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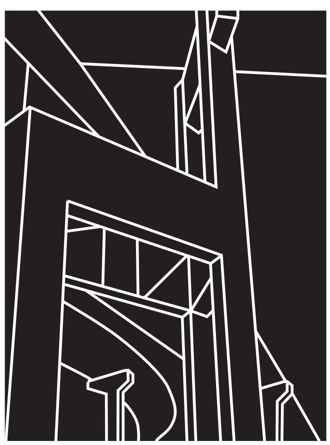
EVALUATION OF THE PERFORMANCE OF PERMANENT RUNOFF CONTROLS: SUMMARY AND CONCLUSIONS

Michael E. Barrett, Michael V. Keblin, Patrick M. Walsh,
Joseph F. Malina, Jr., and Randall J. Charbeneau



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16. Abstract

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Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

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THE UNIVERSITY OF TEXAS AT AUSTIN

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SUMMARY

Concern about the potential impact on the Edwards Aquifer has led to the construction of stormwater controls on highways in the Austin, Texas, area. This study was designed to help the Texas Department of Transportation (TxDOT) identify the types of runoff control systems that are most applicable for highways in this area. The study investigated the capability of vegetative controls (grassed swales and vegetated buffer strips) and sedimentation/filtration systems for treating stormwater runoff.

A grassed swale was constructed in an outdoor channel to investigate the impacts of swale length, water depth, and season of the year on removal efficiency. Results indicate that swale length and water depth affect the removal of constituents by swales. Swales provide effective treatment all year, although there was some variation in removal efficiency related to season. Two vegetated strips treating highway runoff in the Austin, Texas, area also were monitored to determine removal capabilities. The filter strips removed most constituents effectively and consistently, and the inclusion of filter strips is recommended in future highway design if conditions are appropriate and right-of-way is available.

The evaluation of sedimentation/filtration systems consisted of two parts: 1) monitoring and evaluating the Seton Pond sedimentation/filtration facility and 2) evaluating the effectiveness of sedimentation in a prototype-scale detention basin. Results from the Seton Pond facility show sedimentation/filtration is an excellent form of treatment for runoff captured in the system, however, the filter's poor hydraulic performance reduced the capture volume causing untreated runoff to bypass the system. Significant maintenance is required for proper hydraulic operation of the sand filter. Controlled laboratory experiments were conducted to investigate sedimentation as an alternative to sedimentation/filtration. Results indicate that with sufficient detention time, sedimentation offers comparable treatment to systems that incorporate filtration.

1. INTRODUCTION

Stormwater runoff from highways can contain pollutants, including suspended solids, nitrogen and phosphorus, organic material, and metals, which can adversely affect the environmental quality of receiving waters. Consequently, stormwater discharge permits are required for highways in urban areas, as part of the National Pollutant Discharge Elimination System (NPDES). In addition, the Texas Natural Resource Conservation Commission requires a stormwater management plan before development is allowed over the recharge zone of the Edwards Aquifer. In response to these requirements, the Texas Department of Transportation (TxDOT) funded this study to evaluate the applicability of various best management practices (BMPs) for mitigating the impacts of highway runoff on the environment. The BMPs investigated in this study are vegetative controls (grassed swales and vegetated buffer strips), detention ponds, and sand filters.

2. VEGETATIVE CONTROLS

Grassed swales are shallow, grass-lined, typically flat-bottomed channels that are designed to convey stormwater. Treatment occurs in grassed swales as the concentrated runoff flows down the length of the swale. Vegetated buffer strips, also known as filter strips, are not channels, but are relatively smooth, vegetated areas with moderate slopes that accept highway runoff as overland sheet (shallow) flow. The mechanisms of pollutant removal for the two practices are the same: filtration by grass blades or other vegetation, sedimentation, infiltration into the soil, and biological activity in the grass/soil media. The objectives of this portion of the study are:

1. determination of the effectiveness of grassed swales and vegetated buffer strips for treating highway runoff;
2. determination of the factors that affect the removal efficiency of grassed swales and vegetated buffer strips; and
3. evaluation of the deposition of metals on grassed swales and vegetated buffer strips.

The work involved in this study consisted of two parts. The first portion of the study involved monitoring two vegetated buffer strips that receive highway runoff. Monitoring demonstrated the effectiveness of filter strips at removing constituents in highway runoff. It also provided constituent concentrations necessary to evaluate metals deposition on vegetated BMPs. Secondly, a study of grassed swales was conducted in an outdoor channel. This swale provided a controlled environment that allowed for an evaluation of the effects of swale length, water depth, and season of the year on the removal of constituents in simulated highway runoff.

2.1. Field Monitoring of Vegetative Controls

A primary objective of this study is measurement of the efficiency of vegetated buffer strips for removing constituents in highway runoff in the Austin, Texas, area. The efficiency of a vegetated buffer strip was determined by measuring concentrations of pollutants in samples of the runoff directly off the road and after the runoff passes through a filter strip.

Two filter strip sites were monitored in this study. We collected 423 samples over approximately thirty-four (34) storm events at the two sites. Two sites were selected to investigate the potential for variation in performance between vegetated buffer strips with different characteristics. Also, monitoring two sites under different conditions offers a comparison that might provide insight into the factors that affect the removal efficiency of filter strips.

2.1.1. Site Descriptions

The vegetated buffer strip at Walnut Creek is a section of highway median that collects runoff from the northbound and southbound lanes of MoPac just south of Walnut Creek in Austin, Texas (Figure 2.1). The median was designed originally as a hydraulic conveyance and not as a runoff treatment device. The median cross section is V-shaped with a rounded bottom. Runoff from the highway flows as sheet flow down the sides of the grassy slope and then along the center of the median to four drop inlets situated along the centerline of the median. The drop inlets discharge to a storm drain that conveys the runoff to Walnut Creek. This storm drain collects runoff from the road and median, as well as from several grassy shoulder areas. Runoff directly from the highway was collected from the MoPac bridge over Walnut Creek.

The Walnut Creek site was monitored during a previous study and some of that data were utilized in this study. This site was monitored over the period of April 1994 to May 1997. However, only the data collected from the period from February 1996 to May 1997 were used to describe runoff from the road because the sampling system was modified.

The vegetated buffer strip monitored at US 183 at MoPac is the grassy median of US 183 just north of MoPac (Figure 2.2). This median also was designed originally for hydraulic conveyance. Only the three southbound lanes of 183 drain into the median, which is V-shaped with a rounded bottom. The northbound lanes drain to a curb-and-gutter storm drain, providing an appropriate location for sampling road water quality at this site. This site was monitored from March 1996 to May 1997. A summary of the characteristics of the two vegetated buffer strips is given in Table 2.1.

Figure 2.1 MoPac at Walnut Creek Filter Strip

Figure 2.2 Vegetated Buffer Strip at US 183 Site

Table 2.1 Characteristics of the Vegetated Buffer Strips

Characteristic	Walnut Creek	US 183
Centerline length (m)	1055	356
Width of entire median (m)	15.5 to 16.2	14.9 to 19.5
Filter strip treatment length (m)	7.8 to 8.1	7.5 to 8.8
Average median side slope	9.4%	12.1%
Average centerline slope	1.70%	0.73%
Cross-sectional shape	V, rounded bottom	V, rounded bottom
Drainage area (m^2)	104,600	13,000
Vegetation	mixed	mostly Buffalo grass
Average Daily Traffic	47,000	111,000
Filter drainage area % paved	38%	52%
Road drainage area % paved	100%	100%

2.1.2. Monitoring Results

The observed reductions in concentrations demonstrate the ability of a vegetated buffer strip to remove constituents via sedimentation, filtration, dilution, biological activity, and other physical and chemical mechanisms. However, additional removal of constituents occurs as the runoff infiltrates into the soil. The reduction in total load includes the effects of infiltration and represents the total reduction in the mass of constituents that occurs in the filter strip.

An annual pollutant load is the mass of a particular constituent that is discharged over a 1-year period. The calculation of load reduction is directed at establishing the difference between the constituent load (assuming the highway runoff was conveyed directly to a storm sewer without treatment) and the load from the highway runoff after treatment by the filter strip. Annual pollutant loads were calculated using an adaptation of the “simple method” suggested by the EPA, which requires knowledge of the runoff coefficient as well as constituent concentrations.

The runoff coefficient calculated for the Walnut Creek site is 0.30. This value agrees well with runoff coefficients for other sites in Austin having comparable percentages of impervious cover. The runoff coefficient for the filter strip at US 183 was initially calculated to be 0.66; however, a value of approximately 0.40 is normal for a drainage area that is 52% paved, such as the US 183 filter strip drainage area. The higher-than-expected runoff coefficient was caused by runoff entering the drainage area from upstream. Erosion at the upstream drain at the US 183 site caused a varying amount of flow to bypass the drain and flow into the study area. Data collected by the City of Austin indicate that the runoff coefficient for a site with 52% impervious cover is expected to be 0.40; accordingly, this value was used for calculation of load reduction.

The average concentrations and percent concentration reduction observed at both field sites are given in Table 2.2. Table 2.3 includes the pollutant loads and load reductions observed at both sites. The constituent removal rates observed at the two filter strips are generally higher than those found in previous studies. The reasons for the higher removal efficiencies observed in this study are uncertain. One possible reason is that the filter strips in other studies treated runoff from a drainage area larger than those in this study that treated runoff only from a three-lane highway. The larger drainage areas could have resulted in higher runoff velocities and water depths, reducing the effectiveness of the filter strip. Highways provide a relatively small catchment area for filter strips that lie along their entire length. Because water depths and velocities are normally low, filter strips can act effectively in such a configuration.

2.1.3. Grab Sample Results

In addition to the continuous monitoring at the two filter sites, grab samples were taken along the length of the vegetated buffer strip at US 183 during five rain events. The objective of these grab samples was to determine where the treatment was occurring, i.e., down the length of the median or along the side slopes of the median.

Table 2.2 Reductions in Concentrations Observed at Two Vegetated Buffer Strips

	US 183			Walnut Creek		
Constituent	Road Mean mg/L	Swale Mean mg/L	Reduction %	Road Mean mg/L	Swale Mean mg/L	Reduction %
TSS	157	21	87	190	29	85
Turbidity**	55	17	69	70	16	78
Fecal Col*	96000	280000	-192	NA	240000	NA
Fecal Strep*	23000	40000	-74	7100	41000	-477
COD	94	37	61	109	41	63
TOC	33.9	16.7	51	41.3	19.5	53
Nitrate	0.91	0.46	50	1.27	0.97	23
TKN	2.17	1.46	33	2.61	1.45	44
Total P	0.55	0.31	44	0.24	0.16	34
Zinc	0.347	0.032	91	0.129	0.032	75
Lead	0.138	0.082	41	0.093	0.077	17
Iron	3.33	0.69	79	2.04	0.51	75

* units are CFU/100mL
** units are NTU

Table 2.3 Constituent Load Reductions

	US 183			Walnut Creek		
Constituent	Untreated Load, kg/yr	Treated Load, kg/yr	Load Reduction, %	Untreated Load, kg/yr	Treated Load, kg/yr	Load Reduction, %
TSS	748	79	89	5320	671	87
Turbidity**	265	66	75	1980	367	81
Fecal Col*	4600	11000	-136	NA	56000	NA
Fecal Strep*	1100	1500	-41	2000	9600	-380
COD	450	144	68	3060	952	69
TOC	162	65	60	1160	455	61
Nitrate	4.3	1.8	59	36	23	36
TKN	10.3	5.63	46	73	34	54
Total P	2.65	1.20	55	6.73	3.70	45
Zinc	1.66	0.124	93	3.62	0.75	79
Lead	0.661	0.317	52	2.61	1.79	31
Iron	15.9	2.66	83	57	11.8	79

* 10^9 CFU/yr, ** NTU*L/yr

The results of the grab samples are summarized in Figure 2.3. These data show the concentration of TSS along the length of the median. TSS concentration was used as an indicator for determining the removal pattern. The data reveal that some reduction in concentration occurs down the length of the median; however, this removal accounts for only a small part of the over 80% reduction in total TSS concentration. The average TSS concentration observed from the road at this site is 128 mg/L; thus, the majority of removal of TSS must be occurring down the sides of the median. These data indicate that the medians behave more like vegetated buffer strips, which treat runoff as the sheet flow travels across the sides of the median rather than down the length of the median. This observation indicates that the length of the median has only a small effect on pollutant removal. Other factors, such as the length and slope of the sides of the median and density and type of vegetative cover, may have a greater effect on the efficiency of filter strips along highways than the median's length.

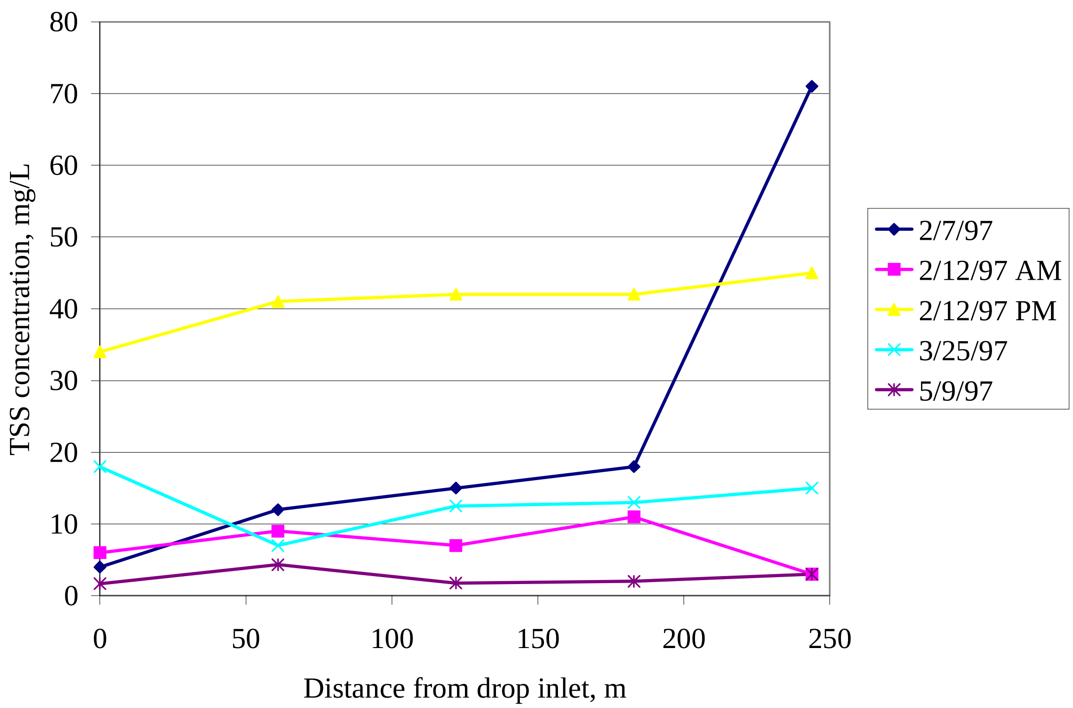

Figure 2.3 TSS Concentrations along the Center of the Median

During the monitoring phase of this study, two important observations were noted regarding filter strips; both observations demonstrate the need for proper design. Significant erosion occurred at the bottom of the Walnut Creek median in seven locations. The erosion exposed bedrock, which was devoid of vegetation (Figure 2.4). These areas diminish the effectiveness of filter strips by contributing sediment to receiving waters and reducing the amount of treatment that occurs along the length of the median. In addition, erosion can result in maintenance problems, hindering routine activities such as mowing. No erosion was noted at the US 183 site, which has a lower average slope than Walnut Creek. The use of additional drop inlets along the median may alleviate the erosion at the Walnut Creek site.

Figure 2.4 Erosion at the Walnut Creek Vegetated Buffer Strip

The second observation regarding the filter strips in the field is the presence of a sediment "lip" that formed where the pavement meets the grassy median at the US 183 site. This lip, which formed from the settling of sediment at the pavement/median interface, was large enough that highway runoff was prevented from entering the median along some sections and was instead diverted to a curb-and-gutter system. This problem has been noted for grassed swales by other researchers as well. This type of lip can likely be avoided during construction by ensuring that the level of the soil near the pavement edge is lower than the pavement. Periodic maintenance can remove sediment from along the highway/median interface.

2.1.4. Accumulation of Metals in Vegetated Controls

Metals that are removed from highway runoff accumulate in various forms in the filter strip itself. The fate and effect of these accumulated toxic metals on the environment is a potential concern. The fate of metals after deposition should be understood before addressing any assessment of risk. Once trace metals are removed from highway runoff, their possible fate within vegetated buffer strips includes the following:

1. Residence in an insoluble form, i.e., attached to particulate matter, in the soil matrix;
2. Uptake of soluble metals by plants;
3. Uptake by animals who consume plants with accumulated metals;
4. Leaching of soluble metals from the soil into groundwater;
5. Removal from the filter strip to receiving waters by runoff from subsequent storm events; and
6. Removal from the filter strip by wind action on particulates containing metals.

The primary concerns for trace metals applied to vegetated areas are the following:

1. Phytotoxicity, or toxicity, to plants that uptake metals;
2. Toxicity to animals that eat plants having high metal concentrations;

3. Contamination of groundwater resources that are sources of drinking water or that provide habitats for plant and animal species.

Assessment of the risk to human health and the environment from the accumulation of metals in the roadside environment has not been reported in any detail. The only guideline relative to metals application and accumulation in vegetated areas are *The Standards for the Use or Disposal of Sewage Sludge*, or Title 40 of the Code of Federal Regulations (CFR), Part 503. This standard provides comprehensive requirements for the management of biosolids generated during the process of treating municipal wastewater. This regulation was passed in 1993 in compliance with requirements of the Clean Water Act of 1987. Of particular interest to this study is that the regulations provide annual and cumulative limits for the application of metals on cropland.

The 503 Regulations for biosolids disposal were based upon an estimate of the environmental risk of biosolids application on cropland. Nonetheless, they provide a reference against which to assess the accumulation of metals in vegetated stormwater controls. The metals limitations that are part of the 503 Regulations include annual and cumulative limits for ten metals. The annual loading limits are the maximum amount of metal, in kilograms of metal per hectare per year, that may safely be applied to cropland; the cumulative loading limits are the cumulative amount of metal, in kilograms per hectare, that may be safely applied to cropland over time.

An annual metals loading rate at each site was calculated and compared to the limits provided by the 503 Regulations. The time in years until the cumulative loading rate limitations were exceeded also was calculated. This time life of the site was based upon metal accumulation limitations. The calculated annual metals deposition rate for each site for two metals is presented in Table 2.4, along with the 503 Regulations limits for comparison. Calculated site lives based upon metals limitations for the two metals are presented in Table 2.5.

Table 2.4 Comparison of Annual Metals Loading Rates

Metal	503 Regulations Limit* kg/ha/yr	US 183 Filter Strip kg/ha/yr	Walnut Creek Filter Strip kg/ha/yr
Zinc	140	4.9	9.2
Lead	15	1.2	0.25

* For metals in biosolids applied to cropland

Table 2.5 Site Lives Based Upon Metal Deposition Limitations

Metal	US 183 Filter Strip years	Walnut Creek Filter Strip years
Zinc	570	304
Lead	244	1202

The metals loading rates at the two sites for lead and zinc are lower than the annual metals loading limits prescribed by the 503 Regulations. Indeed, the metal loading rate on the filter strips was less than one-tenth of the rate limits for application of metals in biosolids to cropland. The site lives for each site based upon both metals accumulation in the filter strip was over 200 years. This analysis was performed for only two metals in highway runoff. Copper was found at concentrations below detection limits in highway runoff in this study, and iron is not regulated by the 503 Regulations. Other metals, however, could be investigated, including nickel, chromium, and cadmium. Cadmium, in particular, has a low annual loading limit (1.90 kg/ha/yr) and is found in highway runoff, though in low concentrations.

2.2. Channel Swale Experiments

Construction of a grassy swale in the laboratory was deemed an ideal method for investigating the influence of individual parameters on swale efficiency. The swale allowed for repeated experiments while varying one parameter, thus demonstrating the effect of that factor on swale efficiency. The channel was used to investigate the effect of water depth, season of the year, and swale length on removal efficiency. The effect of infiltrated highway runoff on groundwater quality also was assessed.

2.2.1. Methods and Materials

A grassed-lined channel (Figure 2.5) was constructed at the Center for Research in Water Resources (CRWR). The soil and grass were installed during May and June of 1996 in a steel flume. Eleven experiments were performed in the swale from October 1996 to May 1997 with simulated highway runoff. The synthetic highway runoff was representative of the average quality of runoff from highways in the Austin area.

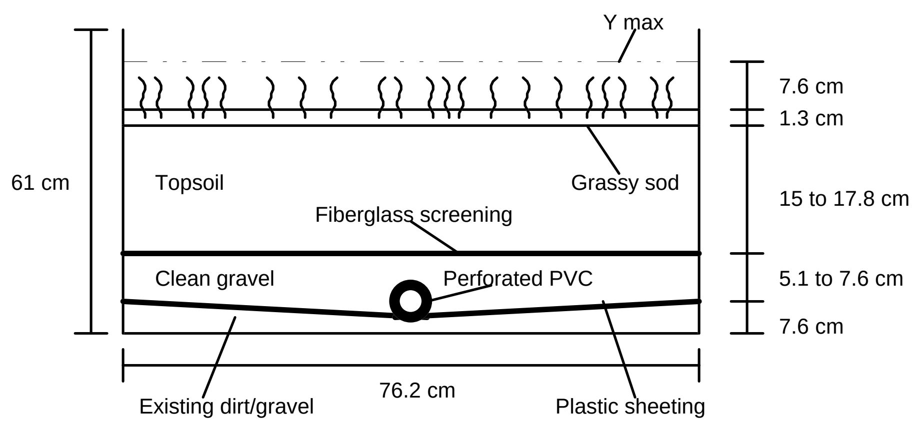

Figure 2.5 Cross section of Channel Swale

2.2.2. Channel Results

The highest removal efficiencies in the swale were for suspended solids and metals. The ranges of pollutant removal efficiencies for all constituents are listed in Table 2.6. Ranges represent efficiencies observed during experiments at different water depths. The maximum observed removal efficiencies agree well with grassed swale field results reported by other researchers.

Table 2.6 Removal Efficiencies for the Channel Swale at Different Water Depths

	Distance along swale, m				
Constituent	10	20	30	40	Underdrain
TSS	35-59	54-77	50-76	51-75	73-87
COD	13-61	26-70	26-61	25-79	39-76
Nitrate	(-5)-7	(-5)-17	(-28)-(-10)	(-26)-(-4)	(-8)-(-10)
TKN	4-30	20-21	(-14)-42	23-41	24-41
Total phosphorus	25-49	33-46	24-67	34-45	55-65
Zinc	41-55	59-77	22-76	66-86	47-86
Iron	46-49	54-64	72	76	75

The removal efficiencies for the swale at the 7.5-cm water depth are similar to removal efficiencies for a swale having similar hydraulic residence time studied by the Municipality of Metropolitan Seattle. The hydraulic residence time for this swale was 8.8 minutes (at 40 m), while the Seattle site had a residence time of 9.3 minutes. The two swales varied in length, slope, and vegetative cover; however, the agreement between removal efficiencies supports the use of residence time as a primary criterion for grassed swale design. The data indicate that a 9-minute residence time can result in removal of more than 80% of TSS under a variety of swale conditions.

Average removal efficiency at different water depths for TSS is presented in Figure 2.6. The data in the graph indicate that TSS removal efficiency was reduced as water depth increased. The reduction in removal efficiency confirms expectations, since the filtration action of the grass blades is expected to be lower for higher water depths. Removal of other constituents was not as strongly correlated with water depth.

The data indicate that removal efficiency increases with length, but the increment of increased efficiency diminishes as runoff proceeds down the swale. This trend is especially evident for total suspended solids, chemical oxygen demand, total phosphorus, and metals. The majority of removal occurs in the first 20 meters of the swale for these constituents. The removal of total suspended solids after 20 meters accounts for 92%, 80%, and 105% of the total removal observed at 40 meters at water depths of 4, 7.5, and 10 cm, respectively.

Removal efficiency for total suspended solids was greater in the growing season than in the dormant winter season. Most of the other constituents did not exhibit strong seasonal variations, indicating that swales sodded with Buffalo grass are effective at removing runoff constituents during all seasons. The higher removal efficiency for TSS may be attributed to the increased density of grass blades. During the growing season, new green Buffalo grass grew alongside the dead, brown grass from the previous season. The dormant Buffalo grass was shorter than the new growth of grass, and this dead grass continued to shrink and decay throughout April and May of 1997. The dead grass nonetheless contributed to the overall grass blade density, thereby increasing the filtration capability of the grass.

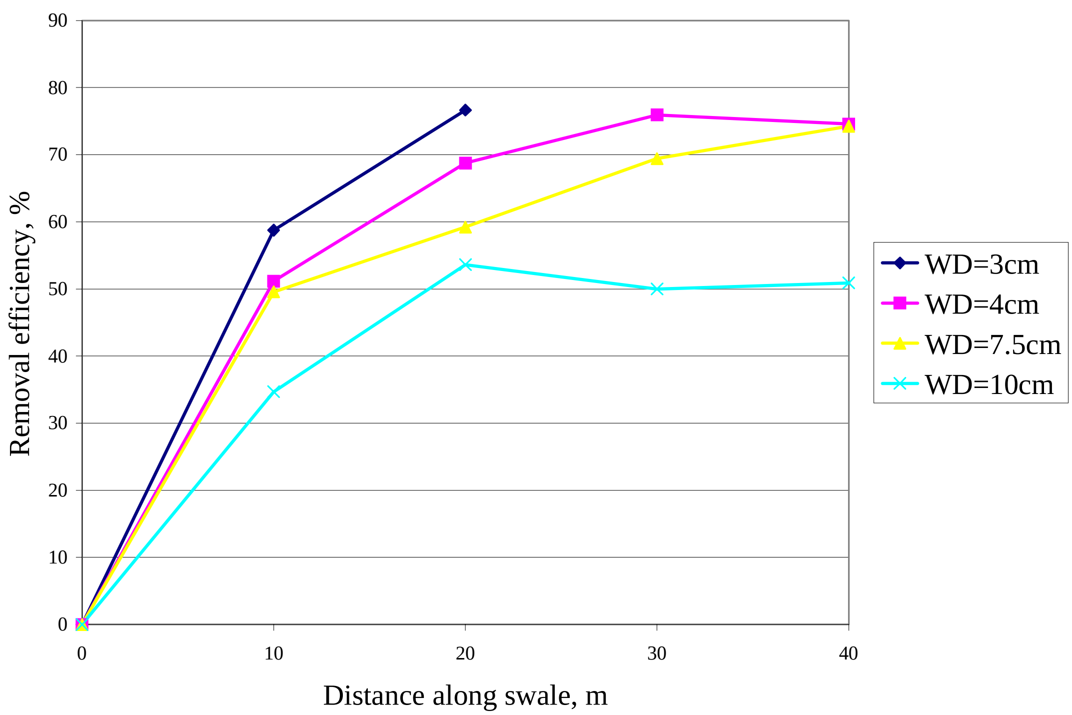

Figure 2.6 Effect of Water Depth and Swale Length on TSS Removal Efficiency

The simulated highway runoff reached the underdrain by percolating through a top layer of grass sod, 16 cm of topsoil, and 6 cm of gravel before entering the underdrain pipe. The underdrain water quality demonstrates the filtering capability of the soil, and indicates the quality of groundwater recharge in areas with thin soils. The quality of the underdrain water was used to calculate average removal efficiencies for the soil during infiltration. These removal efficiencies are listed in Table 2.7. The underdrain water quality was higher than the surface runoff after 40 meters of treatment by the grassed swale.

Table 2.7 Removal Efficiency of Constituents Based on Underdrain Water Quality

Constituent	Average Removal Efficiency %
TSS	78
Turbidity	42
COD	49
NO_3	-45
TKN	37
Total phosphorus	65
Zn	80
Pb	41
Fe	74

3. EVALUATION OF SEDIMENTATION/FILTRATION SYSTEMS

This portion of the study consisted 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 objectives of the field portion of the study are the following:

1) Determine the removal efficiency of constituents commonly found in highway runoff.
2) Determine the effectiveness of sedimentation alone.
3) Evaluate the maintenance and operational requirements of sedimentation/filtration facilities.

A prototype-scale sedimentation basin at CRWR was used to evaluate some of the factors that influence the performance of sedimentation basins. 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, and
3) Evaluate the effects of detention time on pollutant removal efficiency.

3.1. Monitoring of the Seton Pond Runoff Control Facility

3.1.1. Site Description

The Seton Pond facility includes three major components: a hazardous materials trap (HMT), a sedimentation basin, and a horizontal bed (vertical flow) sand filter. This runoff control is an offline facility, capturing the first 13-mm of runoff. Runoff in excess of this amount is discharged directly to the receiving water without treatment. TxDOT constructed the system according to design guidelines developed by the City of Austin. The Seton Pond facility collects and treats stormwater runoff from a section of US Highway 183 between Capital of Texas Highway and Balcones Woods Drive. A plan view of the facility is shown in Figure 3.1 and a picture is presented in Figure 3.2.

Automatic samplers were installed at three locations in the Seton Pond facility, the influent channel (sampler A), the sedimentation basin (sampler B), and the sand filter outlet (sampler E). The locations of the samplers are shown in Figure 3.2. A bubbler-type flow meter was installed at each sampling location to measure and record flow. The sampling equipment was installed in September 1995 and monitoring continued until May 1997; however, problems with the hydraulic performance of the facility limited the amount of data that could be reliably analyzed.

The facility had been in operation for approximately 1 year at the beginning of the monitoring period and extensive 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 cleanout 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. Although facility maintenance was the responsibility of the City of Austin, nothing was done to improve conditions at the site despite repeated requests. In August 1996, staff from CRWR cleaned the filter and attempted to restore the system to the design operating conditions. The cleanout cap was replaced and although drainage times improved, the system never completely drained within 48 hours. After replacing the cap, the performance of the sedimentation basin and sand filter was evaluated. Of the ten monitored storms, the first six were treated by sedimentation alone, while the final four were treated by the combined system.

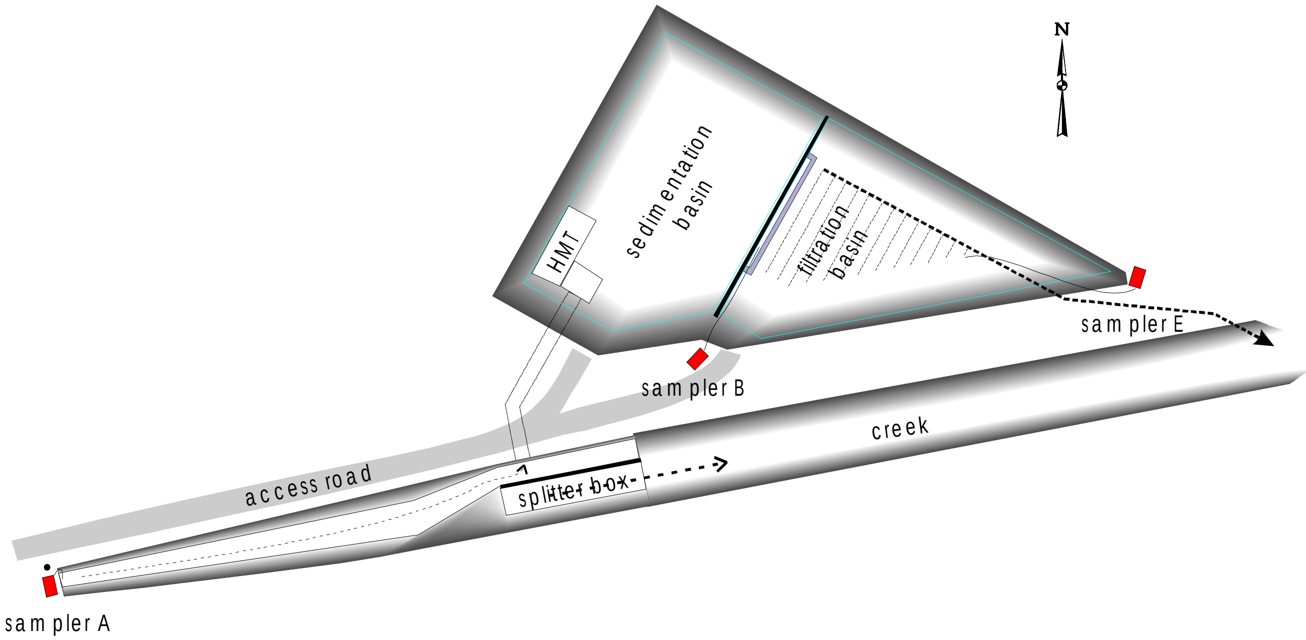

Figure 3.1 The Seton Pond Sedimentation/Filtration Facility: Plan View

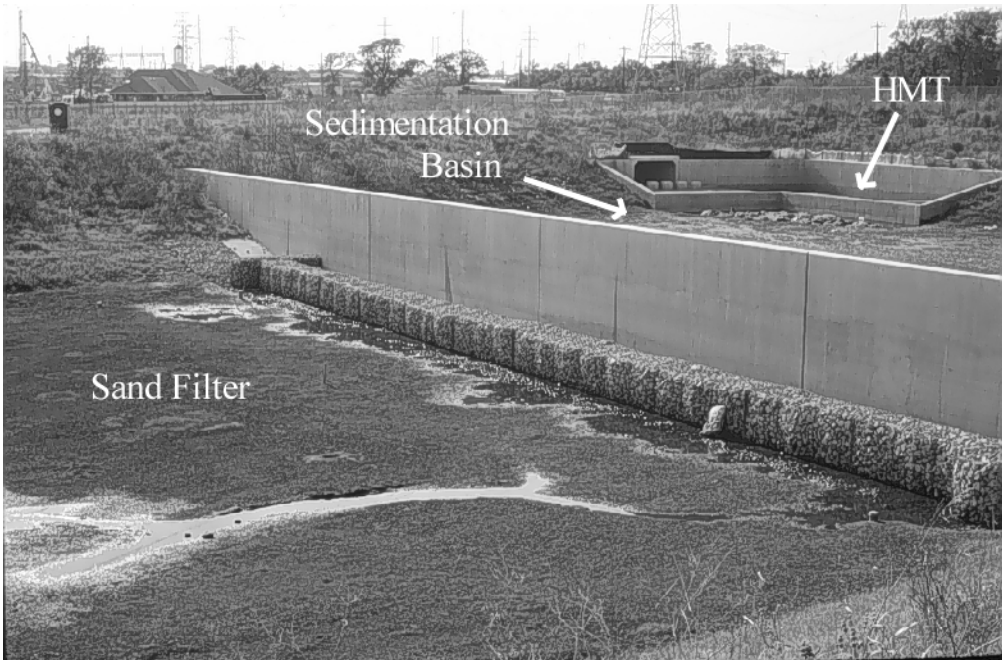

Figure 3.2 Seton Pond Sedimentation/Filtration Facility

3.1.2. Hydraulic Performance

The first six storm events that were analyzed occurred during the period when the underdrain cleanout cap had been removed to increase the rate that runoff was draining from the system. Even with the cap removed, the drainage times for these six events ranged from 4 to >7 days. After the sand filter was moved online in August 1996, the flow rate through the filter generally controlled the drainage time. Examples of the pond drainage times during this period are presented in Figure 3.3, which shows water level in the sedimentation basin following three storm events. The data show a substantial increase in drainage time from the beginning of sand filter operation to the conclusion of the monitoring period. Between

8/25/96 and 4/5/97, the time required to drain to a depth of about 0.5 m increased from 4 days to over 2 weeks.

There were instances when the riser pipe in the sedimentation pond clogged and limited the discharge from the pond. The plot of the event on 4/5/97 shows an example. Maintenance was performed to remove sediment in the pond riser pipe and the drainage rate temporarily increased for a 24-hour period and leveled off again.

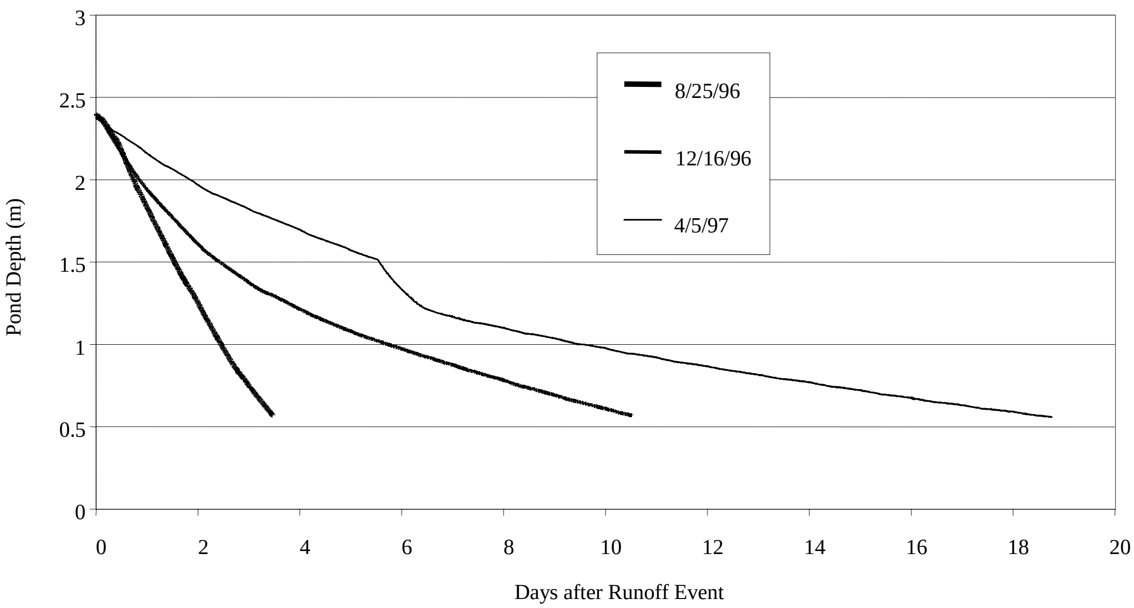

Figure 3.3 Drainage Patterns for the Seton Pond Sedimentation Basin

3.1.3. Pollutant Removal

Ten storms between 11/95 and 12/96 were analyzed to determine the removal efficiency resulting from sedimentation. 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 and availability of flow and quality data.

The removal efficiency of the system and the amount of runoff that is captured and treated control the overall effectiveness of a runoff control system. Consequently, the percentage load reduction from the contributing watershed is always less than the removal in the system if the amount of runoff that bypasses the system untreated is included in the calculation. The monitoring data indicated that 80% of the runoff from the watershed actually entered the system and received treatment. The remaining 20% of the flow bypassed the system. The removal efficiencies were recalculated, factoring in the untreated volume of bypassed runoff. The concentrations and removal efficiency for each constituent are presented in Table 3.1. The removal is calculated based on load reduction and is not exactly equal to the concentration reduction because of small differences in the volume entering and leaving the basin.

Table 3.1 Mass Balance Results for the Sedimentation Basin

Constituent	Influent Conc. (mg/L)	Effluent Conc. (mg/L)	System Removal (excluding bypass) (%)	Watershed Removal (including bypass) (%)
TSS	204	24.0	89	71
Turbidity	53.0	26.3	52	42
COD	90.6	32.4	66	53
TOC	32.0	12.6	62	50
Nitrate	1.24	1.28	3	2
TKN	1.59	1.24	26	21
Phosphorus	0.356	0.181	51	41
Zinc	0.138	0.028	81	72
Iron	3.25	0.81	75	60

The removals that are shown in Table 3.1 are the averages for all events, including those where the runoff remained in the basin for more than a week. If only the first six events are considered, when the facility normally drained in 4-5 days, the pollutant removal effectiveness is somewhat less. TSS removal still exceeded 80% with the shorter detention time, which is comparable to the concentration reduction normally achieved with filtration.

Figure 3.4 shows the reduction in TSS concentration in the sedimentation basin relative to the influent quality for all monitored events. The data show that maximum removal occurs at a detention time of approximately 36 hours, with little improvement in water quality beyond that time. Most other constituents exhibited similar removal patterns. Unfortunately, the highest discharge rate from water quality devices normally occur immediately after the storm event, when water levels in the sedimentation basin are highest and little removal has occurred. Consequently, basins designed to drain completely in 24 hours can be expected to reduce TSS loads by less than 50%. Optimum performance can be expected for sedimentation basins that drain completely in 72-96 hours.

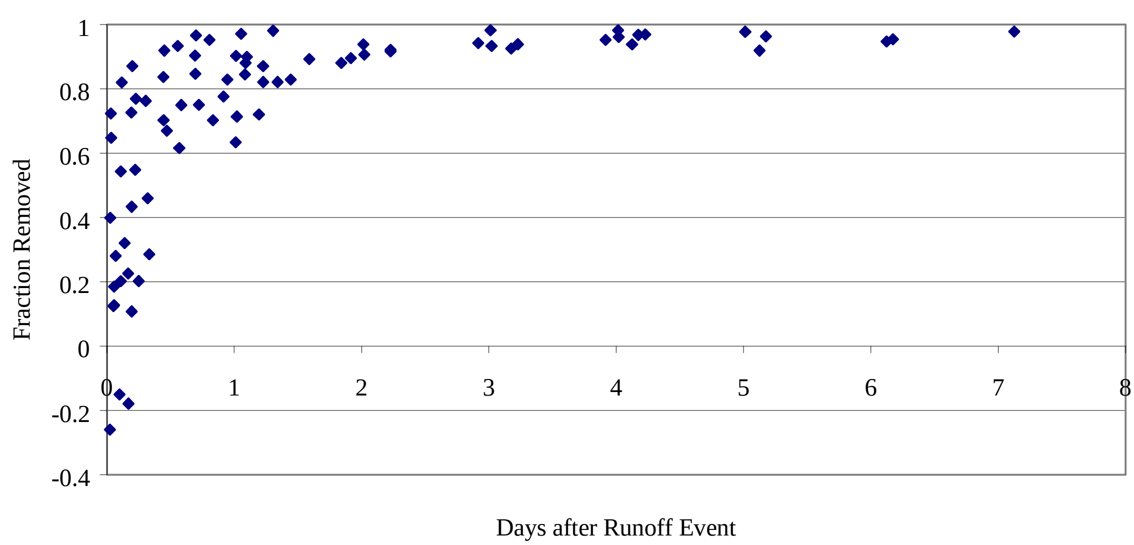

Figure 3.4 Fraction of TSS Removed over Time

The effectiveness of the combined sedimentation/filtration system is summarized in Table 3.2. 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. The mass load in the final effluent discharge was compared to the mass load in the total runoff from the watershed to determine overall system removal efficiency. The overall effectiveness of the system based on the amount of runoff that bypassed the control also is shown in Table 3.2.

Table 3.2 Mass Balance Results for the Sedimentation/Filtration System

Constituent	Influent EMC (mg/L)	Effluent EMC (mg/L)	System Removal (excluding bypass) (%)	Watershed Removal (including bypass) (%)
TSS	204	3.50	98	79
Turbidity (NTU)	53.0	4.60	92	73
COD	90.6	11.0	88	71
TOC	32.0	12.6	62	50
Nitrate	1.24	0.474	64	51
TKN	1.59	0.591	65	52
Phosphorus	0.356	0.126	66	53
Zinc	0.143	0.008	94	76
Iron	3.25	0.175	95	76

3.1.4. Discussion

The exceptional pollutant removal 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 increases removal in the sedimentation basin and 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 that increases the cation exchange capacity of the filter and provides additional adsorption sites for dissolved metals.

Nitrate removal also was much higher than that observed in other sand filter systems in the Austin area. One reason for the increased removal may have been uptake by vegetation that became established in the filter basin. Runoff remained in the filter basin longer as the permeability of the filter declined. The first rainfall event of 1997 occurred in early February; from that date until the conclusion of the study, the sand filter never drained completely. Consequently, the filter basin began to develop characteristics of a wet pond. Algal blooms appeared at certain times of the year and covered the entire water surface. 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. Plant uptake also may have been partially responsible for the removal of metals in addition to nitrogen and phosphorus.

Maintaining efficient operation involves proper maintenance as necessary. Sedimentation/filtration systems may require different time intervals between maintenance work as a result of the different characteristics of each system and differences in sediment load in the runoff. The Seton Pond facility may have been more prone to frequent clogging because construction was occurring in the watershed. Under current conditions, removal of accumulated sediment from this sand filter every 4 months is recommended. The riser pipe in the sedimentation basin also should be inspected and cleaned of any blockage during routine maintenance.

This 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 are 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.

A major consideration in maintaining sedimentation/filtration facilities is the cost of maintenance. The City of Austin's operating budget for pond maintenance and restoration for fiscal year 1997 was approximately $351,000. The City of Austin plans to restore thirty-five ponds during 1997. Therefore the annual cost for the restoration of a sedimentation/filtration pond is roughly $10,000. The eventual goal is to allot $4,000 per pond, with actual amounts fluctuating depending on the maintenance needs of each pond.

3.2. Prototype Experiments

Several experiments were conducted to evaluate the factors that affect the pollutant removal performance of sedimentation basins. The purpose of conducting the experiments in a prototype scale model was the control of variables such as storm volume, drainage time, storm frequency, influent constituent concentrations, and particle size. The objectives of the experiments were the following:

1) Evaluation of the effect of outlet device design on constituent removal, and
2) Evaluation of the effects of detention time on pollutant removal efficiency.

3.2.1. Materials and Methods

Sedimentation basins are commonly drained via an outlet located at the base of the basin or through a riser pipe. Since particles are settling out of the water column, water discharged from the base of the basin should contain the highest concentrations of suspended solids and other pollutants. Riser pipes (like the one located at the Seton Pond facility) discharge water collected over the entire water column in the basin and consequently should result in a slightly cleaner effluent. The primary goal of these experiments was to determine whether a floating discharge device which draws water only from the surface of the basin would increase the pollutant removal by discharging only the cleanest water in the basin.

In the first set of experiments, water was discharged from the sedimentation basin through an orifice located near the floor of the basin. A floating outlet, a skimmer, was developed for the second set of experiments. The skimmer consisted of an outlet supported by styrofoam and connected with a flexible plastic hose to the opening at the bottom of the retaining wall. A diagram of the basin with the skimmer installed is illustrated in Figure 3.5.

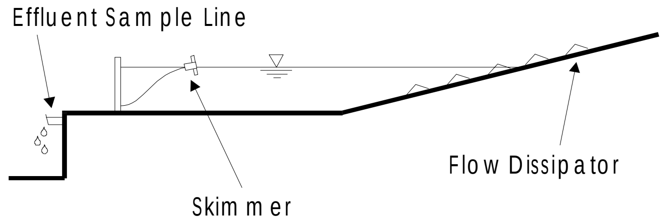

Figure 3.5 Sedimentation Basin with Skimmer Attachment

The affect of detention time on removal efficiency was evaluated by retaining all of the runoff in one experiment for approximately 24 hours before initiating drainage. In other respects, this experiment was identical to those where the water was discharged through the orifice located at the floor of the basin.

3.2.2. Results

The results obtained from the prototype experiments indicate that the improvement from bottom-drained to surface-drained sedimentation was marginal. Removals of TSS, turbidity, TOC, 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 approximately 5% to 6%. TOC was the only constituent whose removal efficiency improved significantly. Removal of COD and zinc was lower in the experiments using the skimmer device; however, there is no obvious explanation for this behavior. A comparison of the removal for all constituents is presented in Table 3.3.

Table 3.3 Comparison of Sedimentation Basin Performance

Constituent	Bottom Drained (%)	Surface Drained (%)	Extended Detention (%)
TSS	70	76	96
Turbidity	35	43	85
COD	73	41	71
TOC	36	56	23
Nitrate	-11	-6	3
TKN	36	41	58
Phosphorus	54	54	87
Zinc	53	33	48

The data indicate that the increase in performance resulting from surface-draining outlet structures was not sufficient to justify replacing conventional outlet structures. Additional reasons to avoid using a floating outlet include possible mechanical problems and additional maintenance requirements.

The results from the extended detention run indicate that delaying drainage for 24 hours improves removal considerably. The removal efficiency data that were 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 did not increase with extended detention. The removal efficiencies for all constituents are shown in Table 3.3.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Highway Medians

- Vegetated channels designed solely for stormwater conveyance can be as effective as sedimentation/filtration systems for reducing the concentrations and loads of constituents in highway runoff. The percent reduction in pollutant mass transported to receiving waters was above 85% for total suspended solids; 68%-93% for turbidity, chemical oxygen demand, zinc, and iron; and 36%-61% for total organic carbon, nitrate, total Kjeldahl nitrogen, total phosphorus, and lead.
- Simple, V-shaped highway medians or shoulder areas with a width (pavement to median centerline) of at least 8 meters, full vegetative cover, and side slopes less than 9 to 12 percent provide protection to receiving waters against constituents in highway runoff. Consequently, many highways in the state that discharge runoff to vegetated channels are already employing an effective best-management practice.
- The removal efficiencies for the two filter strips were similar, despite significant differences in vegetation, traffic density, median side slope, and longitudinal (median centerline) slope. Studies of vegetative controls in other areas of the country have documented similar removal efficiencies.
- Grab samples confirmed that the removal of constituents occurred on the sides of the median, and not down its length. A long median is not required for effective removal of constituents from highway runoff.
- The slopes and lengths recommended in this report are appropriate for highways, but may not be sufficient for other situations. The small drainage areas provided by highways may explain why the filter strips were so effective.
- The deposition rates of lead and zinc on the filter strips were less than one-tenth the allowable rate for metals in biosolids applied to cropland.
- Results indicate that filter strips are effective for three-lane (each direction) highways at average daily traffic counts greater than 50,000.

4.2. Channel Swale

- Removal of total suspended solids, chemical oxygen demand, total phosphorus, total Kjedahl nitrogen, zinc, and iron was highly correlated with swale length. No trend was observed for nitrate.
- Most of the reduction in the concentration of constituents in runoff occurred in the first 20 meters of the swale. Little improvement in water quality was observed during the last 20 meters.
- The removal efficiency for suspended solids, organic material, and most metals decreased with increased water depth. No relationship between water depth and removal efficiency was observed for nitrate and total Kjedahl nitrogen.
- The removal efficiency of the grassed swale was about the same during the dormant and growing season for all constituents except for total suspended solids. Total suspended solids experienced the highest removal during the growing season, when there is a combination of new grass and remaining dormant grass.
- Percolation of runoff through layers of soil and gravel into the underdrain reduced concentrations of all constituents except nitrate.
- Excellent pollutant removal occurred in the channel swale when the hydraulic residence time was approximately 9 minutes. The removal was similar to that of a site monitored in Seattle that had about the same residence time, but differed in other aspects. Hydraulic residence time appears to be an appropriate design criterion for grassed swales.

4.3. Seton Pond Field Study

- The removal of constituents observed for the sedimentation basin alone at the Seton Pond facility was higher than removals reported for many sedimentation/filtration systems. The better removal can be attributed to detention times that commonly exceeded a week or more. The longer detention time allowed a greater fraction of particulate matter and adsorbed constituents to settle out.

- The effectiveness of the combined sedimentation/filtration system was higher than that reported for other systems having a similar design. The nutrient removal was unusually high and may have been the result of algae and other plants growing in the sand filter.
- The overall hydraulic performance of the system was poor. The design drainage time was 24 to 48 hours; however, the drainage time ranged from >4 days to >10 days during the monitoring period. The increasing drainage time adversely affected the capture volume of the sedimentation basin. Approximately 20% of the runoff from the watershed bypassed the Seton Pond facility during the monitoring period.
- Maintenance is essential for proper hydraulic operation. 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 extended detention times provided by the clean sand filter (about 96 hours) were adequate for treating highway runoff. Additional detention time provided no substantial improvement in particulate removal by sedimentation or filtration and caused more runoff to bypass the facility. Detention times increased to such an extent that the sand filter was transformed into a wet pond, increasing nutrient removal for runoff that entered the basin.

4.4. Prototype Sedimentation Analysis

- An evaluation of outlet structure design for sedimentation basins indicated that draining from the surface of the basin provided slightly improved removal for most of the constituents. However, the improvement was not substantial enough to recommend one type of outlet structure.
- Detaining the runoff 24 hours prior to draining significantly improved the removal efficiencies of most constituents. 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 detention time of 72 to 96 hours can be consistently attained. Ponds may have slightly less pollutant removal than sand filters; however, ponds are less expensive to construct and have fewer maintenance requirements.

4.5. Recommendations

4.5.1. Vegetative Controls

1. Include vegetated buffer strips or grassed swales in the design of new highways or renovation of old highways. Vegetated BMPs are especially beneficial in environmentally sensitive watersheds and can be used where treatment of highway runoff is required. Appropriate slopes and sufficient vegetative cover are required for these devices to function effectively. Vegetated buffer strips can be included in highway design at low cost and with little obstruction to other highway design objectives.
2. Avoid curb-and-gutter systems on new highways and roadways. Instead, allow the runoff to exit the pavement as sheet flow into grassy medians or shoulder areas.
3. Medians with a V-shaped cross section should have a maximum side slope of 9 to 12 percent and a minimum distance from roadway to median centerline of 8 meters for effective pollutant removal.
4. Vegetated swales with flat bottoms should be designed with a hydraulic residence time of at least 9 minutes.
5. Review guidelines for design of vegetated channels. Channel erosion was a significant problem in the median of the MoPac Expressway, which was designed to current standards. A storm drain system with drop inlets can be used in conjunction with vegetated channels to minimize erosion and maintain shallow water depths.

4.5.2. Sedimentation/Filtration Systems

1. Sedimentation/filtration systems are recommended in urban areas with high impervious cover and where space is limited.
2. Regular maintenance is required to achieve design drainage rates and maintain the maximum capture volume.
3. Factors that can affect the maintenance frequency are watershed size, the presence of construction activity or unlined channels in the watershed, and the storm frequency in the region. These factors should all be carefully considered in the design of new sedimentation/filtration systems.
4. 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.
5. A pond should be installed with a simple drainage structure that provides adequate detention time and that is not prone to clogging. Discharge of runoff from the surface of a sedimentation basin does not result in substantial improvement in pollutant removal when compared to conventional outlet designs.
6. 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 and from the hazardous materials trap.