Stormwater Pollutant Removal by Two Wet Ponds in Bellevue, Washington

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Abstract

Two wet detention ponds were investigated for their ability to remove pollutants, primarily phosphorus, from stormwater runoff. The two ponds lie within the Phantom Lake watershed, a sub-basin of the Lake Sammamish watershed in Bellevue, Washington, which is developed as a commercial and residential area with impervious surface area as high as 57%. There are design differences between the two ponds, yet both are comparable to design recommendations set forth by local agencies. One pond was built for flow attenuation and water quality treatment; the other serves only to improve water quality. Fifteen storms and two baseflows were successfully sampled during the Northwest's wet season from October 1996 through March 1997. Pollutant removals varied between a fifth to a half for phosphorus, and greater than half for total suspended solids and most of the analyzed metals. Removal efficiencies were consistently better in the pond designed primarily for water quality.

Key Words: Phosphorus, Storm Water, Detention Ponds, Water Quality, Urban Runoff, Water Pollution, Best Management Practices, Treatment, Pollutant Removal

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Introduction

Detention ponds have been used for decades to mitigate the increase in runoff rates that is a typical consequence of urbanization. They do this by detaining stormwater runoff for a period of hours or days, while releasing it slowly to receiving streams and lakes. Although designed primarily for control of water-quantity increases, these ponds are now also being used to reduce non-point pollution (Whipple 1979).

Phosphorus is the pollutant of primary concern to the ecological health of fresh waters in the Pacific Northwest. Phosphorus is an essential nutrient required by all biological life. In freshwater aquatic environments, phosphorus is frequently limited and therefore controls the growth of primary organisms such as algae (Cooke *et al*. 1993). When phosphorus-rich water enters lakes, it can upset this imposed limitation on algal growth and cause algae to grow in abundance. Such uncontrolled growth can lead to water quality degradation through eutrophication (Welch 1992), expressed by such problems as foul taste and odors, depletion of dissolved oxygen, aesthetic and recreational impairment, and increased abundance of toxin-producing blue-green algae.

Detention ponds have become one of the more popular means of removing some portion of the phosphorus carried by stormwater prior to final discharge (Lawrence *et al*. 1996). Ponds can reduce pollutants in a variety of ways, depending on the type and form of the pollutant. Solid constituents such as total suspended solids (TSS) and particulate P are primarily removed by settling, whereas dissolved components can be removed by chemical or biological means. In either case, providing time for the runoff to sit quiescently is key to accomplishing the removal (Horner *et al*. 1994).

Wet ponds have been shown to be more effective at removing pollutants than dry ponds (Field *et al*. 1993). Dry ponds typically hold water only during storms, so there is only a short time for pollutant removal. Wet ponds, however, maintain a permanent pool to hold water between storms. This extended residence time provides greater opportunity for solids to settle and dissolved for components to be acted upon either biologically or chemically.

Studies of phosphorus removal by ponds have reported removal efficiencies that are highly variable (Kulzer 1989, Ellis and Marsalek 1996) but generally less than 50 percent. Total phosphorus removal efficiencies, during individual storms in a detention pond in Pinellas County, Florida, ranged from 13 to 66 percent with a median value of 40 percent (Kantrowitz and Woodham 1995). Another study in Florida reported a pond efficiency for removal of total phosphorus of 21 to 30 percent (Gain 1996). A study of two ponds in North Carolina showed average removal efficiencies of 45 and 36 percent (Wu *et al*. 1996).

The reported removal rates are even more variable for soluble reactive phosphorus than for total phosphorus. One study that compared the removal efficiencies of several dry ponds found a range of soluble reactive phosphorus removal from –12% (i.e., net export) to 26% (Stanley 1996). Dry ponds, however, are not expected to achieve the same degree of treatment as wet ponds because they do not hold and treat water between storms. Another study investigating the performance of an older wet pond found soluble reactive phosphorus “removal” efficiencies as low as –50% (Maristany 1993).

There have been relatively few intensive investigations into the water quality performance of detention ponds, and among the studies done there is very little consistency of results. Better understanding of how wet detention ponds perform with regard to water quality is essential for improving watershed management practices. With improved understanding of pond performance, pond designs can be optimized and the use of sequential best management practices (treatment trains) can be made more efficient.

This study investigated the performance of two ponds, one designed primarily for water quality treatment and the other designed to provide flow attenuation as well as water quality improvement. Ponds designed for flow attenuation have a specified volume of "live storage" space that temporarily holds stormwater releasing it over hours or days. Water quality treatment can be added to such ponds by maintaining a "permanent pool" volume that holds water until another storm refills the pond. Ponds that only provide treatment have a large permanent pool and negligible live storage volume. Runoff that exceeds the capacity of a pond of this type is bypassed.

Project

This project was instigated in response to concerns about rising phosphorus levels in Lake Sammamish, Washington State. The Lake Sammamish basin has undergone rapid urbanization since the 1970s, which has increased non-point sources of phosphorus such as fertilizers, some detergents, animal wastes, soil erosion, and septic tank leachate. A variety of mitigation measures were investigated for use in the basin (King County 1998a) including amended sand filtration with underdrains, block alum applications, soil amendments, alum injection in stormwater facilities, wet detention ponds, and temporary erosion and sediment control.

This study of wet detention ponds included two wet-pond facilities in the Phantom Lake watershed, an area tributary to Lake Sammamish in the southeastern part of the city of Bellevue (Figure 1). The size of the sub-basin served by the ponds is approximately 40 hectares. The Eastgate Business Park covers more than half of this land area. The remaining area is a combination of small commercial businesses and residential areas. Impervious surfaces cover 57 percent of the drainage area.

The first pond in the drainage flow path is "Pond C" (Figure 2). This pond was designed specifically to remove pollutants from stormwater with only limited flow attenuation. Pond C receives runoff from only 5 hectares of the East Gate Business Park. Following treatment by Pond C, discharge is routed via underground pipes to the inlet of "Pond A" (Figure 3), which is designed for both detention and some water-quality improvement. In addition to the water from Pond C, Pond A also receives untreated runoff directly from the remaining 35 hectares of the sub-basin, which contains both commercial and residential areas as well as almost 5 hectares of sparsely vegetated grassland. Outflow from Pond A is discharged into Phantom Creek, which flows into Phantom Lake (approximately 325 hectare drainage basin). Lake Sammamish (approximately 22,700 hectare drainage basin) ultimately receives the water flowing from Phantom Lake.

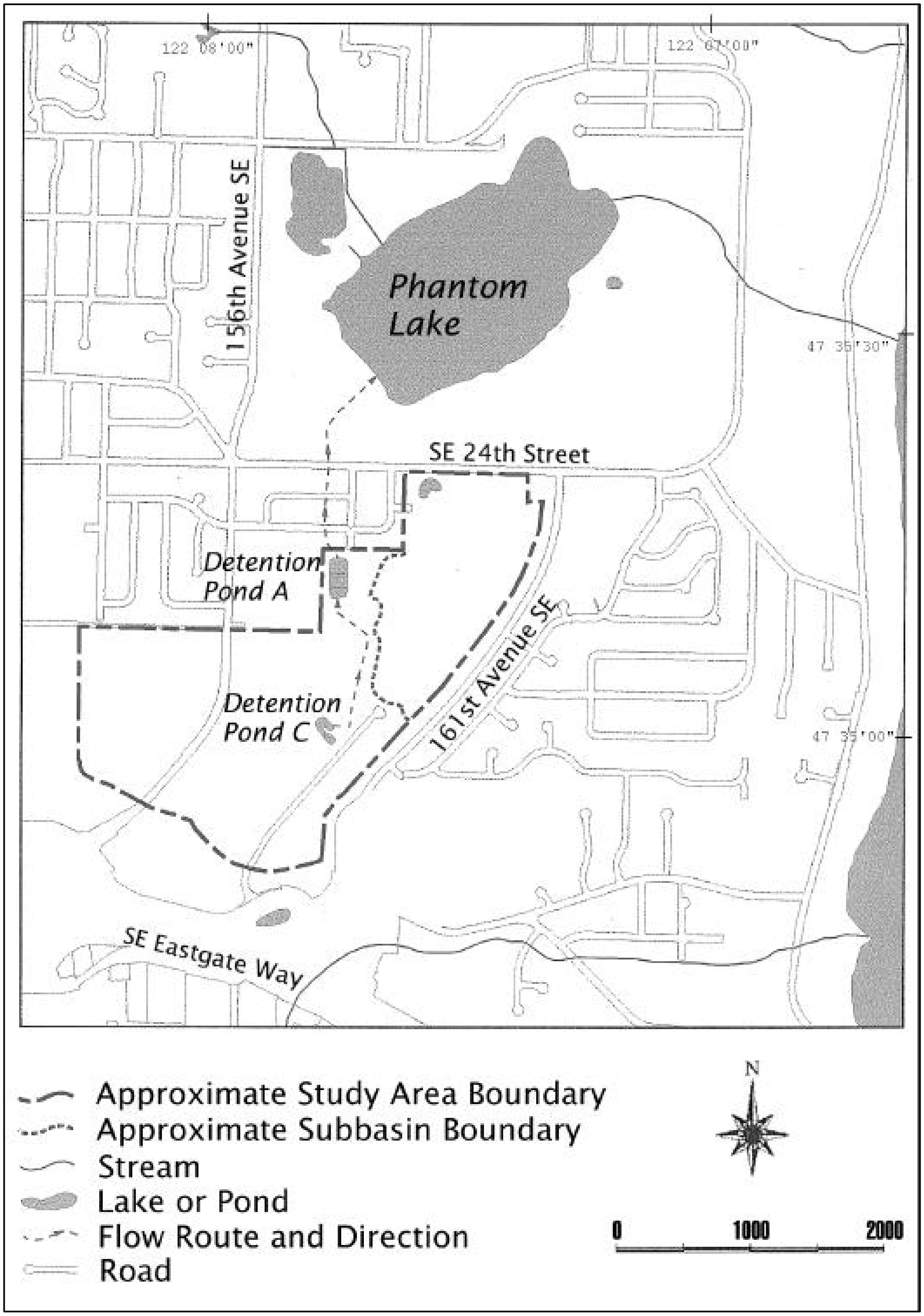

Figure 1 – *Site map showing the southern portion of the Phantom Lake watershed in Bellevue, Washington. Elevation of the site is approximately 100 m. Pond C receives water from the southernmost five hectares. Pond A receives the outflow from Pond C plus additional runoff from the remaining thirty-five hectares in the study area.*

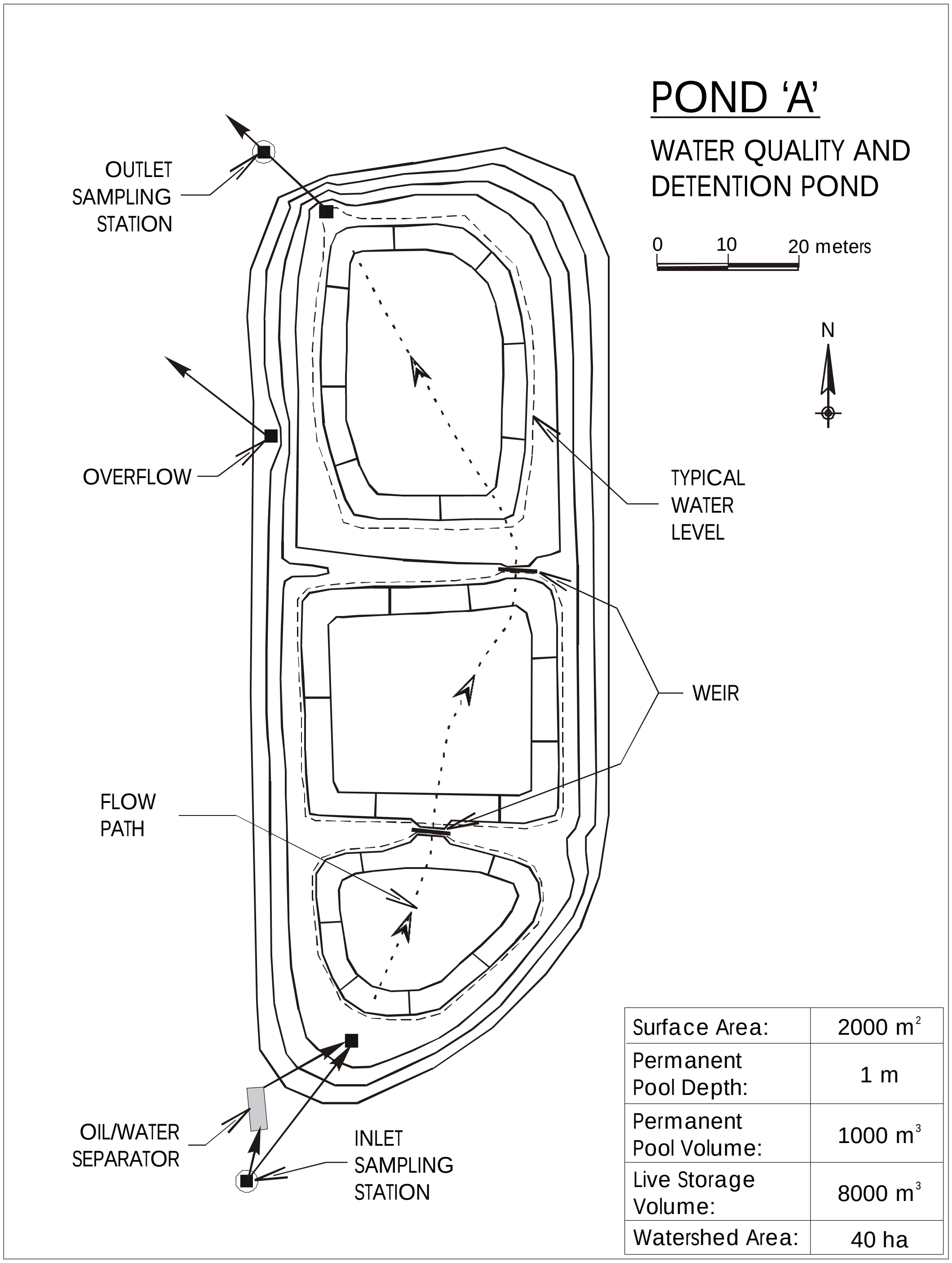

Figure 2 – *Pond C is a single-cell water-quality pond designed to treat one-third of the estimated flow volume from a 2-year 24-hour storm.*

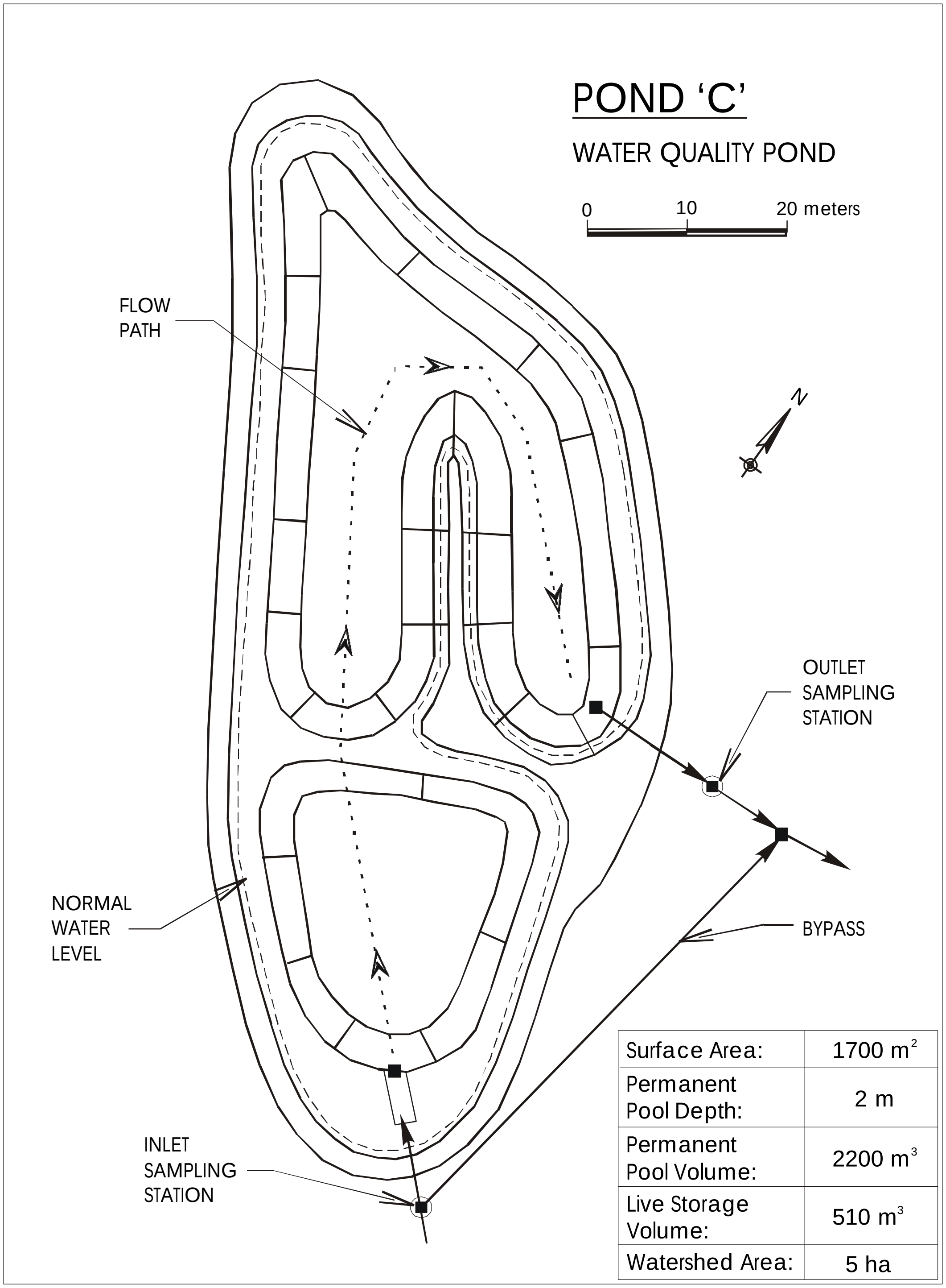

Figure 3 – *Pond A is a three-cell pond that combines the functions of flow attenuation and water-quality improvement.*

The two ponds were chosen to make a comparison between the performance of a water quality pond (Pond C) and a combined water quality/flow-attenuation pond (Pond A). Pond C was designed under the guidelines set forth by the Washington State Department of Ecology (Washington State Department of Ecology 1992) and in fact greatly exceeds these standards (Table 1). Pond C was constructed with a "horseshoe" shape flow path that minimizes short-circuiting. Pond A is an older pond that was upgraded, under the guidelines of the King County Surface Water Design Manual (1990), to improve its pollutant-removal performance. It has three cells, but the flow path allows incoming water to pass straight through the first two cells, suggesting that some short-circuiting may occur. The third cell, however, does force flow to move diagonally across it to react the outlet. Additionally, the detention time provided by Pond C is one week, whereas Pond A has a typical detention time of only one day. With more time spent in the pond, a greater degree of treatment is presumably achieved. This pond will treat a volume of water equal to one-third of a 2-year 24-hour storm. Runoff in excess of this capacity bypasses the pond without treatment and is routed directly to Pond A.

Table 1 – *Comparison of Ponds A and C to agency design standards. N/A indicates the information was not available.*

	Permanent Pool Volume over Basin Area	**Pond Surface Area**	**Length-to-width ratio**
Department of Ecology Standards 1992	24 mm	N/A	3:1 minimum 5:1 preferred
King County Standards 1990	10 mm	1% of impervious area	3:1 minimum
King County Standards 1998	31 mm	N/A	3:1 minimum
Pond A Design	2.6 mm	1% of impervious area	3:1
Pond C Design	44 mm	5% of impervious area	6:1

Methods

Sampling Stations

Sample collection for chemical analyses and measurement of flow occurred at four sampling stations, located at the inlet and outlet of each pond. Equipment was housed above maintenance holes that allowed access to the inlet or outlet pipes of each pond. At each site, the stormwater samples were drawn by American Sigma brand Streamline model automatic samplers. The samplers were triggered to draw water at intervals specified by the flow measuring equipment. A preset volume of water passing by the station would trigger the pull of a sample. Thus, with greater flow rate more samples were drawn. Multiple samples were combined in a single carboy, resulting in a flow proportional composite sample.

The specific arrangement of sampling equipment differed somewhat at each station. At Pond A, ISCO 4150 velocity-flow meter loggers were used at both the inlet and outlet to record flow values at ten-minute increments. Imprecise placement of the flow depth sensor at the outlet of Pond A caused recorded values to be about 15 percent less than the actual flow. At Pond C, the outlet flow was measured through a 60-degree v-notch weir and recorded every fifteen minutes with a Unidata logger. The flow through the weir was calculated by using a stage-discharge algorithm for the weir.

Measuring flow at the inlet to Pond C was not as straightforward as at the other stations, because the inlet pipe to Pond C flows underneath a roadway and enters the pond at a point that is submerged even at low pond water levels. By necessity, the sampling station at the inlet to Pond C was located between the roadway and the pond. Because the inlet pipe is submerged at this point, flow measurements could not be easily measured at this station. Instead, water volumes for this station were determined by mass balance using precipitation data collected on-site and evaporation data collected at the Boeing facility nearby.

Lack of direct flow data at the Pond C inlet also hindered sample collection. As at the other stations, the stormwater sampler needed to be triggered externally to obtain flow-weighted proportional samples. For this station, a flow meter could not be used to determine when to draw the samples and instead the on-site rain gauge was used. Because the lag time (Dunne and Leopold 1978) for this catchment is only about one hour and the high impervious surface area ensures that most precipitation becomes runoff, rainfall was judged to be a reasonable surrogate for flow to collect proportional samples at this station.

Storm Parameters

The Pacific Northwest has a characteristic pattern of winter rainfall. Generally, storms in this region are low in intensity and storm durations can vary widely. A series of storms commonly moves in one after another, resulting in many hours or days of light rain with few breaks between storms. This pattern makes identifying and sampling individual “events” difficult.

Before stormwater samples can be collected, a definition of a “storm event” must be established. For this project, CH2M Hill (1993) specified a commonly applied criteria for a “storm event” as having a minimum rainfall of 0.1 inches over a six-hour period. This is about one tenth of the 2-year 6-hour event and represents the lower limit of rainfall that would produce enough runoff for sampling. Each storm was to be preceded by at least 48 hours of dry conditions. For the practical application to the storms of the Pacific Northwest, these criteria were considered as general guidelines for determining qualifying storms. Most but not all of the sampled storms conform exactly to these guidelines, especially in the case of antecedent dry period.

Sampling Procedures

Throughout the course of a single event, the concentrations of pollutants in the flow changes. Typically, concentrations are highest at the beginning of the hydrograph during the period of “first flush” (Horner *et al*. 1994). The first flush represents the initial period of a storm when runoff begins, and is generally presumed to carry the majority of substances from the landscape. Because the stormwater concentrations change over time, samples are best collected throughout the storm and combined together as a single composite sample. Additionally, as a storm progresses, the flow of water passing by the sampling site rises and falls. To ensure that the composite sample represents an averaging by water volume, it is incrementally augmented by the passage of water volume rather than time. The resulting single concentration obtained from this composite sampling of the storm is called the “event mean concentration” (EMC).

During the 1996-97 rainy season, weather forecasts were regularly monitored for advancing storms. Once an incoming storm was identified that was likely to meet the qualifications of a “storm event,” the samplers were set to begin sampling. Sampling generally began within a few hours prior to the beginning of rainfall to ensure that the first flush of runoff was captured during sampling. Before twenty-four hours had elapsed the samples were retrieved for analysis, even if rain was still falling. This twenty-four hour limitation was set to minimize the time between sample collection and analysis of soluble reactive phosphorus and biologically available phosphorus. The risk this introduced of not sampling the later part of a storm was acceptable because it far exceeded the 12-hour minimum found by the City of Bellevue (1995) to guarantee representative estimation of EMCs.

At the conclusion of each event, four field measurements were taken with portable instruments: pH, temperature, dissolved oxygen, and conductivity. Temperature and dissolved oxygen were measured with a YSI model 58 dissolved oxygen meter, pH was measured with a Beckman model ϕ11 pH meter, and conductivity was measured using a Hanna model HI9033 conductivity probe. These four parameters were measured directly from the water in carboys just prior to leaving the site as a check on field conditions. The carboys were then delivered to the King County Environmental Laboratory, a state certified lab, for chemical analysis.

Events Sampled

Storm samples were collected over a period of six months from October 1996 through March 1997. These six months typically represent 71% of the annual rainfall for the Bellevue area (Table 2) based on data from the Bellevue Service Center (F. Romano,

Table 2 – *Average monthly rainfall data recorded by the Bellevue Service Center (1981 – 1996), representing mean monthly precipitation for the Bellevue area.*

Month	Precipitation mm (in.)
January	103 (4.1)
February	80 (3.2)
March	71 (2.8)
April	70 (2.8)
May	47 (1.9)
June	35 (1.4)
July	25 (1.0)
August	21 (0.8)
September	39 (1.5)
October	80 (3.2)
November	135 (5.3)
December	119 (4.7)
Total	825 (32.7)

Table 3 – *Summary of sampled events. N/A means not applicable. Under "samples taken" 'X' indicates that a sample was collected, 'B' indicated samples that were analyzed for biologically available phosphorus, 'R' indicates field replicates, and '*' indicated samples that were not collected due to equipment failure.*

Storm Characteristics					Samples Taken			
Date	Prior Dry (hours)	Precipitation mm (in.)	Duration (hours)	Intensity (mm/hour)	A in	A out	C in	C out
10/4/96	> 4 days	21.1 (0.83)	11	1.92	*	*	X	X
10/12/96	> 7 days	14.2 (0.56)	17	0.84	B	B	*	X
10/17/96	68	19.6 (0.77)	14	1.40	B	B	B	B
10/21/06	80	17.0 (0.67)	21	0.81	X	X	X	X
10/28/96	81	28.7 (1.13)	15	1.91	X	X	B	B
11/3/96	136	5.6 (0.22)	5	1.12	X	X	X	X
12/4/96	43	20.1 (0.79)	9	2.23	XR	*	*	X
12/19/96	> 7 days	7.4 (0.29)	19	0.39	X	*	X	X
1/2/97	4	49.3 (1.94)	34	1.45	X	X	X	X
1/10/97	147	Baseflow	N/A	N/A	X	X	X	X
1/17/97	> 7 days	32.0 (1.26)	25	1.28	XR	X	XR	X
1/28/97	> 7 days	10.4 (0.41)	6	1.74	B	BR	B	B
1/30/97	44	14.2 (0.56)	11	1.29	B	B	B	B
2/12/97	> 7 days	10.7 (0.42)	10	1.07	X	XR	X	X
3/1/97	> 7 days	28.4 (1.12)	24	1.18	X	X	X	X
3/6/97	39	8.1 (0.32)	16	0.51	B	B	B	B
4/7/97	76	Baseflow	N/A	N/A	X	X	X	X
Data points collected per station:					14	12	13	15

1997, written communication). Although the winter during which this study was conducted was exceptionally wet (Water Year 1997 precipitation was 1964 mm vs. average annual precipitation of 840 mm), the events that were sampled (Table 3) characterize the broad range of storm events typical of western Washington and generally fulfilled the project criteria for storm events (CH2M Hill 1993). Precipitation of collected storms ranged from 5.6 to 49.3 millimeters (0.22 to 1.94 inches), with average intensities ranging from 0.38 to 2.24 millimeters per hour (0.015 to 0.088 inches per hour). All but four of the sampled storms followed a dry period of at least 48 hours;some antecedent dry periods extended for more than one week. In addition to sampling storms, two baseflow conditions were sampled following at least three days without rainfall.

Of particular note is the large storm that was sampled on January 2, 1997. This event was in the midst of a sequence of snow and heavy rainfall that produced overflow conditions in both ponds. Although not a discrete “storm event,” this sample evaluated the water quality during very high runoff conditions and thus was a particularly valuable data point.

Laboratory Analysis

Following collection, the King County Environmental Laboratory in Seattle analyzed the composite samples. The methods used by the laboratory originated from Standard Methods (APHA 1995) and have been adopted by the King County Environmental Laboratory. Total suspended solids were determined gravimetrically by measuring the dry weight of a filtered sample. Total phosphorus was determined colorimetrically following digestion with persulfate. Soluble reactive phosphorus was also determined colorimetrically following filtration of the sample. Biologically available phosphorus was determined in a two-part process. After filtering a known quantity of sample, the filtrate was analyzed for soluble reactive phosphorous. The material left on the filter was then extracted by being soaked overnight in a dilute sodium hydroxide/sodium chloride solution. The extract was then neutralized, filtered, and analyzed for soluble reactive phosphorus. Biologically available phosphorus is the sum of these two phosphorus analyses. Finally, metals were analyzed by inductively coupled plasma mass spectrometry following U.S. EPA (1990) method 200.8.

Data Analysis

The Modified Direct Average Method was used to calculate loading over the sampling period. This method calculates an average value of all the measured EMCs collected during the study, which is then multiplied by the total flow volume measured during the study to determine the loading for that period (Bellevue 1995). A loading calculation that utilizes averages was chosen because the goal of this study was to determine how the ponds perform in any given year and not the winter of 1997 alone. Water volume at the inlet of Pond A was used to calculate loading for both the inlet and outlet of this pond because of a 15% shortfall in the measured flow volume at the outlet.

This substitution was based on the assumption of negligible losses from evaporation and infiltration, and negligible gain from direct rainfall onto the pond.

Knowing the statistical distribution of a data set is necessary so that the appropriate statistical tests can be applied. Previous work with nationwide data has demonstrated the prevalence of the log-normal distribution in urban runoff water quality parameters (Driscoll 1986a). A study that was conducted in the same local area as this study also found that the concentrations of stormwater constituents in this region have a log-normal distribution (Bellevue 1995). A more recent study found that many stormwater constituent concentrations have a log-normal distribution upon entering a pond, but change at the pond outlet to a normal distribution (Van Buren *et al*. 1997).

Although the number of samples in this study was small, a modest effort was made to test the anticipated distribution. Probability data were plotted as both arithmetic and log-transformed concentrations for all data. An example of these plots is provided in Figure 4. Plotting positions were determined by the following formula (Cunnane 1978):

$$F = (i - 0.4) / (n + 0.2)$$

where: F = plotting position
i = rank of the ith smallest value
n = sample size

By inspection, the log-transformed data plotted closer to a straight line more consistently than the untransformed concentrations. The standard assumption of log-normality was therefore made for the data in this study.

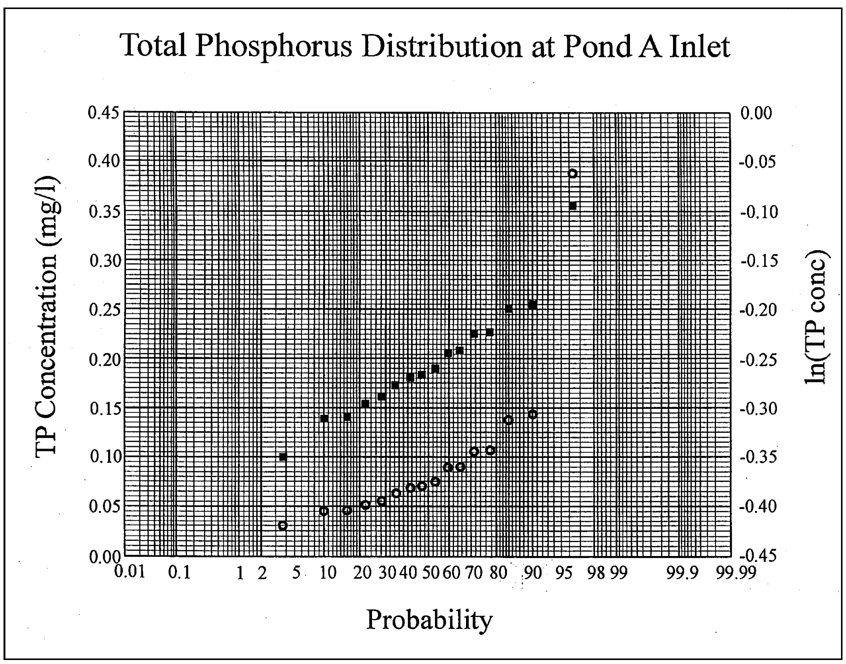

Figure 4 – *Probability Plot for Total Phosphorus data taken at Pond A Inlet.* ***o*** *– untransformed data,* ■ *– natural log transformed data.*

Using the transformed data, the mean of the EMCs (Marsalek 1990) was determined by the following formula:

$$C_{mean} = \exp(\mu + s^2/2)$$

where: exp signifies exponentiation on the base of natural logarithms, *e*;
μ = Mean of natural logarithms of EMCs;
s^2 = Variance of natural logarithms of EMCs.

This mean was then multiplied by the total flow volume over the period of study to obtain the loading for that period. Annual loading was determined by dividing the loading that occurred during the study by 0.71, which is the fraction of mean annual rainfall that typically falls within the period sampled (Table 1).

The efficiency of each pond was determined by dividing the amount of each constituent that was removed by the pond by the loading that entered the pond:

percent efficiency = (inlet load - outlet load)/inlet load.

Results

Both ponds showed some removal of all measured pollutants. Removal ranged from almost none to three-quarters of the measured components, with Pond C (the designed water-quality pond) consistently out-performing Pond A. Plots of the pollutant loads that passed through the inlet and outlet of each pond are shown in figures 5 and 6, illustrating the mass removed and the percent efficiency for each constituent. Of the four conventional constituents measured, total suspended solids (TSS) exhibited the greatest removal efficiencies for both ponds. Removal of total phosphorus (TP) and biologically available phosphorus (BAP) was about half the reduction of TSS in Pond C and about one-third in Pond A. The greatest proportional difference between the two ponds was seen in soluble reactive phosphorus (SRP) with 62 percent reduction for Pond C, a dramatically greater reduction than the 3 percent seen in Pond A.

Removal efficiencies for metals were generally around half or greater (Figure 6), although differences between the two ponds were not nearly as pronounced as for TSS and phosphorus. Copper and lead had very similar removal efficiencies for the two ponds. Pond A showed better results for cadmium, and Pond C for zinc.

Annual loading at each site for both the nutrient and metal constituents studied is summarized in Table 4. Pond C removed more pollutants per hectare than Pond A for all measured constituents even though Pond A, which serves a larger watershed, removed more overall mass of pollutants than Pond C.

The calculated means from the set of EMCs (Table 5) are typical of values reported for the Phantom Lake watershed (KCM 1993). Concentrations of suspended solids were higher at the inlet of Pond A than at Pond C. Phosphorus and metals concentrations are typical of stormwater in this region (Chandler 1995). Variability of the data at the inlet of each pond is notably greater than at the outlet for most constituents.

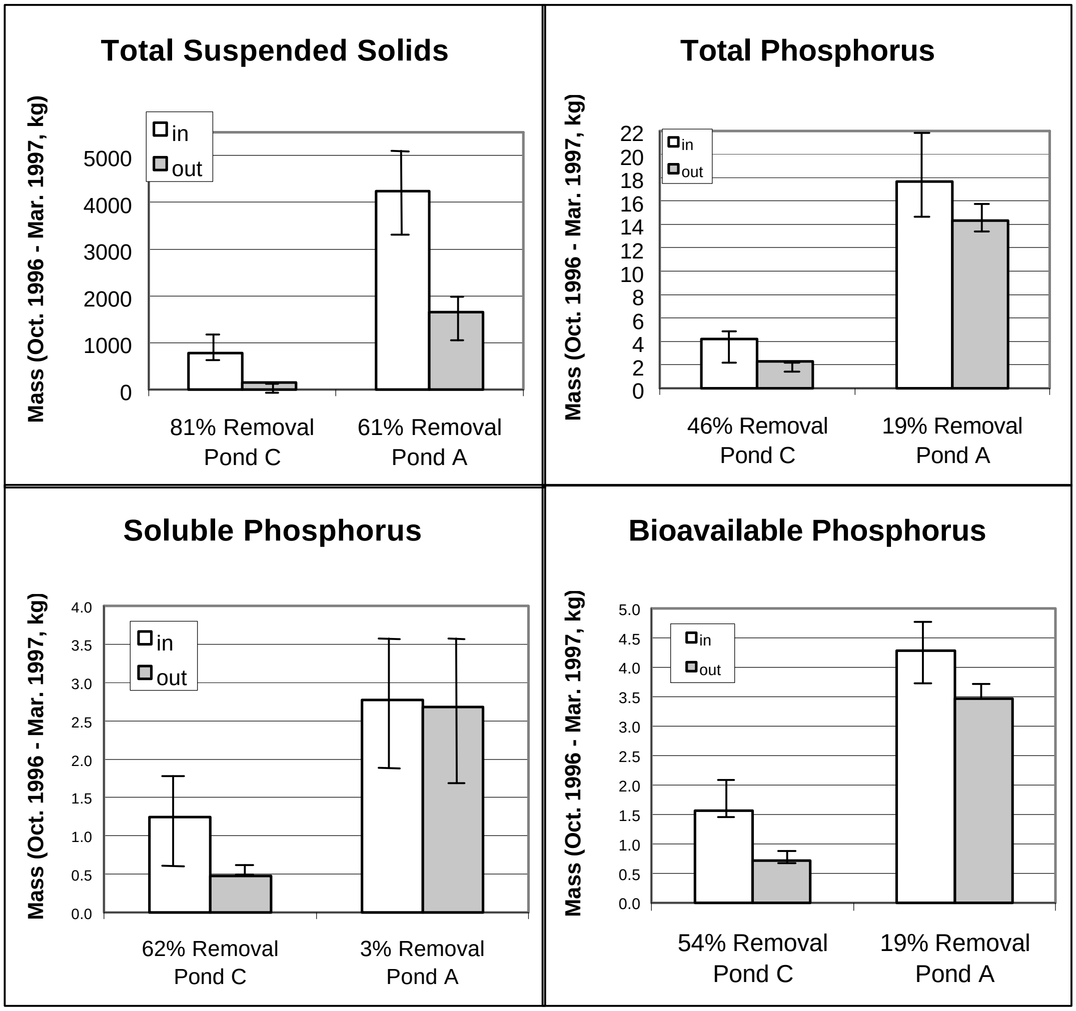

Figure 5 – Removal of conventional constituents by Ponds A and C during the period of study. Error bars indicate 95% confidence.

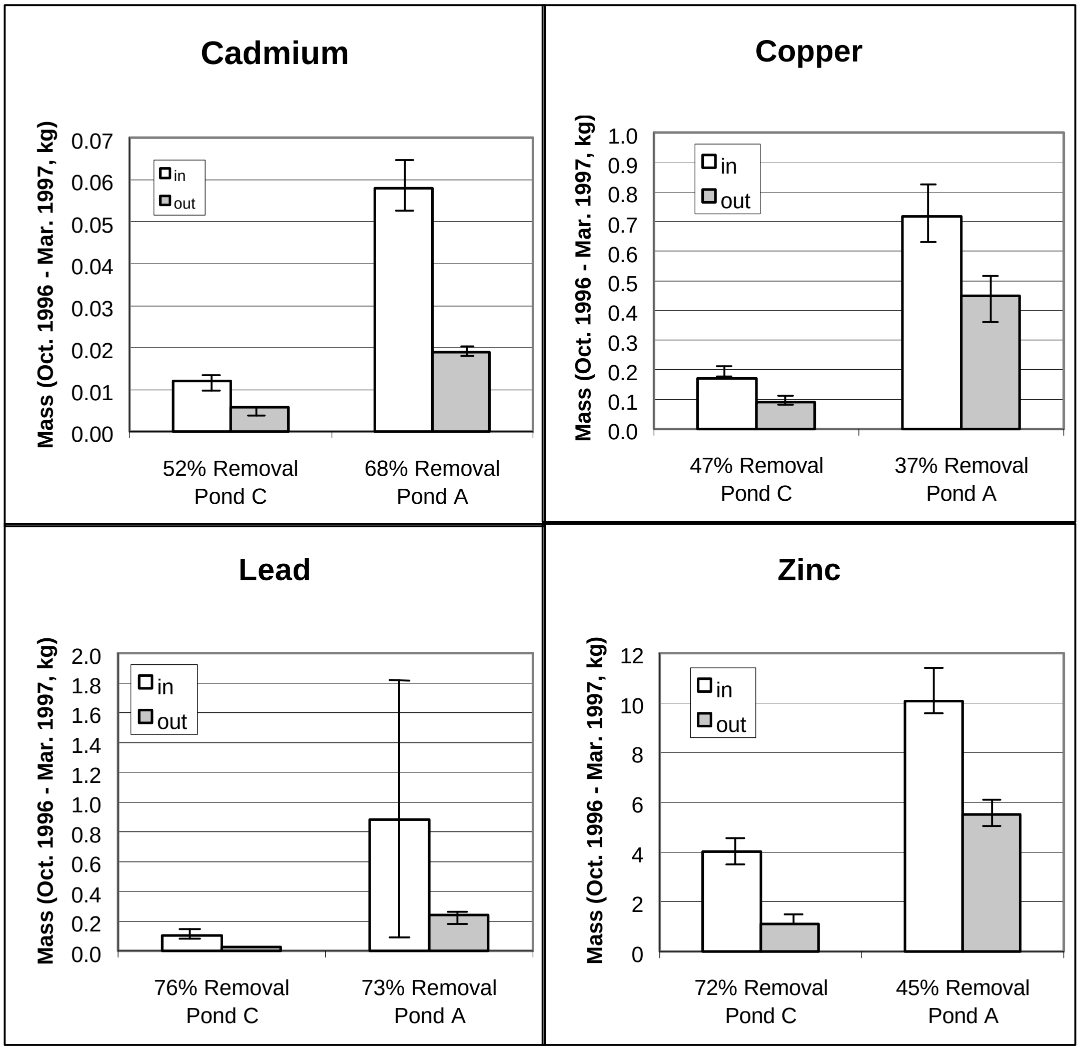

Figure 6 – Removal of metals by Ponds A and C during the period of study. Error bars indicate 95% confidence.

Table 4 – Calculated annual loading at each of the four stations in kg and the yield removed by each pond in kg/ha.

	C inlet (kg)	C outlet (kg)	kg removed/ ha	A inlet (kg)	A outlet (kg)	kg removed/ ha
TSS	1100	200	180	6000	2300	92.5
TP	6.0	3.2	0.56	25	20	0.13
SRP	1.8	0.67	0.23	3.9	3.8	0.0025
BAP	2.2	1.0	0.24	6.0	4.9	0.028
Cadmium	0.017	0.008	0.0018	0.082	0.027	0.0014
Copper	0.24	0.13	0.022	1.0	0.63	0.009
Lead	0.15	0.04	0.022	1.24	0.33	0.023
Zinc	5.6	1.6	0.80	14	7.7	0.16

Table 5 – Mean values of event mean concentrations from sampled storms in mg/l. Below each mean value are the upper and lower 95% confidence boundaries (in parenthesis) and the coefficient of variation for each data set.

		C inlet	C outlet	A inlet	A outlet
TSS	Mean	16.2	2.9	22.8	8.9
	95% CI	(12.4, 21.3)	(2.7, 3.2)	(18.8, 27.8)	(6.6, 12.0)
	CV	87%	41%	86%	64%
TP	Mean	0.087	0.045	0.095	0.077
	95% CI	(0.079, 0.097)	(0.044, 0.047)	(0.080, 0.114)	(0.070, 0.083)
	CV	59%	24%	86%	47%
SRP	Mean	0.026	0.010	0.015	0.014
	95% CI	(0.017, 0.038)	(0.008, 0.011)	(0.011, 0.020)	(0.010, 0.021)
	CV	119%	52%	78%	98%
BAP	Mean	0.033	0.014	0.023	0.019
	95% CI	(0.027, 0.039)	(0.013, 0.015)	(0.021, 0.026)	(0.018, 0.019)
	CV	50%	32%	34%	19%
Cd	Mean	0.00025	0.00012	0.00031	0.00010
	95% CI	(0.00022, 0.00029)	(0.00011, 0.00012)	(0.00029, 0.00034)	(0.00010, 0.00010)
	CV	36%	39%	34%	0%
Cu	Mean	0.0035	0.0018	0.0039	0.0024
	95% CI	(0.0033, 0.0038)	(0.0018,0.0018)	(0.0034, 0.0044)	(0.0020, 0.0030)
	CV	41%	17%	67%	30%
Pb	Mean	0.0022	0.0005	0.0047	0.0013
	95% CI	(0.0019, 0.0025)	(0.0004, 0.0007)	(0.0021, 0.0108)	(0.0011, 0.0015)
	CV	60%	122%	188%	42%
Zn	Mean	0.083	0.022	0.054	0.03
	95% CI	(0.074, 0.093)	(0.021, 0.024)	(0.050, 0.059)	(0.027, 0.033)
	CV	45%	58%	57%	33%

The measurements recorded by the field instruments were consistent with expected values. The pH fluctuates between 6.0 and 8.0 as is typical of stormwater samples. Temperature rises and falls with the changing seasons and was warmest (13.4^{o} C) at the beginning of the study in the fall. The lowest temperature of 3.5^{o} C was recorded following a January storm. Dissolved oxygen was consistently close to saturation values. This is not surprising, as the samples sat in carboys for hours in the field before being measured, while composite sampling was ongoing. Thus, the collection of dissolved oxygen measurements, while specified by the sampling protocol (CH2M Hill 1995), was meaningless in the context of this study. Finally, nearly all conductivity ranged from 17.6 to 438 μS/cm, with the exception of two measurements taken from baseflow samples, which were 743 and 1173 μS/cm.

Discussion

Both of the ponds reduced the pollutant loading from the watershed. Pond A removed a greater amount of solid mass than Pond C by virtue of an eight-fold greater drainage area, although Pond C is more efficient. Pond C's higher efficiency was anticipated because it was designed specifically for the purpose of water-quality improvement. Pond A, although also designed to improve water quality, carries the additional burden of flow attenuation.

The mechanism in wet ponds for removing suspended solids from stormwater is simply gravitational settling (Whipple and Hunter 1981). Based on the data from this study, the detention times in both ponds are long enough to allow for well over half the suspended solids to settle out. Because Pond A receives significantly more runoff than Pond C, it removed more than four times as much sediment (2600 kilograms of suspended solids compared to 600 kilograms in the same six-month period).

Despite this performance for TSS, the removal efficiencies for total phosphorus in both ponds fell short of the desired values. In order to protect lakes that are sensitive to phosphorus, King County has adopted a standard of 50 percent reduction in total phosphorus in stormwater draining from new developments (KCC title 9.04.050.8.b). These standards were developed in a effort to balance protection with "reasonable" and "cost-effective" performance. Yet even the more efficient of the two ponds, Pond C, only approached this standard with 46 percent removal. Pond A fell far short of the 50-percent goal (19 percent efficiency), although it still removed more total phosphorus mass (3.3 kg) than Pond C (2.0 kg). While the 50 percent removal rate has been established by statute, there is little precedent in the published literature; the results of this study are consistent with most others studies (Walker 1987, Maristany 1993, Kantrowitz and Woodham 1995, Gain 1996, Stanley 1996, Wu *et al*. 1996).

The high removal efficiency for soluble reactive phosphorus in Pond C was a surprising result because wet ponds typically perform poorly when removing dissolved constituents. The removal of dissolved nutrients is primarily due to two mechanisms: adsorption by soil or sediment at the bottom of the pond and uptake by biological organisms living in the pond (Kulzer 1989). Because the study occurred during fall and winter months, soluble reactive phosphorus probably was not removed by biological uptake because most organisms are much less active during this time. Thus, measured removal rates are more likely attributable to interaction with the pond sediments.

At the time of this study, the condition of the pond sediments in both ponds was likely to be favorable for the removal of phosphorus. Pond C, a relatively new pond, had fresh sediment throughout its permanent pool area (1700m^2), and Pond A had recently been enlarged thereby exposing new soil primarily in the second cell (900 m^2). Clean sediment has a greater capacity to adsorb soluble nutrients than older sediment (Maristany 1993). Pond C had five times more removal per unit area of new sediment (0.5 g/m^2) than Pond A (0.1 g/m^2) as well as better overall efficiency (62% for Pond C versus 3% for Pond A) indicating that Pond A performs poorly even under potentially favorable conditions. Deciduous vegetation on the banks and berms of Pond A, which are absent at Pond C, may be a contributing factor to this pond's poorer performance. Leaves and twigs dropped by these plants in autumn may cover some percentage of the pond sediment, limiting the soil-water contact in this pond and contributing additional phosphorus as the material decays that can consume the sediments' adsorptive capacity.

Removal efficiencies for metals were good in all cases, and all of the metal concentrations measured at both outlets and inlets were well below the Washington State Water Quality Standards. The ponds showed less difference between one another in their removal capabilities of metals than with the nutrients. This could be due to the tendency for some metals to have high initial settling rates (Whipple 1981), reducing the benefit of Pond C's longer hydraulic residence time relative to Pond A.

Pollutant settling rate plays a major role in the removal efficiency of BMPs such as wet ponds that rely on gravity as the primary removal mechanism. For suspended solids and associated constituents such as metals, large particles settle out quickly but leave behind fine suspended particles that may take weeks to settle out (Whipple 1981). When water is passed from one facility to the next in a treatment train, the upstream facilities will likely show higher removal efficiencies because they remove the heavier particles that settle out rapidly. The downstream facilities would appear to be less efficient, because they contend with smaller pollutant particles that are harder to remove. Even though Pond A receives effluent from Pond C, the effect of this factor on Pond A's efficiency is likely to be minimal because Pond A receives over 80 percent of its inflow directly from the watershed. Even with lower efficiency, Pond A's contribution to the quality of runoff from the entire site is substantial due to the relative volume of water it treats. Figure 7 illustrates this with pie graphs that represent the total loading from the watershed for each constituent.

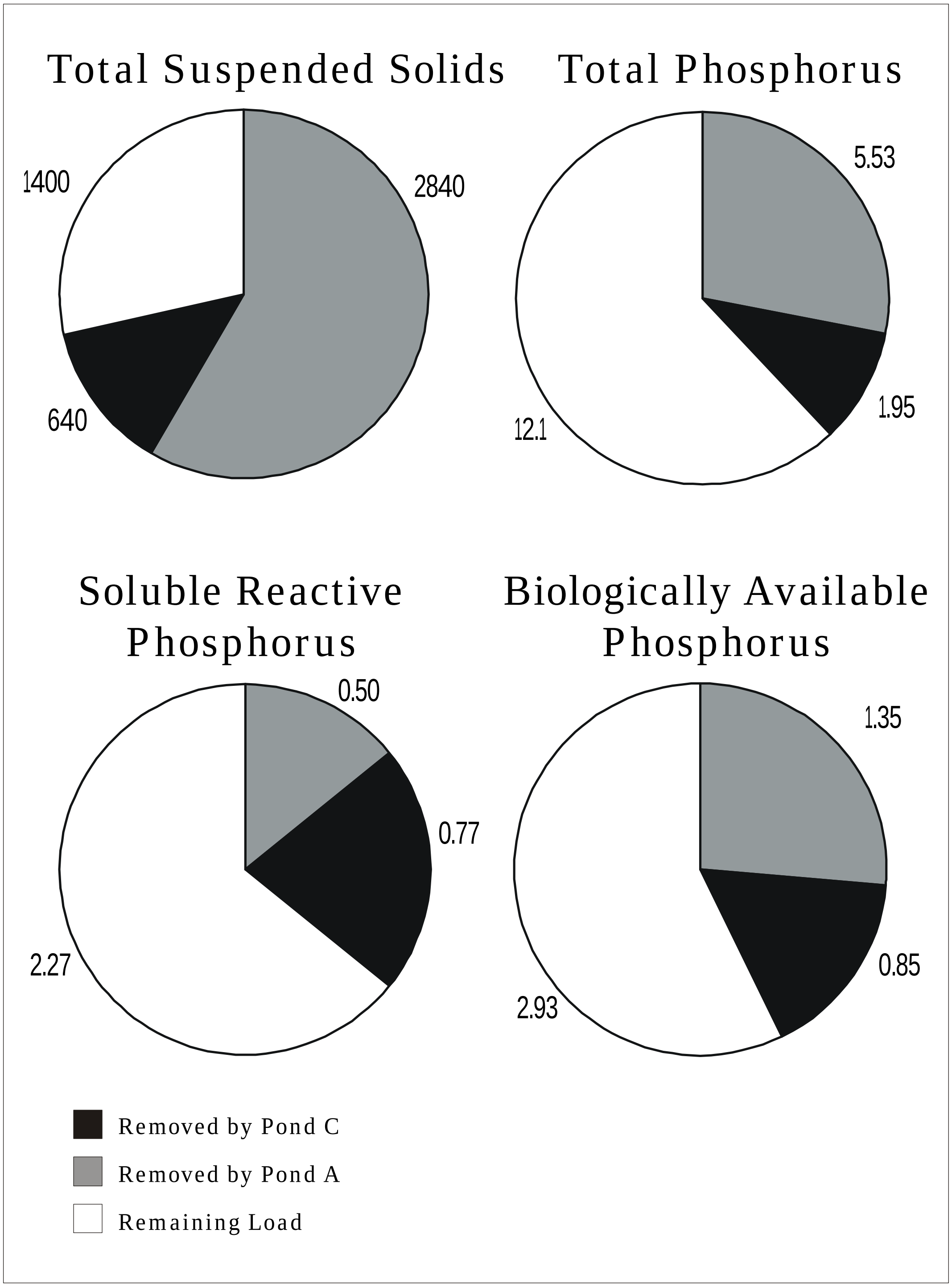

Figure 7 – Distribution of total loading from the study area during the period October 1996 – March 1997. Shaded areas signify the portion of the total loading that was removed by each pond. Values are in kg.

Concentration data from this study suggests that ponds can reduce concentration variability. Table 4 shows that coefficients of variation (CV) are reduced between the inlet and outlet of each pond for most constituents suggesting that water quality ponds tend to reduce pollutant concentrations toward relatively uniform values. Table 4 further indicates that, for the stated range of influent concentrations, there is a 95 percent confidence that effluent concentrations would be no higher than the given values. Schueler (1996) has suggested that BMPs can only reduce pollutant concentrations to certain levels or "irreducible minimums". It is unclear whether the uniform outlet concentrations seen in this study are minimum values or not, yet there does appear to be a consistently reliable value of predictable outlet concentration that is not dependent on the inlet concentration. This phenomenon was seen most clearly for TSS and other settleable pollutants and may represent the approximate limits of performance for a specific pond design. All of the equivalent effluent values, except Cd, were higher for Pond A, thus demonstrating the inability of a pond designed to a lower standard to reduce discharge pollutants as much.

Because this study occurred only during fall and winter months, the performance of the ponds during seasons of biological growth is still unknown and could be different from pond performance when photosynthetic organisms are dormant. Previous pond studies indicate that the presence of aquatic vegetation can improve a pond's performance by the uptake of nutrients (Coffman *et al*. 1993, Kantrowitz and Woodham 1995). Both ponds have aquatic vegetation that grows primarily along their rims. Even so, spring and summer months in the Pacific Northwest produce relatively little rainfall. Thus, runoff is minimal during these months and baseflow in this watershed actually stops. Because of this, impacts from stormwater to aquatic systems in the summer are almost surely less relevant than in fall and winter months.

The size of a pond is a major determinant of pond performance. The larger a pond is in relation to the area it drains, the better it performs at removing pollutants (Driscoll 1986b). Support for this can be found by looking at percent removal versus the size of a pond in relation to its catchment area (Wu 1996). In this study the permanent pool surface area of Pond A in relation to its basin (1%) is one fifth that of Pond C (5%), which is probably a major contributor to the removal efficiencies being consistently poorer than for Pond C.

Detention time is another important factor in pond design. The greater volume of Pond C allows stormwater to remain in the pond up to seven times longer than in Pond A. This provides the settling time needed for solid pollutants to be removed and chemical interactions to take place. Short-circuiting, however, can reduce effective detention time and so the flow path should be carefully considered to fully utilize a pond's storage space and minimize areas of quiescent water. Pond C was designed with a "horseshoe" shaped flow path to minimize short-circuiting, whereas Pond A's flow path is direct across three rectangular cells. Some improvement could be made to Pond A by shifting the first weir toward the west side of the pond to direct the flow diagonally across each cell and alternating the flow direction in consecutive cells.

Conclusion

The results of this study indicate that wet ponds do provide significant improvement in the water quality of urban runoff, and they provide guidance for both appropriate design parameters and the magnitude of pollutant removal that can be anticipated, as well as potential minimum values for effluent concentrations. Of the two ponds evaluated, one considerably out-performed the other in terms of removal efficiencies, demonstrating the importance of variation in pond size, configuration, and drainage conditions. The more efficient pond (Pond C) has the benefits of extended detention time, large volume in relation to its drainage area, and minimal short-circuiting, which greatly contributes to better pollutant removal efficiency. Although, it is not possible to determine directly from the data which of these factors has the greatest influence, our review of pond conditions and previous studies suggests that the pond volume dedicated to water quality treatment is most critical. However, watershed context is also important: although Pond A proved to be less efficient, it achieved a greater reduction in total pollutant loading due to the sheer volume of runoff that passes through it.

This study supports the value of wet pond detention systems in new developments to reduce water quality problems. The results also support the installation of such ponds into older developments where space allows and watershed conditions require such protection. Flow attenuation can be provided as well, albeit at some sacrifice of water quality performance. Where water quality is the primary need, however, a large-volume permanent pool design, such as that of Pond C, is preferable.

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