University of Washington
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PERFORMANCE EVALUATION OF A DETENTION BASIN AND COALESCING PLATE OIL SEPARATOR FOR TREATING URBAN STORMWATER RUNOFF

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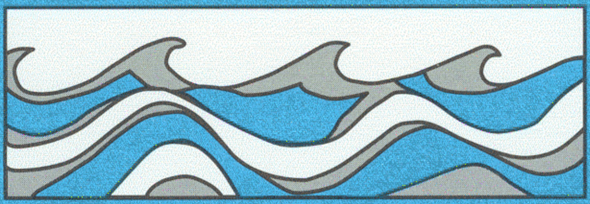

Water Resources Series
Technical Report No. 98
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by

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ABSTRACT

Stormwater runoff from land surfaces put to various uses has been identified as a major factor in the degradation of receiving water bodies. Detention devices and oil/water separators are two of the runoff treatment measures being used to alleviate this problem. However, there has been little basis on which to design and operate these facilities in order to obtain maximum treatment effectiveness. The general goal of this project was to contribute to defining the needed basis by collecting and analyzing operating data on a detention basin/coalescing plate oil separator treatment system installed at Boeing Computer Services Company, a light-industrial site in Bellevue, Washington.

Three natural and four synthetic storms were monitored at the site between November, 1984 and May, 1985. The synthetic storms were produced by applying measured quantities of city water to a portion of the parking lot by means of irrigation sprinklers. Site runoff was sampled at the inlet and outlet of the detention pond and the separator discharge and analyzed for suspended solids, seven metals (total extractable and dissolved), total phosphorus, nitrate + nitrite - nitrogen, and oil and grease. Removal efficiencies of the treatment devices were computed and evaluated with reference to antecedent and storm conditions.

The experiments demonstrated that the detention pond removes the majority of the entering solids, nearly all of the lead, 1/4 to 1/3 of the phosphorus, and variable proportions of nitrogen and other metals. The pond's performance could possibly be improved at relatively low cost by the addition of baffles.

Oil and grease concentrations in the runoff from the site were very low, and the capacity of the coalescing plate oil/water separator was not utilized. Further, unidentified materials in the separator added substantial quantities of zinc to the runoff. Although such oil/water separators are necessary at sites with more heavy equipment and automobile traffic, their use could be limited to areas prone to oil spills at light-industrial sites like the one investigated. Land treatment of detention pond effluent appears to be a more cost-effective alternative for such applications.

Key words: Urban storm runoff, water quality, detention basin, oil separator.

INTRODUCTION

Background

The passage of federal and state legislation in the past 15 years, especially the Federal Water Pollution Control Act 1972 Amendments and 1977 Clean Water Act, has spurred widespread actions to improve surface water quality in the United States. For much of this period the majority of the attention has been directed toward control of point sources of water pollution, e.g. municipal sewage treatment plant and industrial effluents. Continuing water pollution problems in cases where some success has been achieved in reducing point source contributions has suggested, more recently, that diffuse sources of water pollution also are major factors in surface water quality. These diffuse contributors have been termed nonpoint sources and are associated with stormwater runoff from land surfaces put to various uses.

The recognition of nonpoint sources as major pollutant contributors to lakes and streams raised the need to consider means of treating storm runoff to reduce contamination. Clearly, conventional wastewater treatment technology could not be applied with any affordable investment to the very large volumes of water collected intermittently during and after storms. Preceding the concern with runoff water quality, the problem of runoff quantity and receiving stream peak flow increase had begun to receive attention. Retention and detention of stormwater in holding basins, followed by release at relatively slow rates, was prescribed as the solution to the quantity problem, and numerous new retention/detention (R/D) facilities were installed throughout the nation. Recognizing the particulate settling potential offered by such devices, public works personnel soon began to regard them as at least a partial solution to runoff quality problems as well. In most cases R/D facilities represented the only effort at runoff water quality treatment. However, in a significant minority of cases, other devices, such as oil separators, fabric or gravel filters, or natural media (land or wetland treatment), were installed either separately or in series with R/D facilities.

Almost without exception, R/D and other measures have been specified and built with little knowledge of how they would actually perform in improving storm runoff water quality under the anticipated service conditions. Even general performance data usually were very sparse and unrepresentative of a range of possible operating conditions. Thus, there was no real basis on which to design the facilities, specify operating and maintenance procedures, or manage receiving waters. Only now is some history of operation becoming available to provide a partial foundation upon which to make these decisions.

The City of Bellevue, Washington, has been a leader in attacking problems in aquatic ecosystems caused by stormwater runoff, establishing the first drainage utility in the United States. The city has adopted ordinances that require developers to install R/D and other control measures and has constructed regional structural and wetland R/D systems for common use among properties. Today Bellevue has more than 500 R/D facilities in operation, most under private control (Diessner, personal communication). The area under King County, Washington, jurisdiction, outside incorporated cities, has some 2700 R/D installations (Simmler, personal communication). Bellevue also makes use of most of the other common types of runoff treatment devices. However, these jurisdictions have not been able to conduct sufficient studies of the facilities in place to develop operating and maintenance guidelines or to design criteria for future installations with confidence. The general goal of this research was to investigate the performance of a detention basin/oil separator treatment system in sufficient detail to provide a basis both for local purposes and for design and operation of similar facilities elsewhere.

The research approach involved the study of a storm runoff treatment system serving a well-defined, self-contained drainage basin in light-industrial use in Bellevue. The system includes a detention pond followed by a coalescing plate oil separator. This particular type of separator originally was developed for industrial applications and has not received extensive use in stormwater treatment. However, its operating characteristics suggest it should perform better than alternative separators in this service, and one outcome of the proposed research was an evaluation of its applicability.

Study of the water quality of runoff from natural precipitation events lacks the usual experimental control that produces the most definitive results in scientific research. Events vary widely in their pattern, frequency, duration, and intensity and occur with only limited predictability. An alternative is to produce synthetic events using a piped water source and distribution system. Synthetic events can remove much of the variability and unpredictability accompanying natural storms but may introduce other undesirable artificialities, principally excessive intensity from high pressure sprays, without special equipment. It was the initial objective of this project to design and construct a system to produce synthetic events without this drawback. It was intended that the system be suited for immediate application at the site selected for this investigation but be adaptable for use elsewhere in future studies.

Summary of Objectives

1. To design and construct a system to produce synthetic precipitation events having essentially natural characteristics.

2. To investigate the performance of a detention pond and a coalescing plate oil separator in urban runoff service over a range of service conditions, using both synthetic (for control) and natural (for verification) storm events.

3. To apply the resulting data to formulate cost-effective design, operating, and maintenance recommendations for systems of this type.

4. To apply the data to establish appropriate strategies for handling the effluent of such systems and managing the receiving water.

Related Research

Many studies have been performed to characterize the water quality of runoff from surfaces in various urban and other land uses. Thus, runoff quality is well-defined. Wanielista (1978) has summarized the general character of stormwater runoff.

Our research team conducted a large, comprehensive investigation on highway runoff water quality in Washington State and made several advances that are relevant to the work reported here (Mar et al., 1982). This study characterized highway runoff thoroughly statewide by making use of both discrete sampling during storms and the economies of storm composite sampling (Clark et al., 1981). The highway runoff research also involved modeling of pollutant loadings and concentrations (Asplund et al., 1982; Chui et al., 1982; Little et al., 1983), developing means for assessing aquatic impacts of operating highways (Portele et al., 1982), and mitigation of those impacts (Wang et al., 1982).

The use of R/D facilities as treatment devices has been supported by both laboratory and field research, although an insufficient record is available to predict performance over a wide range of conditions or to serve as a strong foundation for design and operating criteria. Whipple and Hunter (1981) quantified pollutant settleability in laboratory water columns and applied the data to estimate detention basin pollutant removal capabilities. They concluded that a 32-hr residence time in an undisturbed pond six ft deep would reduce various stormwater constituents as follows: total suspended solids (TSS)--70%; lead (Pb)--60%; zinc (Zn)--17-36%; hydrocarbons--75%; biochemical oxygen demand (BOD), copper (Cu), and nickel (Ni)--20-50%. In a similar study Randall et al. (1982) found that a 48-hr settling period removed 90, 86, and 64% of the TSS, Pb, and BOD, respectively, from parking lot runoff. Driscoll (1982) proposed an equation relating detention basin solids removal with particle settling velocity, flow rate, basin area, and turbulence.

Basing their work on field data, Davis et al. (1978) analyzed treatment efficiency of detention processes by a series of regression analyses. Curtis and McCuen (1977), through the same process, identified storage volume, basin length, and detention time as significant predictor variables of pollutant removal. Employing the same data as Davis et al. (1978), McCuen (1980) found sediment removal efficiency to vary between 2 and 98% over different storms, with the highest efficiencies associated with the smallest storms and longest detention times. One aspect of the U.S. Environmental Protection Agency's (1982) Nationwide Urban Runoff Program involved detention basin effectiveness. This study established the following typical pollutant removal efficiencies for detention: TSS--65%; Pb--19%; Cu--41%; total phosphorus (TP)--25%. Dally et al. (1983) investigated the performance of two urban detention facilities and documented negative efficiences due to resuspension of sediment.

Various protocols exist to design R/D facilities with respect to hydrologic considerations. Common methods include that of Yrjanainen and Warren (1973) for watersheds under 200 acres in size and the Soil Conservation

Service and Colorado Urban Hydrograph methods for larger catchments. These procedures generally employ the Rational Method to estimate runoff volume from the smallest watersheds (less than 50 acres) and the Unit Hydrograph for larger watersheds. Relative to dual-purpose R/D facilities, Whipple et al, (1983) found that the addition of a requirement to detain the runoff from small storms for 24-36 hr in order to settle particulates results in only a small addition to the storage required to control peak flows from either 2, 10, or 100-year events.

R/D design based on water quality considerations is less standardized. Those procedures available fall into two broad categories: (1) theoretically based methods, generally relying on particle settlement according to Stokes Law, and (2) mechanistic models or statistical treatments derived from empirical data. Methods of the first type are usually based on textbook treatments (e.g., Linsley et al., 1975) but have not been widely checked for accuracy in actual use. The National Cooperative Highway Research Program (1980) produced a design manual for construction site sedimentation basins that bases hydrologic design on the Rational Method and sediment trapping on Stokes Law. Empirical treatments include that of Driscoll (1982), who proposed an equation relating detention basin solids removal with particle settling velocity, flow rate, basin area, and turbulence. Mays and Bedient (1982) constructed a model using a dynamic programming scheme that optimizes cost, size, and location of a detention basin in urban watersheds. Davis et al. (1978) developed a model that illustrates the difference in R/D design criteria for flow rate control versus water quality control and aids a user in finding a design best suited to achieving selected objectives. Ormsbee et al. (1984) developed a methodology for use in the planning of dual-purpose detention basins in urban watersheds. It employs continuous simulation, statistical analysis, and a general design heuristic to obtain an integrated system of detention basins.

In addition to devising formal design procedures, some investigators have published design guidelines based on observation of operating R/D facilities. For example, Kathuria et al. (1976) recommended the following, based on study of surface mine sedimentation ponds:

1. Minimum 10-hr detention time for design storm
2. Maximum 2 x 10^{-5} m/s overflow velocity
3. Maximize basin surface area to the extent possible
4. Install trash barriers, velocity checks at the inlet, and non-perforated risers

Ellis (1985) presented additional R/D design guidelines, including the following:

1. Length/width ratio of at least 3 (5 optimum)
2. Locate the inlet and outlet on opposite sides of the basin
3. Install baffles to guide flow in a manner that prevents short-circuiting from inlet to outlet
4. Consider installing more than one basin in a series arrangement

Assuming proper design for service conditions, R/D performance depends to a large extent on maintenance. Kathuria et al. (1976) provided maintenance recommendations, including regular sediment removal, cleaning of outflow pipes, and repair of spillways and embankments when necessary. Kamedulski and McCuen (1979) added cutting of vegetation in the spillway as a concern.

Although the performance characteristics of oil separators in industrial service are well-known, they have not been widely and thoroughly tested in stormwater applications, where influent concentrations tend to be lower. The Washington State Department of Transportation has installed a number of oil and grease traps on state highways. Finger (n.d.) evaluated the performance of such a device and measured an effluent concentration of 18 mg/l. However, this concentration approximated that in the influent runoff, and little removal occurred in the trap. Parking lot runoff tends to contain somewhat higher oil and grease concentrations than highway drainage due to the contributions of stationary vehicles.

The manufacturer of the coalescing plate separator in use at the study site claims it can produce an effluent oil content of 15 mg/l or less (Fram Industrial Filter Corporation, n.d.). A test of a separator of this type in a system draining a diesel fuel tank area was performed at the Bremerton, Washington, Navy Yard. Oil and grease concentration was reduced from a maximum of 104 mg/l to 17 mg/l by the coalescing plate separator (Markham, personal communication). Lettenmaier and Richey (1985) studied a Fram coalescing plate separator serving the storm drainage system at the Municipality of Metropolitan Seattle transit base in Bellevue. Relatively heavy motor oil leakage from diesel buses stored and maintained at the site created generally higher oil and grease concentrations in this runoff than drainage from highways and automotive parking lots (Horner et al., 1985).

EXPERIMENTAL DESIGN

Site Description

The research was conducted at the Boeing Computer Services Company (BCS) in Bellevue, Washington. Figure 1 shows the location and layout of the site. The developed portion of the catchment totals approximately 18 acres (7 ha) in area and drains via a storm sewer system to Pond B. Most of this portion is covered by buildings, roadways, and parking lots and is impervious. Lawns around buildings and planting areas dividing parking lots represent a small fraction of the total developed plot. The Phase II development area was wooded during the study and was not served by the storm sewer system. The catchment is isolated from any offsite drainage and offers the opportunity for a high degree of experimental control.

The Boeing site is in the Phantom Lake watershed and is situated close to the lake. Phantom Lake has been identified as a eutrophic water body and is currently the subject of a limnological study in preparation for restoration activities. Because of the potential sensitivity of Phantom Lake to uncontrolled stormwater runoff from impervious surfaces, the BCS drainage system was designed to detain runoff on the site, control its release to the lake, and reduce oil and grease in the effluent. In accordance with the Bellevue Development Standards, the drainage detention system is designed to limit the rate of stormwater discharge from the site in conformance with the natural conditions that existed prior to development (based on a 100-year storm of 19 minutes duration). The maximum designated rate in this case is 0.2 cfs/acre (0.0023 m^3/s-ha) (Bellevue Department of Public Works, 1981).

The stormwater collection system consists of roof drains and curb inlets feeding into catch basins. The collected stormwater is conveyed to catch basin number 38 (C.B. 38; see Figure 1); from there it enters a 21-inch (53.3 cm) line and flows in a northward direction toward Pond B. The conveyance system is hydraulically sized to transport the runoff from a 10-year storm of four hours duration without backing up (Olympic Associates Company, 1984).

Figure 2 depicts details of the drainage system in the vicinity of Pond B. All stormwater is normally directed into the pond at C.B. 40, although a slide gate valve at that point can be set to divert up to 550 gpm (0.035 m^3/s)

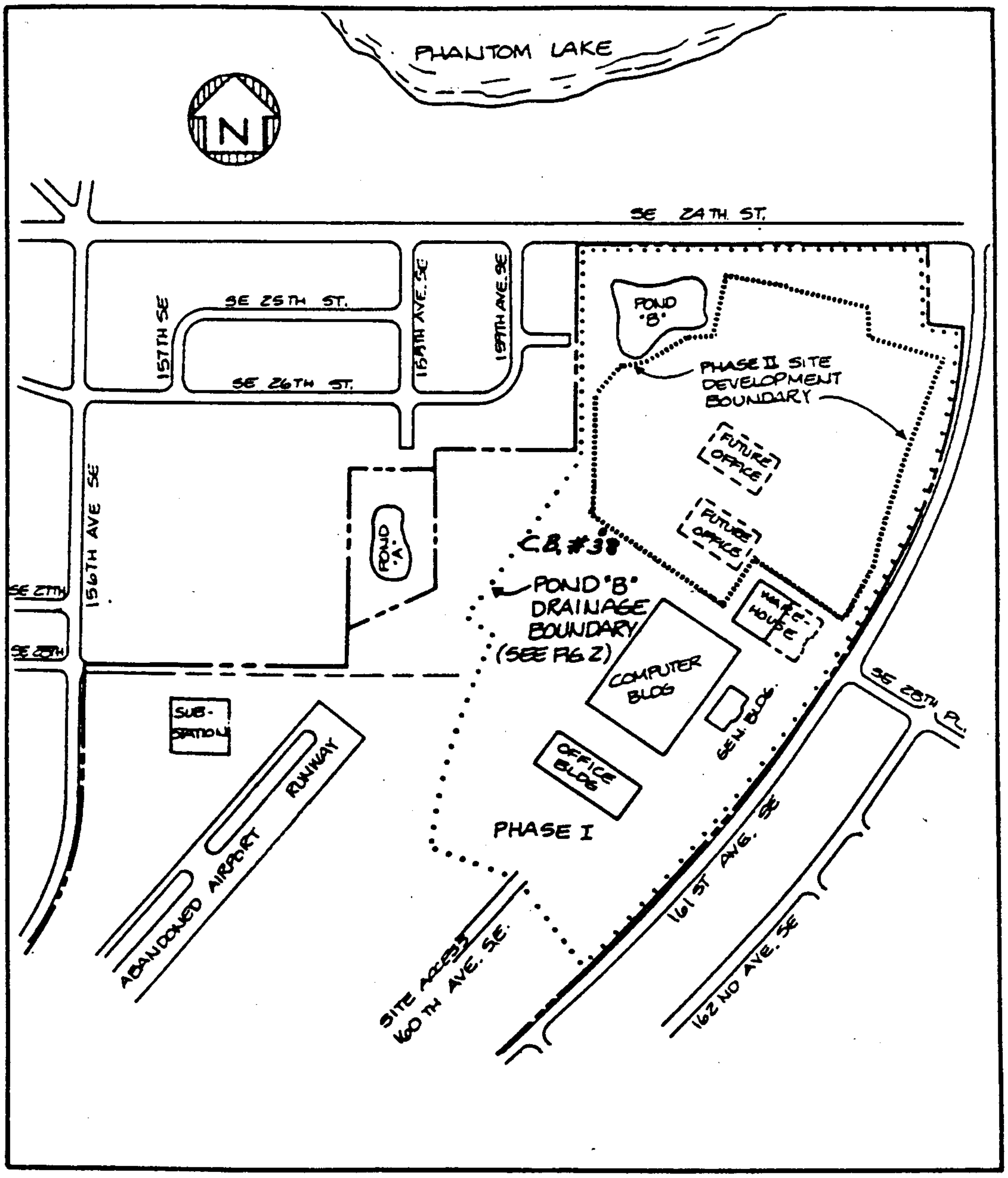

Figure 1. Location and Layout of Boeing Computer Services Company Site (from Olympic Associates Company, 1984)

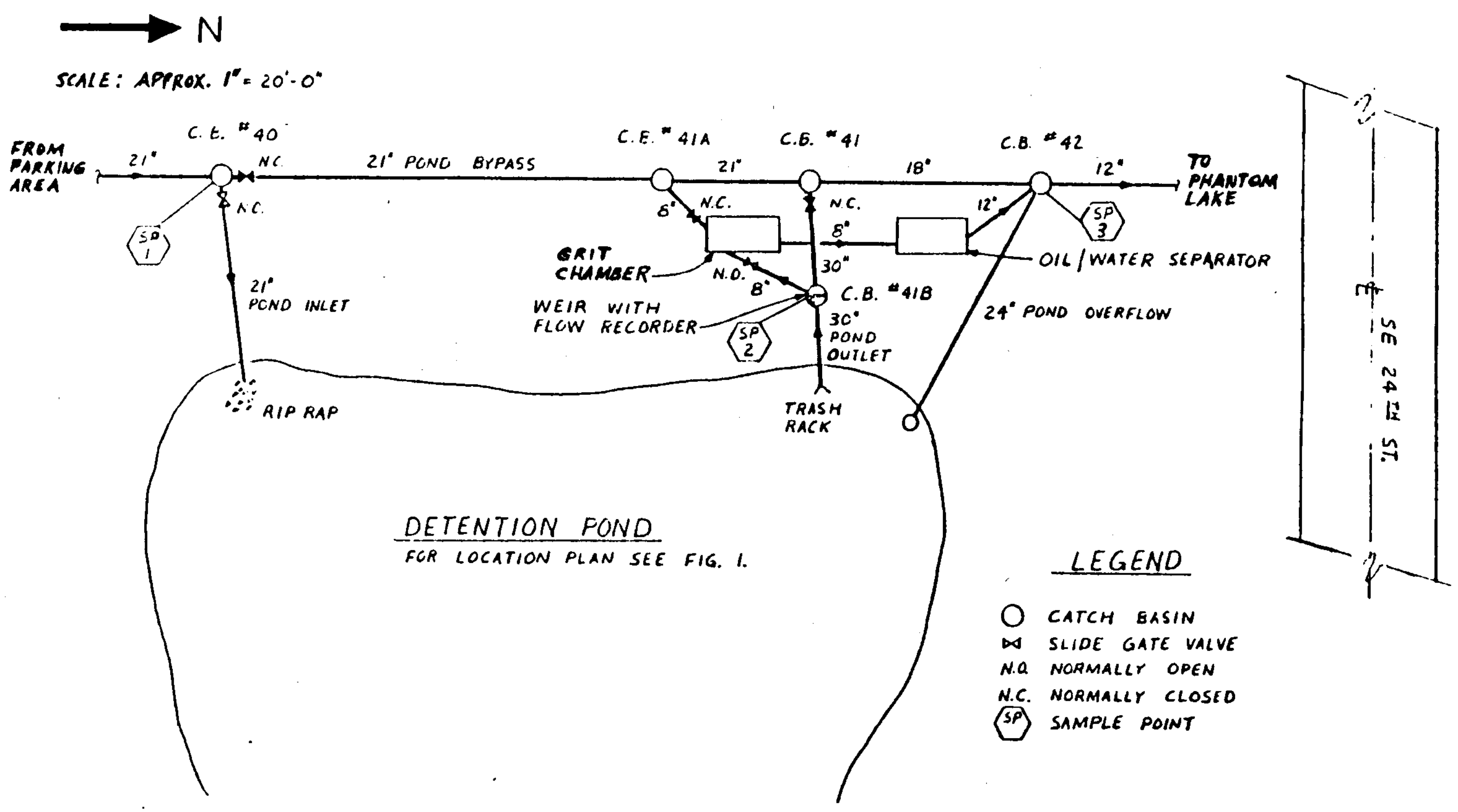

Figure 2. BCS Stormwater Drainage System in the Detention Pond Vicinity

into the pond bypass line. Water held in the pond is discharged through C.B. 41 at the rate of approximately 0.035 m^3/s into the baffle type grit chamber for removal of floating debris and any large sediment particles that escape the pond or subsequently enter the flow. The grit chamber has an orifice that limits flow into the oil/water separator to 0.035 m^3/s, from where effluent discharges via a 12-inch (30.5 cm) line to Phantom lake. If any excess occurs, it will overflow automatically into C.B. 41. An orifice system in this catch basin controls the pond level and any flow diversions that may be necessary. Above a certain level, pond overflow bypasses the grit chamber and separator, controlled by the orifice system to increase incrementally as the pond fills. The maximum flow rate allowed by the restrictor orifices is 3.54 cfs (0.100 m^3/s), in conformance with the design limitation. For very severe storms, an additional grit chamber and separator bypass line to C.B. 42 is also provided. The pond is sized to contain runoff from a 100-year storm of four hours duration, approximately 165,000 ft^3 (4,676 m^3). It generally retains some water between storms during the wet season but often dries completely in the summer.

The oil/water separator is a coalescing plate type manufactured by the Fram Industrial Filter Corporation. This device is an enhanced gravity separator, utilizing the differences in specific gravity between immiscible components of a liquid. It contains an inlet chamber to separate heavy solids and non-emulsified oil. The remaining oil-water mixture flows through the closely spaced, corrugated polypropylene plates, where smaller oil droplets and fine solids are progressively separated. The plate arrangement induces a sinusoidal laminar flow pattern, a condition under which buoyancy forces and droplet collision cause oil droplets to rise until they adhere to the plates. These droplets coalesce into sheets on the undersides of the plates, and the agglomerated oil rises toward the surface through weep holes. Skimmers and drains are provided for oil and solids removal, respectively. It has 125 gal (473 l) of oil storage capacity. The device is capable of removing oil droplets of 23 micrometer diameter or smaller, compared to 60 micrometer for tilted plate separators and 120 micrometer for standard API tanks (Fram Industrial Filter Corporation, n.d.). The separator is sized to produce an effluent having less than 15 mg/l oil with influent concentrations up to 600 mg/l and maximum flow rate of 0.035 m^3/s (Olympic Associates Company, 1984).

Boeing inspects and maintains the stormwater drainage and treatment system according to a regular schedule. This schedule calls for cleaning catch basins 40, 41, 41A, and 41B monthly and upstream catch basins and the grit chamber semi-annually. The oil separator maintenance schedule is as follows:

Inspection --	Weekly
Oil Removal --	When 50% full
Solids Removal --	Semi-annually
Cleaning Plates --	Annually

Detention pond cleaning is on an as-needed basis.

General Experimental Setup

It was desired to study the stormwater treatment system performance under both the tightly controlled conditions of synthetic storms and during natural storms, for verification of trends noted in results from the synthetic events. To produce the synthetic storms, a system was designed and constructed for distributing water from a fire hydrant to a portion of the parking lot. This area is approximately 1.0 acre (0.4 ha) in size and is located in the southwestern portion of the complex. Figure 3 illustrates the system. It consists principally of PVC pipe of 1 1/2 - 4 inches (3.8-10 cm) diameter, hose, and irrigation sprinklers. The use of sprinklers permitted the creation of a synthetic storm condition without applying water at artifically high pressures from hoses. Sprinklers were placed to produce nearly complete coverage of the area with spray while minimizing delivery outside of the parking lot area. This placement and a flow meter at the hydrant outlet allowed a relatively accurate estimation of the synthetic precipitation volume. A throttle valve permitted control of the hydrant flow rate. The maximum discharge capacity of the system was approximately 0.5 cfs (0.014 m^3/s).

For flow measurement a V-notch weir was designed and constructed and installed in C.B. 41B, along with a Stevens Model A-71 water level recorder (see Figure 2). Figure 4 depicts details of the weir design. During the November, 1984-May, 1985 period of sampling, the pond remained wet and the lag between inflow and outflow was brief. Therefore, flow measurement at the pond

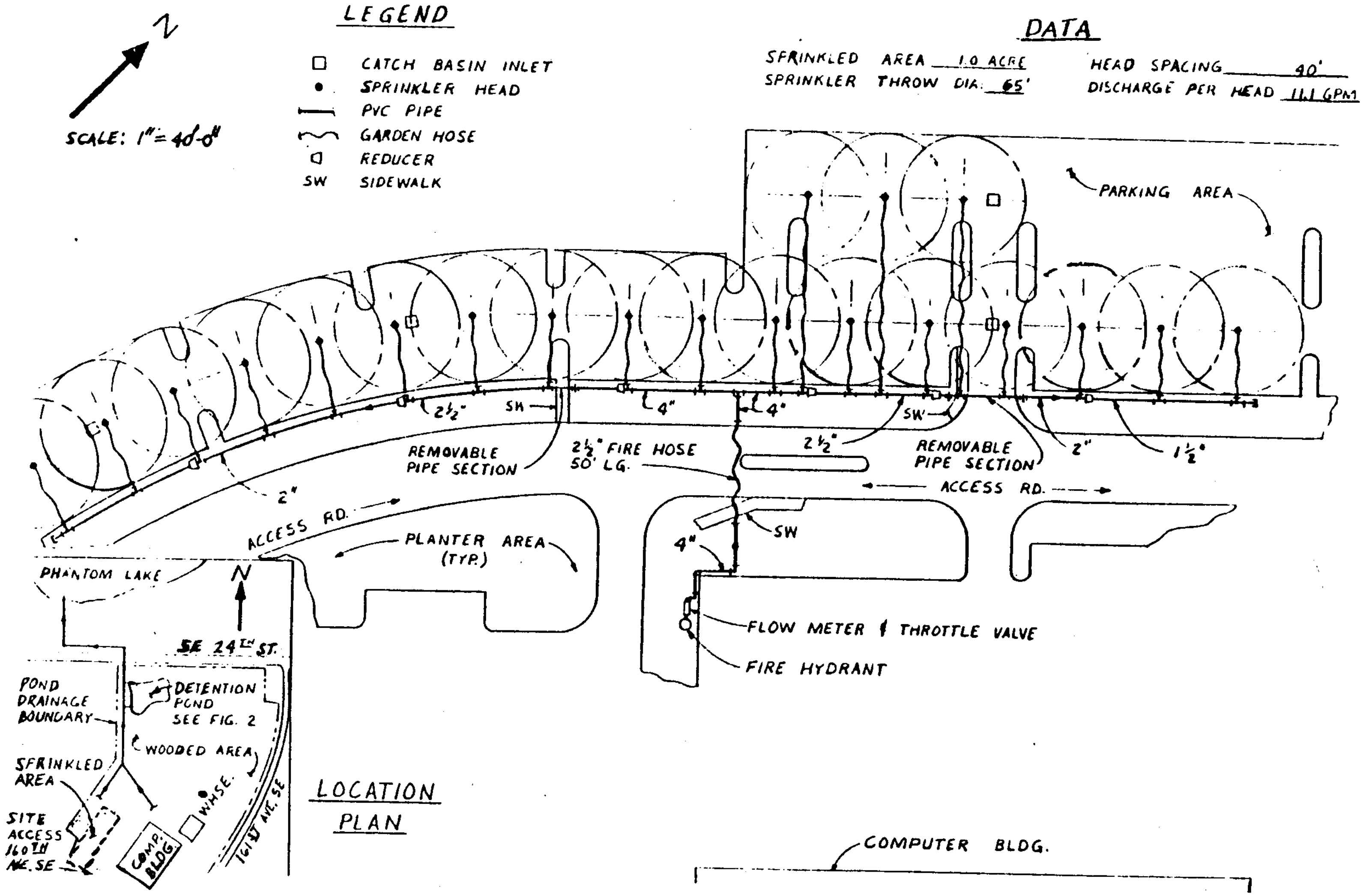

Figure 3. Distribution System for Synthetic Storms

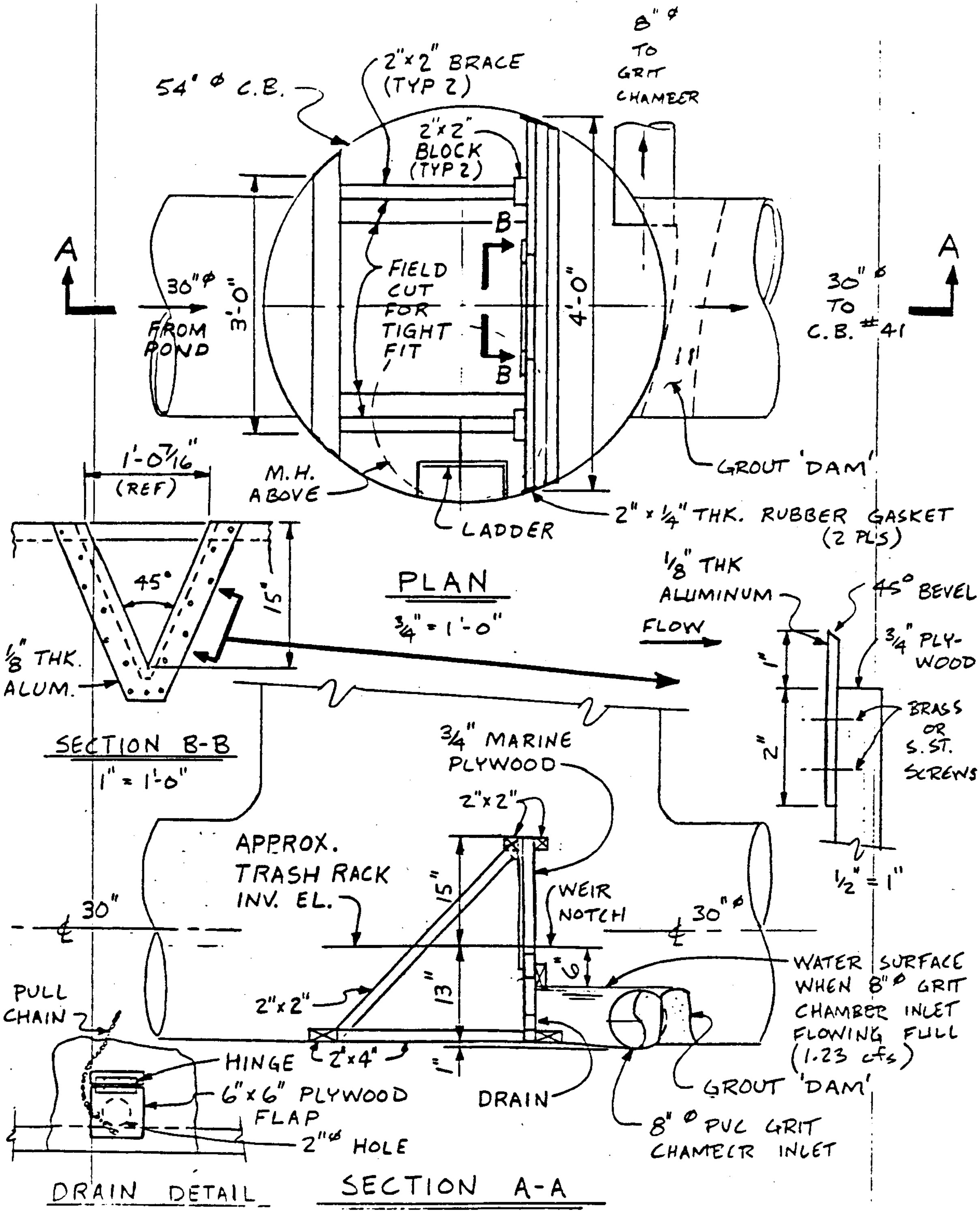

Figure 4. V-Notch Weir Design

outlet, along with synthetic or natural precipitation data, was adequate to characterize the hydrology of the system.

The synthetic storm distribution system and weir constructed for this project will be available for use elsewhere in future work, with appropriate adaptation. The ability to study storm runoff water quality from experimental catchments, economically and under a relatively high degree of control, is a major addition to our capability to perform nonpoint water pollution research.

Sampling Procedures

Samples were collected by a manual grab method at the three sampling points (SP1, 2, and 3 in Figure 2). SP1 represents the detention pond influent, SP2 the pond outlet and grit chamber inlet, and SP3 the oil/water separator effluent. Manual sampling was used in preference to automatic sampling because of the need to sample at three points at roughly the same time and the unavailability of three automatic samplers. The collection was made using a long-handled sample bottle holder constructed to order for the project. The device could hold either a glass bottle for collection of an oil and grease sample or a polypropylene container for other constituents. It had a hinged lid to permit capture of a sample at a selected depth. Samples generally were taken at approximately 2/3 of full depth. Turbulence at each sampling point ensured a high degree of homogeneity with depth, so that floatable and settleable material tended to be retained in the water column.

In the first several storms, samples were collected frequently (i.e., at 7.5 or 15 minute intervals) for the first hour of events and less frequently thereafter. After the pollutant flushing pattern of the site became apparent, some samples were composited on a time-proportional basis, in order to represent a relatively homogeneous portion of the storm with a single sample. Because the flow was uniform throughout synthetic storms, time-proportional compositing was also usually flow-proportional.

Detention pond and oil/water separator effluents were sampled on different schedules in order to investigate the pattern of pollutant removal. In early storms these effluents were sampled as described above, beginning just after the pond began to drain. Pond drainage generally lagged the beginning of inflow to the pond by less than an hour. This drainage did not represent the water applied to the parking lot on the same day but water entering the pond on a previous date, however. Therefore, the effluents were sampled at different times, ranging up to approximately 24 hours after the cessation of influent, in the last several storms.

Sample Handling and Analysis

All water samples were collected in acid-washed containers and were held at 4°C until processing. Sample handling and preservation techniques were according to the guidelines of the U.S. Environmental Protection Agency (1979). Table 1 presents the analytical methods employed.

Table 1. Summary of Analytical Methods

Constituent	Type Sample	Preservation	Method	References (Method No.) American Public Health Association (1980)	References (Method No.) U.S. EPA (1979)
Total Suspended Solids (TSS)	Unfiltered	4°C Refrigeration	Gravimetric	209C	160.2
Metals (As, Cd, Cr, Cu, Ni, Pb, Zn)	Filtered and Unfiltered	HNO_3 to pH $<$ 2	Inductively Coupled Plasma Spectrometry	Section 300	Section 200
Total Phosphorus (TP)	Unfiltered	None	Ascorbic Acid following Persulfate Digestion	424F	365.2
Nitrate + Nitrite - Nitrogen (NO_3+NO_2-N)	Filtered	4°C Refrigeration	Automated Cadmium Reduction	418F	353.2
Oil and Grease	Unfiltered, collected specially	HCl to pH $<$ 2	Partition-gravimetric	503A	413.1

RESULTS

Characteristics of Storms and Antecedent Periods

Table 2 summarizes the antecedent conditions for each storm. Sampling of natural storm runoff generally did not begin until after several hours of precipitation. Two of the four synthetic storms followed relatively long antecedent dry periods, while some light precipitation preceded the other two synthetic storms.

Full maintenance, including cleaning the oil/water separator plates, predated the first sampling occasion by about 4 1/2 months. The interval between more routine maintenance (catch basin cleaning and solids removal from the grit chamber and separator) and a sampling occasion ranged from 19 days (1/26/85 and 4/20/85) to 82 days (3/30/85).

Table 3 summarizes the meteorological and hydrological measurements for each storm. Natural storms for which samples were collected represented total precipitation volume ranging from 0.21-0.37 inch (5.3-9.4 mm) and average intensity ranging from 0.030-0.053 in/hr (0.8-1.3 mm/hr). Synthetic events were more intense, ranging from approximately 0.21-0.33 in/hr (5.3-8.4 mm/hr) on the 1.0-acre (0.4 ha) catchment served by the sprinklers, representing total synthetic precipitation of 0.55-0.68 inch (14.0-17.3 mm). These events were equivalent to storms of 2-2 1/2 hr duration having return periods of 2-5 years in the Seattle area. They were regarded as relatively heavy events, having the capability of effectively removing pollutants from the pavement, that also occur with some frequency in actuality.

The rate at which the detention pond filled and drained depended on the precipitation volume and intensity and the antecedent water level. All but the first sampling date occurred during a long period deficient in precipitation relative to long-term monthly averages. Consequently, the pond had more storage volume than would be the case in most years. In no situation observed did the pond effluent rate approach the maximum allowable rate of influent to the separator.

To illustrate the effect of pond storage volume on water retention time, estimates of theoretical retention time were made for different influent rates and storage depths available at the beginning of a runoff event. The

Table 2. Summary of Antecedent Conditions for Each Storm

Date	Type of Storm	Antecedent Precipitation (inch)[a] 24 Hr	48 Hr	1 Wk	Antecedent Maintenance[b]
11/19/84	Natural	0.17	0.17	1.42	Full maintenance 7/3/84 Routine maintenance 9/28/84
1/26/85	Synthetic	0	0	0.37	Routine maintenance 1/7/85
3/22/85	Natural	0.37	0.61	0.61	None since 1/7/85
3/30/85	Natural	0.24	0.44	1.25	None since 1/7/85
4/20/85	Synthetic	0.30	0.72	0.87	Routine maintenance 4/1/85
5/5/85	Synthetic	0.06	0.12	0.34	None since 4/1/85
5/18/85	Synthetic	0	0	0.71	None since 4/1/85

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[a] Precipitation in period preceding beginning of sampling as measured at the Seattle urban station on Portage Bay (National Climatic Data Center, 1985). 1 inch = 25.4 mm.

[b] From Boeing Computer Service Company records (Sullivan, personal communication). Routine maintenance consists of catch basin cleaning and removal of solids from the grit chamber and oil/water separator. Full maintenance includes cleaning the separator plates plus routine maintenance.

Table 3. Summary of Meteorological and Hydrological Data for Each Storm

Date	Type of Storm	Sampling Period	Water Application Pattern	Total Water Volume		Average Water Application Rate		Flow Measurement		
				cu ft	inch	cfs	in/hr	cu ft	Period^c	cfs^c
11/19/84	Natural	16:10-21:10	Precipitation for 4 hr preceding and 2 hr during sampling	13,720^a	0.21	0.64	0.035	4,131	5 hr	0.21
1/26/85	Synthetic	13:47-16:32	Uniform for 125 min	2,461	0.68^b	0.33	0.33	1,382	24.5 hr	0.016
3/22/85	Natural	07:00-10:00	Precipitation for 7 hr preceding sampling	24,180^a	0.37	0.96	0.053	2,510	3 hr	0.23
3/30/85	Natural	09:15-12:15	Precipitation for 8 hr preceding sampling	15,680^a	0.24	0.54	0.030	1,095	3 hr	0.10
4/20/85	Synthetic	SP1: 09:47-11:40 SP2/3: 11:00, 4/21	Uniform for 120 min	2,049	0.56^b	0.28	0.28	5,107	25 hr	0.06
5/5/85	Synthetic	SP1: 11:12-13:12 SP2/3: 20:30	Uniform for 157 min	2,008	0.55^b	0.21	0.21	1,213	10.5 hr	0.03
5/18/85	Synthetic	SP1: 10:14-12:14 SP2/3: 14:45	Uniform for 125 min	2,299	0.63^b	0.31	0.30	136	4.5 hr	0.008

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[a] Calculated for a total site area of 18 acres (7 ha).

[b] Calculated for an area of 1.0 acre (0.4 ha) served by the sprinkler system.

[c] Flow was recorded for various lengths of time as the detention pond drained. The flow rate (cfs) is the average over the period of time that flow was recorded.

[d] 1 ft^3 = 0.028 m^3; 1 inch = 25.4 mm; 1 cfs = 0.028 m^3/s.

Table 4. Estimated BCS Detention Pond Theoretical Water Residence Times for Different Influent Rates and Pre-storm Storage Depths

	Theoretical Retention Time (hr)					
Influent Rate (cfs):	0.10	0.20	0.25	0.33	0.50	1.0
Storage Depth (inches)						
6	45	23	18	14	9.0	4.5
9	64	35	28	21	14	7.0
12	92	46	37	28	18	9.0
18	136	68	54	41	27	14
24	181	90	72	55	36	18

[a] 1 cfs = 0.028 m^3/s; 1 inch = 2.54 cm.

estimates were based on a pond surface area of approximately 0.75 acre (0.30 ha) (Table 4). Typical storage depths observed in the winter and spring of 1984-85 were 9-12 inches (22.9-30.5 cm). Therefore, theoretical water residence times for the approximately 0.20-1.0 cfs (0.006-0.028 m^3/s) water application rates observed during the project ranged from about 7-92 hr. Short residence time detracts from the treatment efficiency of detention ponds. Studies cited earlier determined that retention times of the order of 32-48 hr are necessary to remove the majority of solids (Whipple and Hunter, 1981; Randall et al., 1982). This pond would provide that much retention time at the 1984-85 water level only for smaller storms ($\leq$ 0.25 cfs, which is equivalent to 0.014 in/hr precipitation distributed over the whole 18 acres draining to the pond). In wetter years less available storage capacity would cut theoretical retention time further. The times estimated in Table 4 are theoretical because short-circuiting from inlet to outlet could reduce the actual period of retention of a given parcel of water.

Water Quality

Discrete samples were collected at SP1 at a number of points during the storms of 11/19/84, 1/26/85, 4/20/85, 5/5/85, and 5/18/85 to study the variability in pollutant concentrations during storms. A similar sampling strategy was applied at SP2 and SP3 on 11/19/84 and 1/26/85. The runoff usually exhibited elevated TSS concentrations during the first flush just after the beginning of runoff. The degree of elevation and the exact pattern depended on conditions, such as storm intensity and characteristics of the antecedent period. Figure 5 presents the variation in TSS concentrations at the three sampling points over the course of the 1/26/85 synthetic storm. The elevated peak seen at SP1 (pond inlet) was attenuated at the two downstream stations by the settling action in the pond.

Tables 5 and 6 summarize storm composite data, along with characteristic measurements at discrete points for the seven storms and three sampling points. Table 6 presents metal data, and Table 5 provides the data for the other contaminants. Appendix A contains additional data not summarized in Table 5.

All oil and grease concentrations reported in the tables were under 10 mg/l, and only one value in the entire program was above that level (40 mg/l

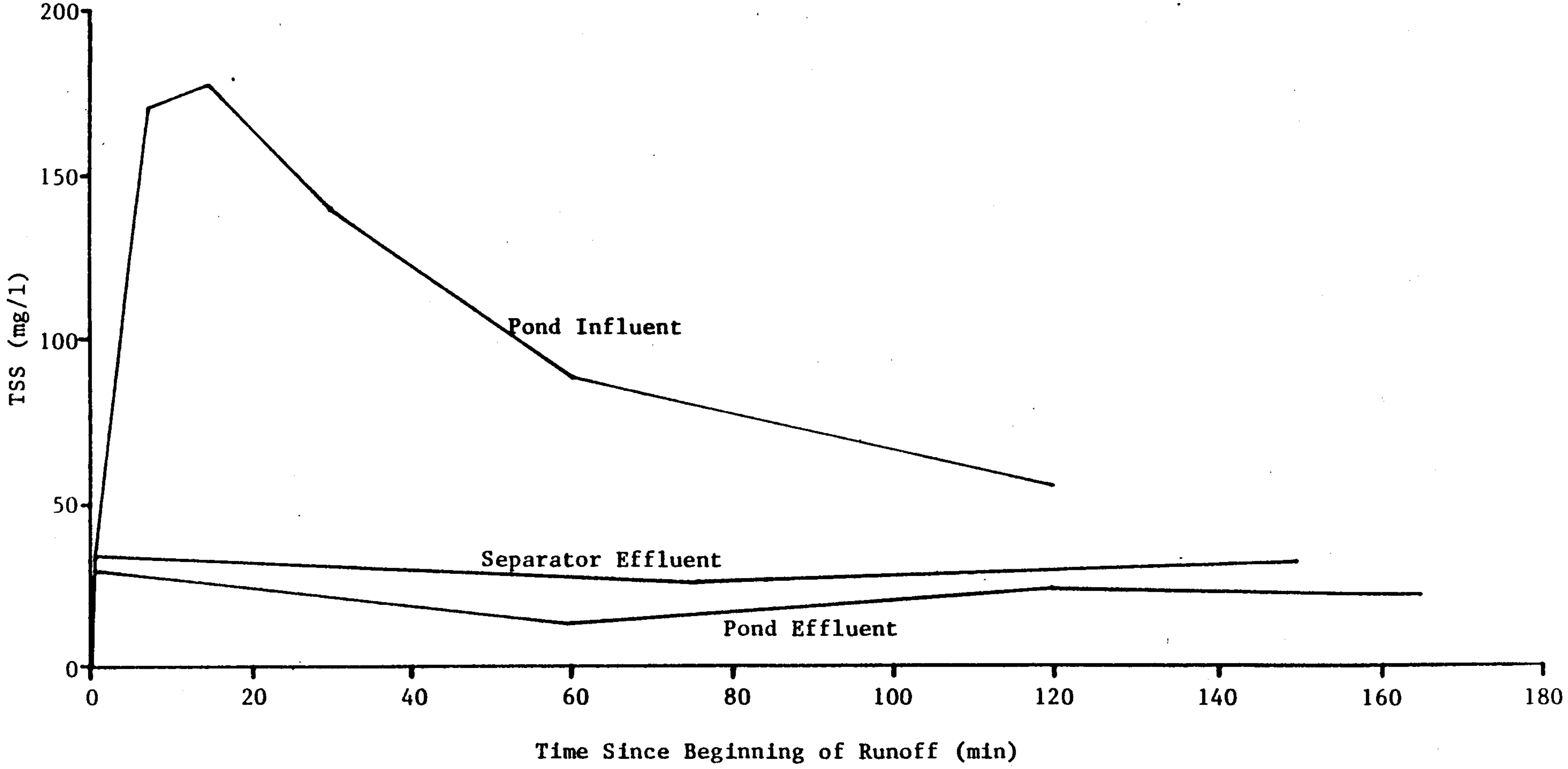

Figure 5. TSS Versus Time Since Beginning of Runoff for Synthetic Storm of January 26, 1985

Table 5. Summary of Discrete and Composite Sampling Results for TSS, TP, NO(3)+NO(2)-N, and Oil and Grease

Date	Sampling Point	Type of Sample [a]	TSS (mg/l)	TP (µg/l)	NO_3+NO_2-N (µg/l)	Oil and Grease (mg/l)
11/19/84	1	Discrete (0 min)	206	109	NA	3
		Composite (whole storm)	7.0	81	NA	
	2	Discrete (0 min)	6.5	55	NA	<1
		Composite (whole storm)	4.5	63	NA	
	3	Discrete (0 min)	1.0	45	NA	<1
		Composite (whole storm)	2.9	62	NA	
1/26/85	1	Discrete (15 min)	177	330	NA	4
		Composite (whole storm)	124	186	NA	
	2	Discrete (60 min)	13	80	NA	<1
		Composite (whole storm)	19	64	NA	
	3	Discrete (75 min)	25	62	NA	<1
		Composite (whole storm)	28	73	NA	
3/22/85	1	Discrete (30 or 60 minutes)	5.4	50	114	<1
		Composite (60-180 min)	5.2	32	104	
	2	Discrete (30 or 60 min)	9.6	37	96	2
		Composite (60-180 min)	12	35	83	
	3	Discrete (30 or 60 min)	12	54	121	<1
		Composite (60-180 min)	7.8	41	102	
3/30/85	1	Discrete (30 or 90 min)	3.2	44	228	1
		Composite (60-180 min)	1.8	45	270	
	2	Discrete (30 or 90 min)	3.2	36	298	<1

Table 5. (Cont.)

Date	Sampling Point	Type of Sample [a]	TSS (mg/l)	TP (μg/l)	NO_3+NO_2-N (μg/l)	Oil and Grease (mg/l)
		Composite (60-180 min)	6.6	37	78	
	3	Discrete (30 or 90 min)	0.2	28	1134	<1
		Composite (60-180 min)	1.4	31	110	
4/20/85	1	Discrete (Baseline)	1.8	23	794	6
		(0 min)	2.6	26	978	
		(7.5 min)	14	34	778	
		(15 min)	27	53	354	
		Composite (30-93 min)	28	439	138	
4/21/85	2	Discrete (25 hr)	12	75	35	5
	3	Discrete (25 hr)	6.2	61	29	4
5/5/85	1	Discrete (0 min)	4.4	80	117	2
		(5 min)	3.0	76	95	
		(10 min)	6.0	80	83	
		(15 min)	8.4	86	86	
		Composite (30-120 min)	16	113	105	
	2	Discrete (9.5 hr)	7.8	116	8	1
	3	Discrete (9.5 hr)	4.2	101	51	2
5/18/85	1	Discrete (0 min)	7.4	1086	1050	6
		(5 min)	104	1186	603	
		(10 min)	90	503	381	
		(15 min)	60	355	321	
		Composite (30-120 min)	41	144	127	
	2	Discrete (4.5 hr)	12	130	2	7
	3	Discrete (4.5 hr)	11	218	39	1

[a] 0 min. was the beginning of runoff for storms of 4/20/85, 5/5/85, and 5/18/85, and the initial sampling occasion for the storm of 11/19/84 (runoff had already begun). Baseline represents continuing runoff from a natural storm preceding the synthetic storm of 4/20/85. Where two times are given for a discrete sample, the second indicates when the oil and grease sample was taken, and the first indicates when the sample for the other constituents was collected.

Table 6. Complete Discrete and Composite Sampling Results for Total Extractable and Dissolved Metals

	Total Extractable Metals (µg/l)							Dissolved Metals (µg/l)						
	As	Cd	Cr	Cu	Ni	Pb	Zn	As	Cd	Cr	Cu	Ni	Pb	Zn
Date - 11/19/84														
Sampling Point-1														
Type of Sample [a] -														
Discrete (0 min)	23	2.4	8.2	23	3.5	26	60	32	2.7	6.0	19	1.6	<.1	48
Composite (whole storm)	20	2.2	7.2	25	2.4	7.1	78	17	2.2	6.6	24	3.4	<.1	76
Sampling Point-2														
Type of Sample [a] -														
Discrete (0 min)	23	2.3	7.1	22	4.1	<.1	64	19	2.5	7.2	19	2.9	<.1	42
Composite (whole storm)	18	2.2	6.6	25	2.4	3.1	79	11	1.8	6.2	23	3.2	2.7	59
Sampling Point-3														
Type of Sample [a] -														
Discrete (0 min)	24	2.3	6.4	26	3.4	<.1	218	17	2.1	6.4	22	1.5	<.1	187
Composite (whole storm)	11	2.4	5.6	27	4.1	<.1	184	19	2.2	6.5	24	2.2	<.1	149
Date - 1/26/85														
Sampling Point - 1														
Type of Sample [a] -														
Discrete (15 min)	89	2.5	13.8	37	10.7	154	108	23	2.0	5.8	19	2.2	2.7	109
Composite (whole storm)	57	2.7	10.7	34	7.8	124	223	20	2.4	5.7	24	3.9	4.4	178
Sampling Point - 2														
Type of Sample [a] -														
Discrete (60 min)	35	2.0	6.8	18	4.2	<.1	73	27	2.1	6.5	18	4.0	<.1	305
Composite (whole storm)	29	2.5	7.1	23	3.5	4.1	155	26	2.2	6.7	24	5.4	8.5	214
Sampling Point - 3														
Type of Sample [a] -														
Discrete (75 min)	36	2.6	7.4	21	5.5	8.1	562	27	2.1	6.3	19	3.8	1.0	502
Composite (whole storm)	21	2.8	6.6	23	5.4	7.8	569	11	2.5	6.3	23	3.9	7.8	546

Table 6. (Cont.)

	Total Extractable Metals (µg/l)							Dissolved Metals (µg/l)						
	As	Cd	Cr	Cu	Ni	Pb	Zn	As	Cd	Cr	Cu	Ni	Pb	Zn
Date - 3/22/85														
Sampling Point - 1														
Type of Sample [a] -														
Discrete (30 min)	<10	2.3	6.5	34	<1.0	<.1	100	18	1.5	6.4	70	1.0	<.1	298
Composite (60 - 180 min)	<10	1.9	7.4	33	<1.0	<.1	108	<10	2.2	7.3	31	<1.0	<.1	105
Sampling Point - 2														
Type of Sample [a] -														
Discrete (30 min)	21	1.7	6.3	23	0.9	<.1	56	<10	2.6	5.7	21	0.5	<.1	52
Composite (60 - 180 min)	10	1.4	6.7	23	<1.0	<.1	50	<10	1.8	5.3	21	<1.0	<.1	47
Sampling Point - 3														
Type of Sample [a] -														
Discrete (30 min)	20	1.8	6.0	23	1.1	<.1	99	15	2.3	5.5	22	<1.0	<.1	94
Composite (60 - 180 min)	12	1.7	6.0	23	2.6	<.1	87	<10	1.7	5.4	21	<1.0	<.1	81
Date - 3/30/85														
Sampling Point - 1														
Type of Sample [a] -														
Discrete (30 min)	12	2.3	6.3	26	2.2	<.1	59	<10	2.0	5.3	23	<1.0	<.1	57
Composite (60 - 180 min)	20	2.1	6.8	27	2.9	0.4	65	10	1.8	7.0	25	0.3	<.1	66
Sampling Point - 2														
Type of Sample [a] -														
Discrete (30 min)	14	2.3	6.0	21	1.1	<.1	49	<10	1.9	4.9	21	3.1	<.1	49
Composite (60 - 180 min)	28	2.3	5.8	20	2.9	<.1	41	17	1.9	6.2	19	1.0	<.1	42
Sampling Point - 3														
Type of Sample [a] -														
Discrete (30 min)	15	2.0	6.6	20	0.5	<.1	85	19	2.4	5.7	23	2.2	<.1	251
Composite (60 - 180 min)	25	2.3	6.2	21	4.1	<.1	86	22	1.9	6.4	20	3.4	<.1	89

Table 6. (Cont.)

	Total Extractable Metals (µg/l)							Dissolved Metals (µg/l)						
	As	Cd	Cr	Cu	Ni	Pb	Zn	As	Cd	Cr	Cu	Ni	Pb	Zn
Date - 4/20/85														
Sampling Point - 1														
Type of Sample [a] - Discrete (baseline)	32	2.1	5.7	24	1.6	<.1	99	<10	2.0	5.0	23	2.6	<.1	125
(0 min)	31	1.9	4.5	24	1.5	<.1	99	28	1.4	4.5	22	<1.0	<.1	100
(7.5 min)	28	1.8	4.5	18	2.8	<.1	52	<10	1.8	4.2	16	<1.0	<.1	53
(15 min)	44	3.3	6.4	21	8.0	95	41	18	2.0	3.8	14	2.0	<.1	40
Composite (30 - 93 min)	55	2.3	5.6	19	6.8	44	27	19	1.4	4.1	13	1.6	<.1	24
Date - 4/21/85														
Sampling Point - 2														
Type of Sample [a] - Discrete (25 hr)	35	1.8	6.3	17	4.2	2.6	32	22	1.6	4.5	14	<1.0	<.1	26
Sampling Point - 3														
Type of Sample a - Discrete (25 hr)	21	1.7	5.9	18	5.9	<.1	214	30	1.6	4.4	16	1.5	<.1	203
Date - 5/5/85														
Sampling Point - 1														
Type of Sample [a] - Discrete (0 min)	41	1.6	7.6	22	3.7	<.1	81	26	1.7	6.7	22	3.5	<.1	85
(5 min)	28	2.2	6.4	21	5.2	<.1	62	28	1.6	6.2	20	7.3	<.1	70
(10 min)	37	1.6	5.8	19	4.7	<.1	50	37	1.7	5.2	17	3.4	<.1	48
(15 min)	43	1.8	5.5	18	4.0	<.1	41	<10	1.6	4.2	16	4.6	<.1	37
Composite (30 - 120 min)	48	1.9	6.1	19	4.7	5.1	34	27	1.7	4.3	15	1.6	<.1	24
Sampling Point - 2														
Type of Sample [a] - Discrete (9.5 hr)	19	2.1	6.0	19	6.2	<.1	39	36	1.5	5.5	16	3.0	<.1	38
Sampling Point - 3														
Type of Sample [a] - Discrete (9.5 hr)	41	2.0	5.9	19	3.8	<.1	229	33	1.1	5.0	18	1.8	<.1	219

Table 6. (Cont.)

	Total Extractable Metals (µg/l)							Dissolved Metals (µg/l)						
	As	Cd	Cr	Cu	Ni	Pb	Zn	As	Cd	Cr	Cu	Ni	Pb	Zn
Date - 5/18/85														
Sampling Point - 1														
Type of Sample [a] -														
Discrete (0 min)	60	2.2	6.8	35	3.1	<.1	86	42	2.1	6.4	35	3.1	<.1	84
(5 min)	61	2.0	9.4	39	6.9	92	108	47	1.3	6.9	26	5.3	<.1	74
(10 min)	49	2.4	7.0	30	8.8	91	84	41	1.8	5.4	20	3.9	<.1	46
(15 min)	54	2.3	7.1	27	8.8	46	71	27	1.7	5.2	20	4.7	<.1	46
Composite (30 - 120 min)	47	1.8	5.2	20	6.8	45	35	36	1.6	4.6	16	3.1	<.1	25
Sampling Point - 2														
Type of Sample [a] -														
Discrete (4.5 hr)	50	2.2	6.1	18	4.8	<.1	48	24	<1.0	4.5	15	4.0	<.1	31
Sampling Point - 3														
Type of Sample [a] -														
Discrete (4.5 hr)	62	2.4	5.1	17	5.6	<.1	588	39	1.7	5.0	15	4.0	<.1	32

[a] 0 min was the beginning of runoff for storms of 4/20/85, 5/5/85, and 5/18/85, and the initial sampling occasion for the storm of 11/19/84 (runoff had already begun). Baseline represents continuing runoff from a natural storm preceding the synthetic storm of 4/20/85.

in a 11/19/85 discrete sample; see Appendix A). Therefore, the full capability of the coalescing plate device to separate oil and grease from runoff could not be evaluated. It is clear that the BCS site yielded little oil and grease to stormwater runoff under the conditions prevalent during the project.

On the basis of the evidence gathered during the sampling program, it is believed that the observed oil and grease concentrations would be typical of most runoff events at the site. No difference in concentration was apparent with differences in precipitation intensity or total volume in the ranges occurring during the program. It appears that only an event exceeding the design capacity of the separator, a change in vehicular usage, or an accidental spill of a petroleum product could lead to the release of oil and grease from the site in substantially higher concentrations than those observed.

Except for oil and grease, substantial variability is apparent in the results. This variability is characteristic of storm runoff water quality and is due to variations in numerous antecedent and storm conditions. Some patterns are evident, however:

1. Except when TSS was very low already, the detention pond tended to reduce its concentration; however, further reduction was not always achieved in flowing through the grit chamber and oil/water separator.

2. Pond and separator effluent P concentrations were usually, but not always, less than those in the influent and tended to reflect the level of influent P; i.e., relatively high effluent values usually followed relatively high yields from the site and vice versa. This trend was not evident for N, however.

3. The TP range in the separator effluent leaving the site was 28-218 μg/l, and the $NO_3 + NO_2$ - N range was 29-1134 μg/l. The settling provided by the pond apparently prevented comparably high concentrations of TSS in the site effluent, which exhibited a range of 0.2-28 mg/l.

4. Dissolved and total extractable As, Cd, Cu, and Ni tended to fluctuate relatively little with differing conditions and to be minimally affected by the treatment system.

5. Dissolved and total extractable Pb and Zn exhibited much greater fluctuation. Total extractable Pb in the pond influent ranged from below detection in a number of samples in different storms to 154 μg/l. It tended to reflect the TSS concentration. The total extractable Zn range was less (41-223 μg/l).

6. All of the metals were present primarily in the dissolved form, except for relatively insoluble Pb, which usually was undetectable in the dissolved phase.

7. Pb tended to be reduced effectively by treatment (total extractable Pb in the site effluent ranged from undetectable in most samples to 8.1 µg/l). Most of the reduction occurred in the detention pond.

8. The detention pond often, but not always, reduced Zn, but with less efficiency than in the case of Pb. However, the treatment system downstream of the pond (piping, catch basin, grit chamber, or separator) contributed large concentrations of Zn to the flow. These concentrations were almost always higher than those upstream and ranged up to 588 µg/l. This zinc increase was the most consistent result of the study.

The water quality results were compared qualitatively with the antecedent, meteorological, and hydrological conditions tabulated in Tables 2 and 3 in order to note any associations. The clearest apparent association was that TSS, TP, $NO_3 + NO_2 - N$, Pb, and Zn concentrations in runoff flowing off the site to the pond appeared to be highest when the period preceding the storm was dry. For example, TSS in discrete samples collected within the first 30 min of the 1/26/85 and 5/18/85 storms (dry > 48 hr before event) averaged 88 mg/l, compared to 25 mg/l in the remaining storms, which were preceded by precipitation within the previous 24 hr. There appeared to be no association between effluent concentrations and the length of time since treatment system maintenance. It seems that the maintenance schedule is effective in keeping the system functioning as well as its design premits. There was also no obvious relationship between pollutant concentrations and the total volume or rate of application of natural or synthetic precipitation. It must be emphasized, however, that the monitoring did not occur during any relatively large or intense events, and the relationship between runoff water quality and meteorological conditions may differ substantially in such events.

Because of lag time in the system depending on storm volume and intensity and pond storage capacity, calculation of meaningful treatment efficiencies is difficult. In order to get some idea of removal efficiencies for the constituents most affected by the treatment system, some calculations were performed for two different cases: (1) a comparison of essentially simultaneous flows into and out of the treatment system, and (2) a comparison of inflow to later outflow, after a period of residence in the pond. Table 7 summarizes the results of this analysis.

Using all of the available data to estimate TSS removal efficiencies produced misleading results in the first case considered. When the TSS concentrations were already at very low levels, the pond resulted in little reduction or even an increase in solids. Eliminating those data demonstrated that the pond and the overall treatment system were achieving very high TSS removal efficiencies when influent concentrations were high (see Table 7, note d). All of the available evidence indicates that the treatment system captures the majority of the suspended solids when they are elevated, and it is important for water quality protection that large reductions be realized.

The remaining results presented in Table 7 provide documentary evidence of some general trends noted earlier. Total phosphorus removals were very variable in the pond and the treatment system as a whole. That variation does not follow a discernible pattern, and its cause is not apparent. Over a span of time encompassing a number of storms, it appears that cumulative TP reduction, reliably, is no more than 1/4 to 1/3 of the influent quantity. On the other hand, lead removal efficiencies were consistently high, always over 50 percent and often approaching 100 percent. The tabulated zinc removal efficiencies clearly show the augmentation of Zn occurring downstream of the detention pond, as discussed above.

Table 7. Estimated Treatment Efficiencies of the BCS Detention Pond and Overall Treatment System.

		Treatment Efficiency (%)[c]							
		TSS		TP		Pb		Zn	
Case[a]	System[b]	Range	Average	Range	Average	Range	Average	Range	Average
1	Pond	-267 to 97[d]	26	-9 to 76	68	56 to 99+	>86	-7 to 54	26
	Overall	-122 to 99+[d]	33	-28 to 81	32	75 to 99+	>92	-420 to 19	-129
2	Pond	51 to 71	60	-3 to 83	30	94 to 99+	>97	-37 to -15	-23
	Overall	73 to 78	75	-58 to 86	15	98 to 99+	>99	-1000 to -574	-756

[a] Case 1 compares essentially simultaneous flows into and out of the treatment system. Case 2 compares inflows at one time to later outflows after a period of residence in the pond.

[b] Overall represents total treatment efficiency in the entire system, including catch basins, pond, grit chamber, and oil/water separator.

[c] Efficiency was calculated in terms of concentration as [(inflow-outlfow)/inflow] x 100. A negative efficiency indicates outflow concentration greater than inflow concentration.

[d] The results reported represent all of the available data. If cases where pond inflow TSS was $\leq$ 7 mg/l are eliminated, all remaining concentrations are $\geq$ 124 mg/l. For this latter subset of the data, the pond efficiency range and average were 85 to 97 and 91, respectively. For the overall system the range and average were 77 to 99+ and 88, respectively.

DISCUSSION AND RECOMMENDATIONS

This study was not directly concerned with the sources of pollutants in stormwater runoff from the BCS site. Potential sources are routine deposition from moving and parked vehicles, accidental spills, atmospheric deposition, and site maintenance. It has been documented that vehicles traveling on Washington State highways primarily deposit pollutants when subjected to the spray from wet roads during and just after storms and that pollutant concentrations in runoff from these highways are generally lower than in drainage from commercial and industrial areas (Mar et al., 1982). On the basis of these findings, it is hypothesized that parked vehicles are greater contaminant contributors than vehicles moving slowly on intermittently wet pavement at a site such as BCS. It has also been shown that atmospheric deposition is an important additional source of various pollutants entering Washington State highway runoff (Mar et al., 1982). It is believed that the atmosphere is also a significant source of parking lot contamination, but the relative contributions of vehicles and the atmosphere could not be determined from the BCS data. There is no record of any accidental spills during or shortly before the sampling program, but sand was applied to the parking lot on several occasions during the winter (Sullivan, personal communication). Although the lot was swept, sanding was probably responsible for the relatively high TSS measured at the beginning of the January 26, 1985 event.

There has been a debate regarding how strongly stormwater runoff in the maritime Pacific Northwest depends on the antecedent dry period and whether or not an initial flush of relatively high pollutant concentrations occurs very early in the runoff period. There has been some evidence that urban (Dally et al., 1983) and highway (Mar et al., 1982) runoff water quality in the Northwest does not depend strongly on the length of the antecedent dry period. There have also been indications that Northwest urban (Farris et al., 1979) and highway (Mar et al., 1982) runoff exhibits first-flush characteristics to a lesser extent than elsewhere, possibly because of the general lighter intensities of rainfall in the region. Dally et al. (1983), however, did observe an obvious first flush for some contaminants. The results of the present study suggest that the water quality of storm runoff from a Northwest light industrial site both depends on the antecedent meteorological conditions and exhibits a relatively highly concentrated initial flush with precipitation intensities ranging from 0.03 to 0.33 inch/hr (0.8-8.4 mm/hr).

The only pollutants sometimes present in the effluent from the BCS site in relatively high concentration were Total P and Zn, (maximums of 218 and 588 µg/l, respectively). P concentrations of that order could be a significant factor in the Phantom Lake trophic state. The aquatic life protection standard for Zn in receiving waters with total hardness of 50 mg/l as $CaCO_3$ (typical of Western Washington) is 180 µg/l (Federal Register 45 FR 79318-79379, November 18, 1980). It is likely that dilution of the BCS runoff would be sufficient to protect aquatic life in Phantom Lake. Nevertheless, the occasional occurrence of these elevated concentrations encourages consideration of alternative means of managing stormwater at this and similar sites.

The detention pond treatment efficiencies estimated from the data collected during this study agree rather well with those reported previously (see section on Related Research, above). It appears that the BCS pond is capable of consistently removing the majority of elevated influent TSS. Phosphorus reductions were variable, as observed elsewhere, but reliably were approximately 1/4 to 1/3, near the consensus of the literature. Lead removal appeared to be consistently higher than reported elsewhere, although zinc reduction by the detention pond was not as high on a sustained basis. Other metals and nitrogen were not consistently affected by the detention pond or by conditions preceding and during the storm. It was noted previously that the residence time of the BCS pond may not be long enough to achieve the maximum benefits of the technique. The residence time apparently is not detracting from its performance in TSS, TP, and Pb reduction. It is uncertain whether a longer residence time would achieve higher Zn removals or more consistency with respect to the nutrients. The dissolved phase constitutes a significant proportion of all of these quantities, and detention ponds serve best in solids removal.

Other work, especially that by Ellis (1985), has identified design features that could improve detention pond performance. They include designing a rectangular shape, locating the inlet and outlet far apart, avoiding short-circuiting from inlet to outlet by baffling, and breaking one pond into a series of two or more. The BCS pond did not incorporate any of these features. Only baffle installation would be a relatively easy modification, although it may be possible to relocate the inlet or the outlet for greater separation. It is recommended that a dye study be undertaken to determine the exact water travel and residence times in the pond. With the results of that study, a system of baffles should be designed, installed, and evaluated concerning its effect on treatment performance.

During the period of study, the Boeing site did not produce oil and grease concentrations even as high as the claimed effluent quality of the Fram coalescing plate oil/water separator (15 mg/l). Therefore, it appears that the separator is not serving a purpose under routine conditions. It must be emphasized that this conclusion applies only to the site studied under the prevailing conditions. Other types of urban land use (e.g., heavy equipment yards and shopping center parking lots) are known to produce higher oil and grease concentrations, and a coalescing plate or other relatively advanced separator may be needed for water quality protection even under routine conditions. On a site such as BCS, however, with little heavy equipment and automobile movement other than in the morning and afternoon, other strategies may be appropriate in future installations. It may be best to serve with a separator only the delivery portion of the site, where an oil spill could occur. This separator could be smaller and require less maintenance than one serving the whole site, therefore saving on installation and operating costs. Instead of the protection offered by a separator to the remainder of the site, it is recommended that the detention pond be supplemented with some form of land treatment.

The general forms of land treatment that may be considered for a light industrial park are overland flow through vegetation, flow through a natural or artificial wetland, or soil infiltration. The characteristics and use of these systems in the Bellevue area was reviewed in detail elsewhere (Welch et al., 1985). All can provide effective removal of nutrients, metals, and oil and grease, in addition to any solids escaping the detention pond. For example, a vegetated channel 180 ft (55 m) in length receiving freeway runoff near Seattle achieved consistent TSS and Pb reductions of 80 percent and Zn and Cu removals of 60 percent (Wang et al., 1982). More limited data on other contaminants indicated > 50 percent reduction of N and P, except in the winter when vegetation died back, and 67-93 percent removal of oil and grease with influent concentrations < 20 mg/l (Little et al., 1983). Such a system has much lower maintenance requirements than an oil/water separator, and original installation would be much less costly, if the land were available.

The clearest result of this study was the introduction of zinc to the flow downstream of the detention pond. Lettenmaier and Richey (1985) observed a very similar phenomenon in their investigation of the performance of a Fram coalescing plate separator at the Municipality of Metropolitan Seattle transit base in Bellevue, which was coincident with this work. Because of their independent observation in another system, it has been concluded that the separator itself, rather than some other component of the BCS system, was responsible for the Zn increase. However, the exact source within the separator has not been traced. It is recommended that a review of the Fram design be undertaken to determine potential zinc sources and the implications of redesigning and replacing parts in existing systems. It should be noted that use of land treatment instead of the structural device where possible would have the additional advantage of avoiding this zinc source.

It appeared that the maintenance schedule followed by Boeing contributes materially to the levels of performance achieved by the stormwater treatment system. It is recommended that other similar installations adopt an equivalent schedule, which involves routine cleaning of catch basins and other solids collection areas four times per year and complete maintenance of the oil/water separator once a year.

SUMMARY AND CONCLUSIONS

A useful means of studying nonpoint pollution in experimental catchments is to develop general understanding using well-controlled synthetic storms, followed by verification through natural storm monitoring. A system was designed and constructed to provide synthetic storms having characteristics similar to typical natural events.

Synthetic and natural storm experiments demonstrated that a detention pond on the Boeing Computer Services Company site in Bellevue, Washington, removes the majority of the entering solids, nearly all of the lead, 1/4 to 1/3 of the phosphorus, and variable proportions of nitrogen and other metals. The pond's performance could possibly be improved at relatively low cost by the addition of baffles.

Oil and grease concentrations in runoff from the site were very low, and the capacity of a coalescing plate oil/water separator was not utilized. Further, materials in the separator added substantial quantities of zinc to the runoff. Additional work is recommended to identify the exact source of zinc. Although such oil/water separators are necessary at sites with more heavy equipment and automobile traffic, their use could be limited to areas prone to oil spills at light-industrial sites like BCS. As an alternative, land treatment of detention pond effluent is recommended. Data have shown that land treatment could achieve greater nutrient and metal reductions than an oil/water separator and equivalent oil and grease removal, as long as oil and grease concentrations are low (< 20 mg/1). Also, both the initial and annual operating costs for land treatment would be significantly lower at a site with sufficient land.

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APPENDIX

Appendix A. Complete TSS, TP, NO(3)+NO(2)-N, and Oil and Grease Data

Date	Sampling Point	Type of Sample	TSS (mg/l)	TP (μg/l)	NO_3+NO_2-N (μg/l)	Oil and Grease (mg/l)
11/19/84	1	Discrete - 0	26	109		2.8
		15 min	15			<1
		30	9.0			40
		45	7.0			0.1
		60	8.0			3.7
		75	7.0			
		90	6.5			
		105	6.0			
		120	8.0			
		150	4.0			<1
		180	2.5			
		210	3.5			
		240	1.5			
		270	1.0			
		300	0.5			
	2	Discrete - 0	6.5	55		<1
		15 min	3.0			
		30	3.5			
		45	3.5			
		60	4.0			
		75	7.0			
		90	4.0			
		105	5.0			
		120	6.0			
		150	6.0			5
		180	4.0			
		210	4.0			
		240	4.0			
		270	4.0			
		300	3.0			
	3	Discrete - 0	1.0	45		<1
		15 min	1.5			
		30	0.5			
		45	2.0			
		60	2.5			
		75	4.5			
		90	4.5			
		105	5.0			
		120	6.0			
		150	5.0			2
		180	3.5			
		210	2.0			
		240	2.0			

Appendix A. (Cont.)

Date	Sampling Point	Type of Sample	TSS (mg/l)	TP (μg/l)	NO_3+NO_2-N (μg/l)	Oil and Grease (mg/l)
		270	2.5			
		300	0.5			
	1	Whole storm composite	7.0	81		
	2	Whole storm composite	4.5	63		
	3	Whole storm Composite	2.9	62		
1/26/85	1	Discrete - 0	33			
		7.5 min	170			
		15	177	330		4
		30	140			
		Composite - 45, 60, 75	76			
		105, 135	55			
		whole storm	124	186		
		Discrete - 135 min				<1
	2	Discrete - 0	29			
		60 min	13	80		<1
		Composite - 105, 135	23			
		Discrete - 165	21			
		Composite - whole storm	19	64		
		Discrete - 135 min				6
	3	Discrete - 0	21			
		75 min	25	62		<1
		Composite - 135, 165	31			
		whole storm	28	73		
		Discrete - 135 min				<1
3/22/85	1	Discrete - 0	9.6			
		30 min	5.4	50	114	
		60				<1
		180				<1
		Composite - 60 - 180	5.2	32	104	

Appendix A. (Cont.)

Date	Sampling Point	Type of Sample	TSS (mg/l)	TP (μg/l)	NO_3+NO_2-N (μg/l)	Oil and Grease (mg/l)
4/21/85	2	Discrete -				
		25 hr	10	70	27	5
		25	13	80	43	
	3	Discrete -				
		25 hr	6.2	61	30	4
		25	6.2	61	27	
5/5/85	1	Discrete - 0	4.4	80	117	2
		5 min	3.0	76	95	
		10	6.0	80	83	
		15	8.4	86	86	
		Composite -				
		30 - 120	16	113	105	4 (60 min)
	2	Discrete -				
		9.5 hr	7.8	116	8	1
		95	7.8	-	-	
	3	Discrete -				
		9.5 hr	4.2	101	51	2
		9.5	4.4	-	-	
5/18/85	1	Discrete - 0	7.4	1086	1050	6
		5 min	104	1186	603	
		10	90	503	381	
		15	60	355	321	
		Composite -				
		30 - 120	41	144	127	3 (60 min)
	2	Discrete -				
		4.5 hr	11	130	2	7
		4.5	12	-	-	
	3	Discrete -				
		4.5 hr	11	218	39	1
		4.5	11	-	-	