0.58	0.471	0.05	0.002	0.364
3/12/97 6:37	27.0	2.6	15	13.0	0.10	0.807	0.10	0.07	NA
3/13/97 6:37	1.0	2.2	20	15.2	0.10	0.391	0.20	0.075	NA
3/14/97 6:37	9.0	2.5	23	17.9	NA	0.807	0.25	0.095	NA
3/26/97 10:49	1.7	1.6	19	18.1	0.16	0.766	0.13	0.04	NA

Summary of Constituent Concentrations in the Filter Effluent (continued)

Sample	TSS	Turbidity	COD	TOC	Nitrate	TKN	Total	Zinc	Iron
Date and Time							Phos.		
	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
3/27/97 10:48	1.5	1.6	19	16.3	0.14	0.879	0.15	0.05	NA
3/28/97 10:48	1.0	1.1	19	18.1	0.19	1.094	0.13	0.04	NA
3/29/97 10:48	1.0	1.1	27	17.5	0.26	0.500	0.15	0.04	NA
3/29/97 15:53	1.0	1.5	19	17.5	0.26	0.729	0.12	0.04	NA
3/30/97 15:52	0.5	1.0	22	16.3	0.29	0.613	0.14	0.04	NA
3/31/97 15:52	1.0	1.1	15	17.5	0.18	1.245	0.15	0.08	NA
4/1/97 15:52	1.0	0.9	20	16.3	0.19	0.766	0.13	0.09	NA
4/3/97 9:57	1.0	NA	20	15.5	0.28	1.103	0.16	0.04	NA
4/4/97 9:56	1.0	0.6	14	15.5	0.13	1.008	0.15	0.05	NA
4/5/97 9:56	1.0	0.6	18	15.5	0.14	0.741	0.10	0.06	NA
4/6/97 9:56	1.0	0.4	14	15.5	0.15	1.022	0.22	0.07	NA
4/8/97 8:47	1.0	NA	12	13.0	0.13	0.854	0.13	0.13	NA
4/9/97 8:46	1.0	NA	21	13.0	0.12	0.625	0.14	0.06	NA
4/10/97 8:46	1.0	NA	7	13.0	0.11	0.992	0.14	0.03	NA
4/11/97 8:46	NA	NA	NA	14.8	NA	NA	NA	0.05	NA
4/12/97 9:06	NA	NA	11	12.8	0.10	0.882	0.14	0.05	NA
4/13/97 9:06	NA	NA	9	12.5	0.11	0.628	0.13	0.04	NA
4/14/97 9:06	NA	NA	15	12.5	0.11	0.633	0.13	0.04	NA
4/15/97 9:06	NA	NA	11	14.3	0.10	0.929	0.14	NA	NA

APPENDIX D

Mass Balance Results for the Sedimentation Basin: Individual Storm Events and Prefilter and Postfilter Storms

Storm 3 (11/17/95)

Constituent	Influent EMC (mg/L)	Influent Load (g)	Effluent EMC (mg/L)	Effluent Load (g)	Removal (%)
TSS	84	328432	16	58435	82
Turbidity	35	136113	23	83181	39
COD	38	147361	32	117343	20
TOC					
Nitrate					
TKN					
Phosphorus	0.22	856	0.19	704	18
Zinc	0.054	212	0.049	180	15
Iron	1.396	5446	0.687	2513	54

Storm 4 (12/8/95)

Constituent	Influent EMC (mg/L)	Influent Load (g)	Effluent EMC (mg/L)	Effluent Load (g)	Removal (%)
TSS	321	185330	66	35951	81
Turbidity	70	40638	54	29540	27
COD	190	109440	63	34304	69
TOC					
Nitrate	1.63	942	1.59	872	7
TKN	1.61	930	0.76	414	56
Phosphorus	0.51	297	0.27	146	51
Zinc	0.200	115	0.063	35	70
Iron	5.536	3196	1.555	852	73

Storm 5 (12/17/95)

Constituent	Influent EMC (mg/L)	Influent Load (g)	Effluent EMC (mg/L)	Effluent Load (g)	Removal (%)
TSS	534	325435	22	13611	96
Turbidity	52	31415	20	12071	62
COD	135	82045	25	15325	81
TOC					
Nitrate	0.77	467	0.68	411	12
TKN	1.04	634	0.48	291	54
Phosphorus	0.49	296	0.13	78	74
Zinc	0.308	188	0.017	10	95
Iron	5.618	3427	0.468	285	92

Storm 6 (2/29/96)

Constituent	Influent EMC (mg/L)	Influent Load (g)	Effluent EMC (mg/L)	Effluent Load (g)	Removal (%)
TSS	203	262155	64	81109	69
Turbidity	63	81032	41	52350	35
COD	94	121448	46	58382	52
TOC					
Nitrate	1.14	1472	1.53	1946	-32
TKN	1.02	1316	0.61	773	41
Phosphorus	0.36	469	0.28	359	23
Zinc	0.174	225	0.056	71	68
Iron	3.403	4403	1.152	1463	67

Storm 11 (4/22/96)

Constituent	Influent EMC (mg/L)	Influent Load (g)	Effluent EMC (mg/L)	Effluent Load (g)	Removal (%)
TSS	208	199584	19	19918	90
Turbidity	49	46793	24	25680	45
COD	82	79212	71	75095	5
TOC	29	27554	12	12712	54
Nitrate	1.50	1441	1.06	1123	22
TKN					
Phosphorus	0.40	381	0.19	202	47
Zinc	0.122	117	0.012	13	89
Iron	2.218	2131	0.693	736	65

Storm 15 (6/22/96)

Constituent	Influent EMC (mg/L)	Influent Load (g)	Effluent EMC (mg/L)	Effluent Load (g)	Removal (%)
TSS	222	154155	35	25435	84
Turbidity	50	34735	24	17775	49
COD					
TOC	30	21092	29	21147	-0.3
Nitrate	1.71	1186	2.04	1490	-26
TKN					
Phosphorus					
Zinc	0.156	109	0.026	19	82
Iron	3.183	2212	0.543	396	82

Storm 19 (8/23/96)

Constituent	Influent EMC (mg/L)	Influent Load (g)	Effluent EMC (mg/L)	Effluent Load (g)	Removal (%)
TSS	217	1628362	20	153787	91
Turbidity					
COD	107	798737	39	294988	63
TOC	32	240145	11	80913	66
Nitrate					
TKN	1.88	14056	1.27	9592	32
Phosphorus	0.39	2911	0.16	1241	57
Zinc					
Iron	3.484	26110	0.713	5392	79

Storm 21 (8/29/96)

Constituent	Influent EMC (mg/L)	Influent Load (g)	Effluent EMC (mg/L)	Effluent Load (g)	Removal (%)
TSS	210	1333144	25	139020	90
Turbidity					
COD	96	609040	24	133766	78
TOC	28	179991	9.3	52593	71
Nitrate	1.38	8761	2.12	11996	-37
TKN	1.53	9735	1.85	10506	-8
Phosphorus	0.37	2373	0.17	944	60
Zinc					
Iron					

Storm 24 (10/27/96)

Constituent	Influent EMC (mg/L)	Influent Load (g)	Effluent EMC (mg/L)	Effluent Load (g)	Removal (%)
TSS	129	149466	17	21921	85
Turbidity	96	110451	29	37302	66
COD	79	91841	37	46747	49
TOC	41	47284	21	26827	43
Nitrate	0.64	741	0.47	604	18
TKN					
Phosphorus	0.33	379	0.19	242	36
Zinc					
Iron	3.120	3609	1.158	1480	59

Storm 28 (12/16/96)

Constituent	Influent EMC (mg/L)	Influent Load (g)	Effluent EMC (mg/L)	Effluent Load (g)	Removal (%)
TSS	230	1139251	21	94938	92
Turbidity	54	268799	23	100314	63
COD	88	434835	16	70023	84
TOC	36	176017	15	67633	62
Nitrate	1.12	5562	0.34	1494	73
TKN	1.44	7119	0.74	3272	54
Phosphorus					
Zinc	0.168	831	0.005	21	97
Iron	3.981	19705	0.927	4124	79

Prefilter Storms (Storms 3, 4, 5, 6, 11, and 15)

Constituent	Influent Load (g)	Effluent Load (g)	Removal (%)
TSS	1455092	234459	84
Turbidity	370726	220597	40
COD	539505	300449	44
TOC	48646	33859	30.4
Nitrate	5507	5844	-6
TKN	2881	1477	49
Phosphorus	2298	1489	35
Zinc	966	328	66
Iron	20815	6245	70

Postfilter Storms (Storms 19, 21, 24, and 28)

Constituent	Influent Load (g)	Effluent Load (g)	Removal (%)
TSS	4250223	409666	90
Turbidity	379250	137616	64
COD	1934453	545525	72
TOC	643436	227966	65
Nitrate	15064	14094	6
TKN	30910	23370	24
Phosphorus	5663	2427	57
Zinc	831	21	97
Iron	49424	10997	78

APPENDIX E

Raw Data for the Prototype Sedimentation Basin Experiments

Constituent Concentrations for the Bottom-Drained Experiment

(* = Drainage was Delayed 24 hours for the Experiment)

Sample	TSS	Turbidity	COD	TOC	Nitrate	TKN	Total P.	Zinc
ID	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
TK 1.1	332	168	24	3.9	0.2	1.964	0.39	0.1
TK 1.2	140	132	10	2.8	0.21	1.099	0.26	0.025
TK 1.3	100	124	6	0.4	0.21	1.692	0.23	0.025
TK 1.4	80	108	7	0.4	0.27	1.006	0.22	0.1
TK 1.5	72	104	7	0.4	0.2	0.571	0.21	0.1
TK 4.1	242	156	31	25.8	0.34	1.191	0.25	0.166
TK 4.2	140	140	7	16.1	0.39	1.163	0.14	0.13
TK 4.3	71	96	5	15.9	0.37	0.793	0.08	0.007
TK 4.4	37	60	5	9	0.39	0.756	0.05	0.008
TK 4.5	23	40	9	11.2	0.37	0.375	0.03	0.001
*TK 5.1	270	164	33	22.1	0.46	0.996	0.23	0.114
*TK 5.2	18	28	18	15.8	0.46	0.478	0.02	0.061
*TK 5.3	6	25	5	16.6	0.42	0.234	0.02	0.08
*TK 5.4	7	23	6	15.7	0.42	0.58	0.04	0.042
*TK 5.5	15	23	5	24.3	0.54	0.327	0.06	0.049
TK 6.1	337	NA	18	23.3	0.22	0.861	0.33	0.28
TK 6.2	162	180	5	23.3	0.26	0.486	0.18	0.18
TK 6.3	106	150	5	19.7	0.26	0.732	0.14	0.18
TK 6.4	84	130	5	21	0.24	1.094	0.1	0.13
TK 6.5	45	100	5	21	0.25	1.337	0.08	0.12
TK 7.1	288	200	17	22.7	0.33	1.47	0.27	0.3
TK 7.2	167	170	5	15	0.35	0.984	0.18	0.18
TK 7.3	107	160	5	13	0.36	0.623	0.15	0.14
TK 7.4	64	120	5	12.7	0.39	0.492	0.12	0.17
TK 7.5	58	110	5	11.1	0.34	0.73	0.11	0.12

Constituent Concentrations for the Surface-Drained Experiment

Sample	TSS	Turbidity	COD	TOC	Nitrate	TKN	Total P.	Zinc
ID	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
TK 8.1	279	144	26	34.1	0.31	1.098	0.29	0.22
TK 8.2	98	144	24	15	0.32	0.976	0.14	0.16
TK 8.3	69	92	15	16.5	0.33	0.972	0.16	0.14
TK 8.4	64	88	20	16.5	0.37	0.482	0.14	0.17
TK 8.5	46	68	18	16.5	0.33	0.735	0.12	0.18
TK 9.1	254	190	30	27.9	0.35	1.094	0.27	0.22
TK 9.2	100	150	14	16.5	0.33	0.488	0.16	0.16
TK 9.3	67	120	18	14.6	0.33	0.486	0.16	0.15
TK 9.4	54	100	20	14.6	0.37	0.486	0.11	0.1
TK 9.5	19	36	12	14.6	0.3	0.486	0.14	0.17
TK 10.1	246	152	30	23	0.25	0.723	0.34	0.21
TK 10.2	92	112	17	3.8	0.3	0.608	0.16	0.13
TK 10.3	79	106	15	6.1	0.3	0.362	0.13	0.13
TK 10.4	58	80	17	8.6	0.3	0.608	0.16	0.13
TK 10.5	43	63	15	6.3	0.29	0.242	0.1	0.13

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