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16. ABSTRACT

The Washington State Department of Transportation (WSDOT) designs, operates, and maintains stormwater detention basins. These basins are used to control storm water runoff from highways, thereby controlling flows in down gradient areas. Historically, storm water basin design has been based solely on hydraulic considerations. Recent initiatives by the Washington State Department of Ecology have indicated that storm water quality has become a high priority. Consequently, future design must consider water quality as well as flood control

To have control of the variables associated with removal efficiencies (flow rate, contaminant type, contaminant concentrations, particle size distribution, and basin configuration) a scale model of a typical detention basin was constructed. Experiments to determine removal efficiencies for suspended solids with diameters <75 μm were conducted and the results were compared with the Type 1 sedimentation theory for an ideal basin. Preliminary investigations into the removal efficiencies for lead, zinc, cadmium, and copper were performed at one flow rate and optimized piping configuration.

The removal of suspended solids ranged from 65-80%. Type 1 sedimentation theory for an ideal basin yielded good predictions of sediment removal. This implies that Type 1 sedimentation theory could by used to estimate sediment removal in full scale systems under similar system conditions. Care should be taken when predictions are required at high surface overflow rates or for highway runoff that contains a significant fraction of small particles. The removal of metals ranged from 28-40% indicating that removal of smaller particles is necessary to achieve better removal efficiencies for metals.

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for
Research Project GC 8720
"Sediment Basin Design Criteria"

SEDIMENT BASIN DESIGN CRITERIA

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SUMMARY

The Washington State Department of Transportation (WSDOT) designs, operates, and maintains stormwater detention basins. These basins are used to control storm water runoff from highways, thereby controlling flows in down gradient areas. Historically, storm water basin design has been based solely on hydraulic considerations. Recent initiatives by the Washington State Department of Ecology have indicated that storm water quality has become a high priority. Consequently, future design must consider water quality as well as flood control.

To have control of the variables associated with removal efficiencies (flow rate, contaminant type, contaminant concentrations, particle size distribution, and basin configuration) a scale model of a typical detention basin was constructed. Model scaling was based on surface overflow rate equivalency between the prototype and model. Experiments to determine removal efficiencies over a range of flow rates (5, 7, 9, and 12 gpm) for suspended solids with diameters < 75 μ were conducted and the results were compared with the Type 1 sedimentation theory for an ideal basin. In addition to the sediment removal experiments, preliminary investigations into the removal efficiencies for lead, zinc, cadmium, and copper were performed at a single flow rate under an optimized piping configuration. The major project findings are summarized below.

- Type 1 sedimentation theory for an ideal basin yielded good predictions of sediment removal over the range of flow rates studied. Sediment removal predictions could, therefore, be made using known flow, surface area, sediment concentration, and sediment size distribution for a particular basin. Predictive estimations would be applicable to systems that maintained sufficient water depth to minimize sediment scouring.

- Suspended solids removal ranged from 65-80% and was inversely proportional to flow.

LIST OF FIGURES

- Modification of the basin inlet and outlet configuration to an "optimum" configuration did not afford a significant increase in sediment removal efficiency. This does not imply that enhanced removal would not be realized for other basins, only that the basin studied was insensitive to modification.

- The removal of metals ranged from 28-40% and was function of the degree of individual metal partitioning. The sediment that was not removed in the basin (27%) contained over 50% of the metals in the simulated stormwater. This indicates that enhanced removal of small particles will significantly increase metal removal.

CHAPTER 1

INTRODUCTION

INTRODUCTION

Contaminants in highway runoff can have a deleterious impact on aquatic environments of receiving waters. Several investigations have been conducted to determine the effects of contaminants associated with highway runoff. In one study, Portle, *et al.* reported the adverse effects of the soluble fractions on zooplankton and algae, while suspended solids caused high mortalities of rainbow trout fry. [1] In a separate study, increased lead concentrations were reported in barn swallows nesting near highways. [2] Reports detailing the adverse effects of contaminants in highway runoff have increased awareness of the potential impacts associated with highway runoff. Recent initiatives by the Washington State Department of Ecology have indicated that limiting contaminants in highway runoff has become a high priority.[3] Several studies have been conducted to quantify contaminants found in highway runoff and to examine the best management practices for contaminant removal.[4,5,6,7] Management practices include wetlands, grassy swales, retention/infiltration basins, and dual-purpose detention basins.

Wetlands and grassy swales function as natural water filtration and purification systems. One of the most valuable features for stormwater contaminant removal is the wetland's ability to trap suspended solids.[8] Removal efficiencies for grassy swales have been shown to be a function of the distance traveled in the channel and channel slope. Although grassy swales can be effective, they require significant maintenance to control sediment accumulation and subsequent deterioration in performance. [9]

Retention/Infiltration basins contain runoff in a basin with a highly permeable bottom. A large volume is required for retention/infiltration basins due to the storage capacity necessary for storm events. The basin must be able to accommodate an entire storm event since perculation to the groundwater system occurs at a notably slower rate than accumulation of storm water. One problem associated with retention/infiltration basins is the need for periodic removal of accumulated sediments to prevent clogging and to maintain the recharge capacity.

Historically, detention basins for storm water runoff have been designed solely for hydraulic considerations. The Washington State Department of Transportation (WSDOT) designs, operates, and maintains many such basins. These basins are generally designed for peak flow rate control where water quantity, not quality, has been the governing design parameter. Periodic cleaning requirements reveal that these basins capture sediment, however, the sediment and contaminant removal efficiencies are typically unknown.

Removal of suspended solids is a practical and cost-effective approach to treatment. It is well documented that the removal of total suspended solids (TSS) from highway runoff will remove partitioned contaminants (those contaminants associated with the solid phase) such as metals. Consequently, the removal of TSS has been the physical treatment process used most often. Information exists regarding the removal efficiencies for the systems mentioned above. However, little information exists regarding the removal of size fractions less than 75μm. Table 1 shows the best estimate of particle size distribution in highway runoff from several studies across the USA. Calculated particle

diameters are based on the settling velocity of discrete particles and Stokes Law.[10,11]

Table 1. Calculated particle diameter for particles in urban runoff.[10,11]

Size Fraction	Percentage of Mass	Average Settling velocity (m/hr)	Calculated particle diameter(μm)
1	00-20	0.01	2
2	20-40	0.09	6
3	40-60	0.48.	14
4	60-80	2.2	30
5	80-100	20	90

From 60-80% of the particles are less than 30 μm in diameter and all particles are less than 90 μm in diameter. Yousef[10] states, the failure to remove the small particulate would prevent achievement of target concentrations for contaminants. This is due to the smaller diameter particles' ability to adsorb the metals more efficiently than larger size fractions.[12,13,14,15] Thus, the metals partitioned onto the smaller particles may be discharged in the effluent. Better understanding of the mechanisms of removal for the smaller size fractions could enhance contaminant removal from highway runoff. Results from a study quantifying metals associated with particle size ranges can be seen in Figure 1.

Removal Efficiencies of Wetlands

Establishing and maintaining wetlands is an effective management practice for controlling contaminants associated with highway runoff. The ability of these systems to trap suspended solids can be attributed to three basic mechanisms:

water velocity reduction, filtering effects of vegetation present in wetlands, and electrochemical flocculation effects.[16] Wetland removal efficiencies as high as 94% for TSS have been reported.[17] However, the long-term concentration of contaminants, including heavy metals, and their potential bioaccumulation has not been addressed.[8]

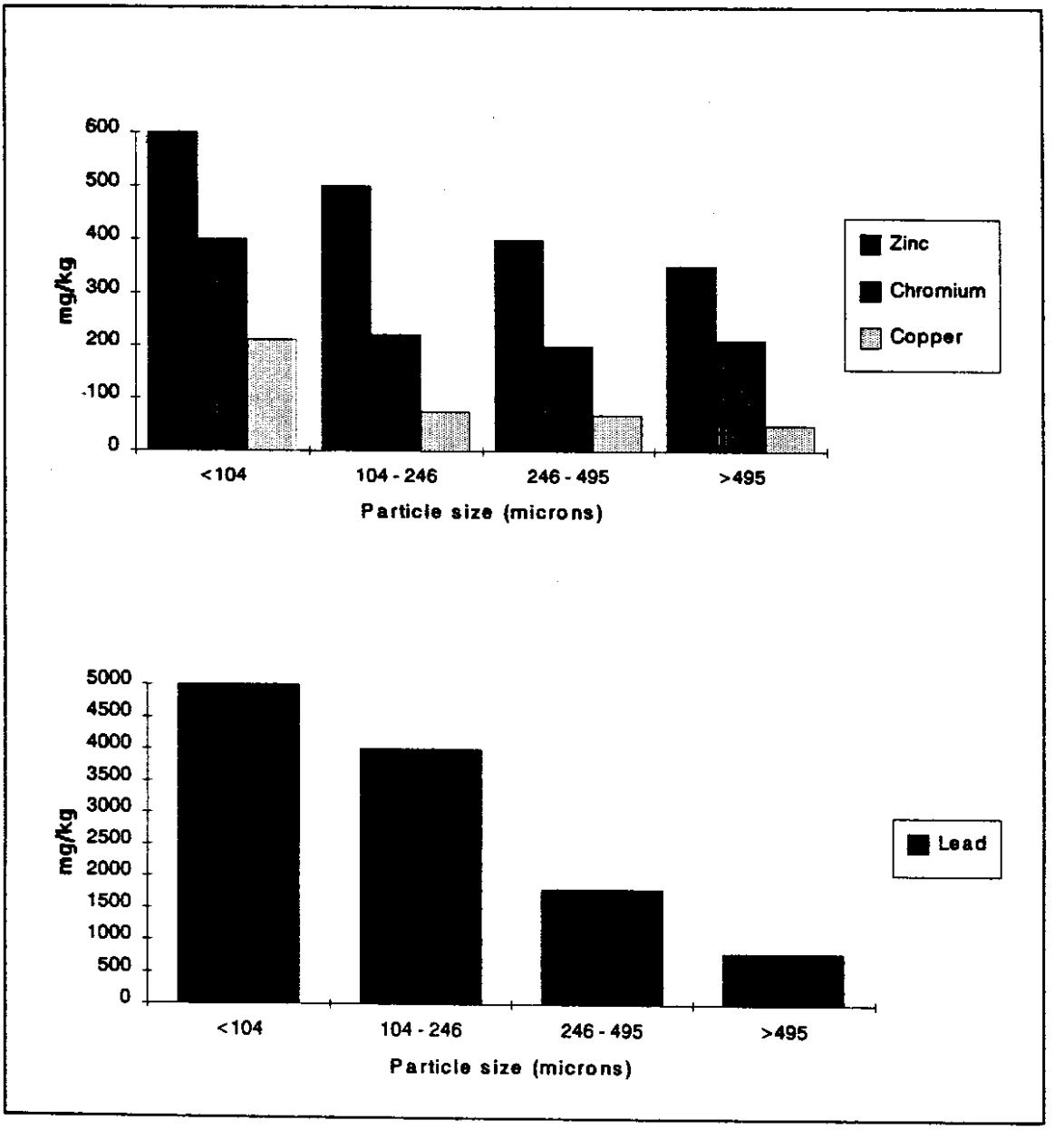

Figure 1. Concentrations of four metals in street dust by particle size ranges. [12]

Removal Efficiencies of Grassy Swales and Grass Lined Channels

The mechanisms of particle removal for grassy swales and grass-lined channels are similar to wetlands.[8] Yousef reports metal removal rates of grass-lined swales for lead, zinc, copper, and cadmium of 2.61, 5.76, 0.60, and 0.26 $mg/m^2 \cdot hr$, respectively. In another study, respective removals for lead, zinc, and copper were reported as 1.14, 1.85, and 0.42 $mg/m^2 \cdot hr$.[18] It is important to note that removal efficiencies are related to many site specific conditions including stormwater characteristics and swale design. For example, removal as a function of swale length for TSS, VSS, lead, copper, cadmium, and zinc reported by Wang [9] are summarized in Tables 2 and 3.

Table 2. Grass channel removal as a function of length for TSS and VSS.[9]

Swale Length (m)	TSS[1]	VSS[2]
21	90.4	90.9
43	93.2	86.4
67	94.5	100

[1] total suspended solids
[2] volatile suspended solids

Table 3. Grass channel removal efficiencies.[9]

Site	Distance (m)*	number of samples	Cadmium Removal (percent)	Copper Removal (percent)	Lead Removal (percent)	Zinc Removal (percent)
1	15-21	6	51.4	24.6	59.3	35.5
	31.0	1	60	53.5	70.4	31.4
	40-50	6	80	39.2	72.0	69.7
	67.0	6	100	63.1	83.8	69.7
2	15-20	2	100**	40.1	37.5	23.6
	30-40	2	100**	51.1	54.1	50.8
	50-60	2	34.8**	20.3	66.9	64.2
	67.0	1	**	43.4	90.2	65.4
	77.0	2	**	57.5	80.6	72.1
3	2.5	1	**	<0	2.9	2.1
	10.0	1	**	29.3	58.6	16.6
	15.0	1	**	51.9	68.1	19.4
	20.0	1	**	63.7	77.3	45.9
	25.0	1	**	70.7	86.7	57.1
4	2.5	1	<0	<0	2.1	12.9
	5.0	1	45.8	34.4	72.4	60.2
	15.0	1	100	68.1	78.5	93.2
	25.0	1	100	53.3	82.4	94.0

* - distance in channel from beginning of vegetated area.

** - One or more values were below detectable limit.

Design of Dual-Purpose Detention Basins

The design of basins for water quality can differ from flood protection design. A basin designed for flood prevention is sized for a storm event that rarely occurs. Conversely, the major pollutant load results from the cumulative effects of contaminants contained in smaller events that occur frequently throughout the year. Consequently, the need for dual-purpose detention basins is growing. A dual-purpose detention basin should be designed to: (1) retain the design runoff long enough to achieve the targeted level of treatment; and (2) to evacuate the design runoff quickly enough to provide available storage for the next flood.[19]

The removal efficiencies for dual-purpose detention basins vary considerably. This is due primarily to the site specific character of highway runoff and the different methods employed for basin design. One aid for design considers the site specific character of runoff by relying on locally monitored data. [20] Other aids for design include mathematical models to estimate removal efficiency, [21] design charts based on reservoir-routing equations, [19] and application of computer models such as SWMM, ILLUDAS, and UDSWM.[22] Whipple [23] applied an approach for basin design that incorporated sedimentation theory as proposed by Camp.[24]

Two detention basins involved in this study were modified by constructing outlets that provided prolonged retention of stormwater. Observed removal efficiencies of various pollutants were compared to predicted removal efficiencies. The predicted removal efficiencies were determined using laboratory settling data and application of discrete particle settling assumptions, as described by Camp.

Discrete Particle Settling - Type 1 sedimentation

The removal of sediment from highway runoff is best described by Type I sedimentation. Type I sedimentation is gravity separation of non flocculating discrete particles (particles that retain their individual characteristics) in a dilute suspension. Under such circumstances, the settling is unhindered and a function only of fluid properties and the characteristics of the particle.

A discrete particle in water accelerates until the drag force reaches equilibrium with the gravitational force; the settling velocity then becomes constant. Since equilibrium is reached rapidly, this terminal settling velocity is the parameter of interest in Type I settling. [25] For a given particle, the terminal settling velocity is a function of particle diameter, angularity, and density. At Reynolds numbers less than one, the settling velocity can be determined from Stokes law presented below.

$$V_s = \frac{g(\rho_s - \rho)d^2}{18\mu} \tag{1}$$

where:

V_s = settling velocity [m/s]

g = acceleration due to gravity [m/sec^2]

ρ_s = density of particle [kg/m^3]

ρ = density of water [kg/m^3]

d = diameter of particle [m]

μ = dynamic viscosity of water [kg/m·s]

Using Stokes law to calculate a settling velocity for each size fraction from a particle size distribution a type 1 settling curve (settling velocity distribution) can be generated to aid in removal predictions *see* Figure 2.

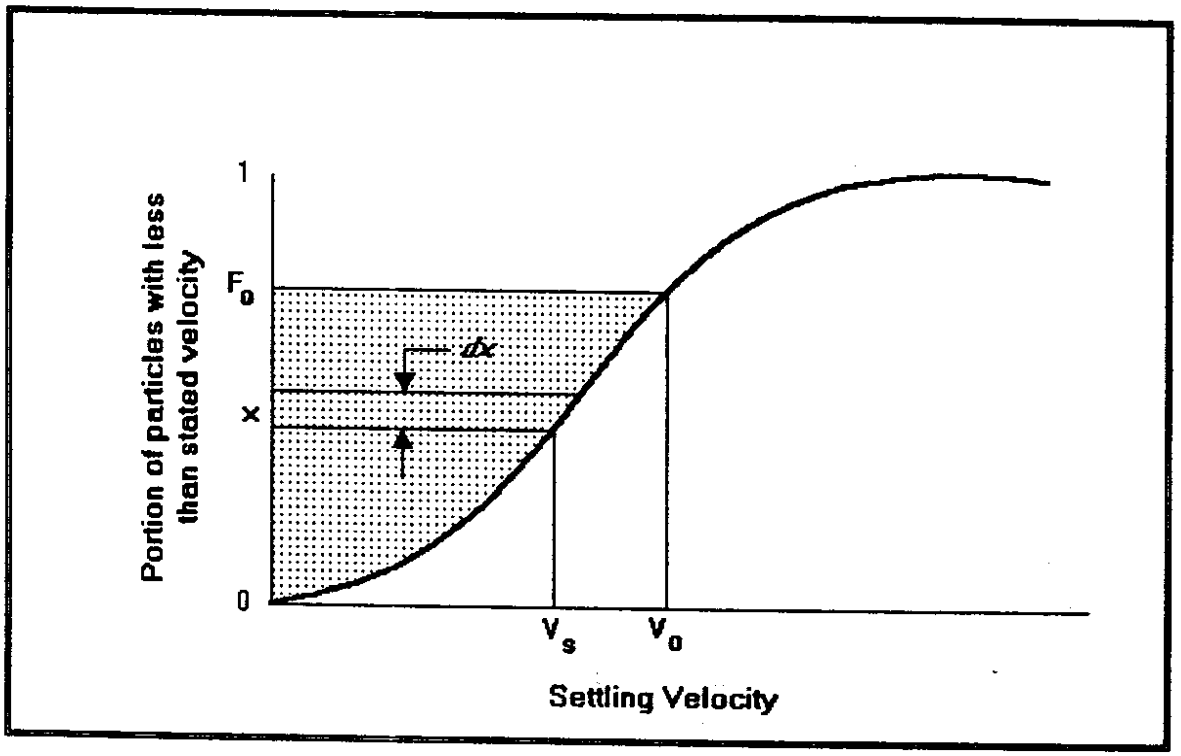

Figure 2. Type 1 settling curve.

Camp's Removal Theory

Sedimentation in an ideal basin, as described by Camp,[26,27] uses the settling velocity distribution, surface area, and flow rate to estimate the percentage removal for discrete particles. Use of this theory is based upon the following assumptions:

1. Discrete particle settling.
2. An even distribution of flow entering and leaving the basin.
3. An idealized settling, entrance, outlet, and sludge zone.
4. Uniform distribution of particles throughout the entrance zone.
5. Particles entering the sludge zone remain there.

6. All particles entering the outlet zone are carried out in the basin effluent.

The total removal is estimated by Equation 2:

$$R = (1 - F_o) + \frac{1}{V_o}\int_0^{F_g} VdF \qquad (2)$$

where:

R = total percentage removal

V_O = surface overflow rate expressed as velocity

$1\text{-}F_O$ = fraction of particles with velocity greater than V_O

$\frac{1}{V_o}\int_0^{F_g} VdF$ = fraction of particles removed with velocity less than V_O

To estimate total percent removal for a given basin the surface overflow rate (SOR) must first be calculated.

$$SOR = \frac{Q}{SA} \qquad (3)$$

where:

SOR = surface overflow rate [l/min·m^2]

Q = flow rate [l/min]

SA = surface area of sedimentation basin [m^2]

By appropriate unit conversion, the surface overflow rate can be expressed as a velocity:

$$V_o = SOR \qquad (4)$$

where V_O is equivalent to the settling velocity of the smallest particle that exhibits 100 percent removal. The y-axis coordinate of the intersection of V_O with the settling velocity distribution curve defines F_O as seen in Figure 2. A fraction of the particles with settling velocities less than stated surface overflow rate will be removed as a function of the initial depth of the particle upon entering the basin. This fraction can be determined analytically as defined by the integral portion of Equation 2. More frequently however, an approximate solution is obtained by graphical integration as shown in Figure 2.

Basin Modification to Minimize Short-circuiting

Historically detention basin design has not been governed by contaminant removal. The main purpose of the basins was to retain runoff from a storm event and discharge it gradually so that the capacity of the receiving stream was not exceeded. As a result, piping configurations in these basins have been a function of cost-efficiency and constraints imposed by system specific conditions such as highway design and local topography. To maximize contaminant removal, stormwater retention time should be maximized and short-circuiting minimized. If short-circuiting occurs, contaminant removal efficiencies would be less than the theoretical optimum.

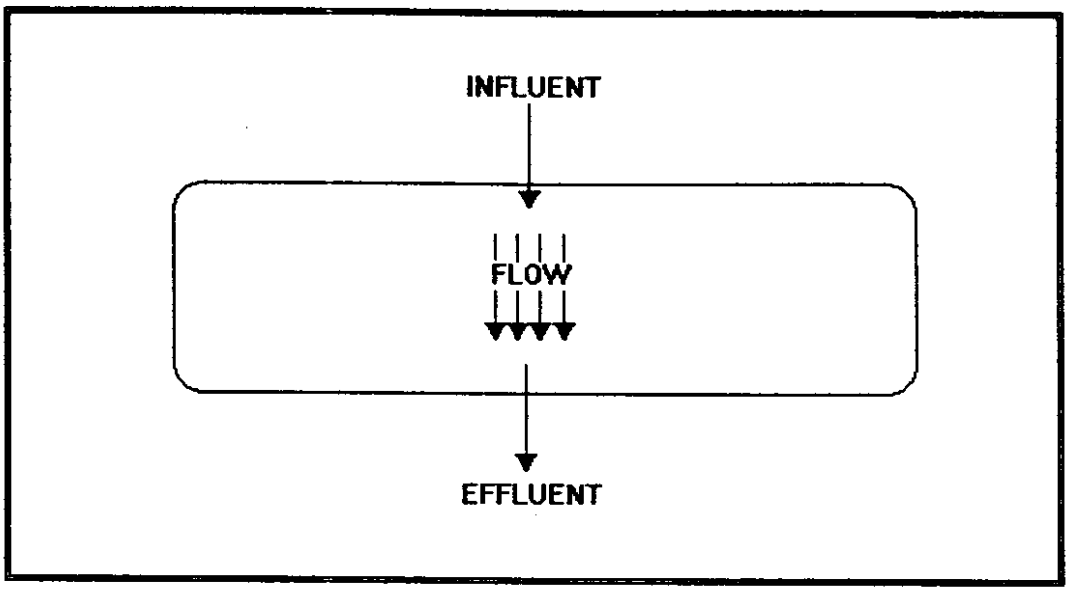

Figure 3. Basin with short-circuiting piping configuration.

A schematic representation of a short-circuiting system is presented in Figure 3. Clearly, the flow entering the basin is not being retained as long as is possible. Modification of basin piping configuration to minimize short-circuiting and enhance removal efficiencies is shown below. Retention time is increased by eliminating short-circuiting and as a result removal efficiency is enhanced.

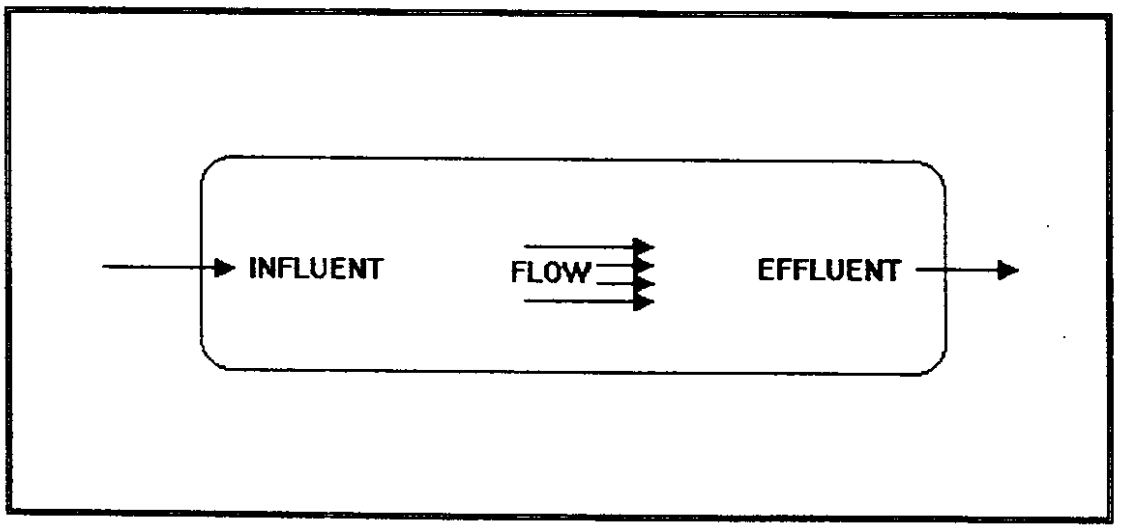

Figure 4. Basin modified to minimize short-circuiting.

CHAPTER 2

RESEARCH OBJECTIVES

RESEARCH OBJECTIVES

The purpose of this project was to generate a data base that can be used in the development of a rational design approach for storm water sedimentation basin design. A scale model of an existing dual purpose detention basin was constructed so the variables of concern could be varied under controlled conditions. These variables include flow rate, contaminant type, contaminant concentrations, particle size distribution, and basin configuration. The model was modified to minimize short-circuiting. Removal efficiencies were compared to the existing configuration. Results from both configurations were compared to Camp's type 1 settling theory for an ideal rectangular basin to determine if this theory can be used to predict sediment removal. Preliminary investigations were performed to evaluate the removal potential of metals common to highway runoff (lead, copper, cadmium, and zinc).

CHAPTER 3

RESEARCH APPROACH

RESEARCH APPROACH

The scale model constructed as part of this project replicates an existing detention basin located on the NE corner of the Henderson Blvd. interchange on I-5 in Olympia, Washington. This basin was selected as a prototype because of it's geometric similarity to many basins in the region. An initial field survey of the basin was performed and the resulting basin dimension data used to design experimental parameters for scale model construction and testing.

Scale Model Development

The prototype basin flow was used as the basis for developing the scale factor. Prototype flow estimation was based on effluent pipe length, pipe type, slope, and hydrostatic head. The maximum head above the effluent pipe was defined as the height at which water would top over the lowest point in the basin berm. Using Manning's equation for closed-conduit flow, the maximum flow was estimated, and the resulting maximum surface overflow rate (SOR) was calculated.

Theoretically, removal efficiency of discrete particles is dependent on SOR only. Consequently, removal for the prototype can be predicted in scale model testing by equating the SORs of the prototype and scale model as indicated by Equations 5 and 6.

$$SOR_p = SOR_m \tag{5}$$

$$\frac{Q_p}{SA_p} = \frac{Q_m}{SA_m} \tag{6}$$

where:

Q_p = flow rate to prototype

SA_p = surface area of prototype

Q_m = flow rate to model

SA_m = surface area of model

It is important to note that scale model development can be based upon many parameters. The mechanism to be studied by modeling dictate the parameter chosen for scaling. The most common approach used when predicting the hydraulic responses of a particular system is to keep the ratio of forces in the prototype and model constant throughout the flow field. This requirement is necessary in addition to maintaining geometric similarity. The dimensionless force ratios used to accomplish dynamic similitude are chosen based on the forces that will be acting on the system. In a free surface hydraulic model, such as the one considered in this study, the dimensionless force ratio used to accomplish dynamic similitude is the Froude number.

The objective of this study was to determine the removal rates of suspended solids and metals sorbed onto them. Consequently, flow rate determinations for the scale model were based solely upon sedimentation basin design theory, Equations 5 and 6. As a result, the removal efficiencies predicted by the scale

model can be applied to the prototype at corresponding surface overflow rates. However the hydraulic responses acting throughout the flow field may not be accurately predicted because Froude number similarity was not considered.

Scale Model Flow Range Determination

A range of model flow rates were determined from calculated surface overflow rates in the existing basin. The maximum SOR was determined by calculating the flow rate out of the prototype at maximum capacity and dividing by the surface area of the basin. The scale model flow rate was determined using Equation 6.

The minimum SOR was determined using Camp's Theory to calculate the SOR corresponding to an 80 percent removal efficiency. This removal efficiency was selected to minimize analytical problems at TSS concentration of less than 100 mg/L. Using the SOR from Camp's theory approximations in Equation 6, the minimum scale model flow rate was determined. The range of SORs and corresponding basin flow rates are summarized below:

Table 4. Estimated SOR for prototype and scale model and corresponding flow rate for model.

Surface Overflow rate [μm/s]	Surface area of model[m^2]	Flow rate [L/min]/[gpm]
0.3542	2.14	45.42/12
0.2655	2.14	34.07/9
0.2066	2.14	26.50/7
0.1475	2.14	18.93/5

Scale Model Construction

Based on the topographical information obtained from the field survey and estimated basin flow rates, a scale of 1:15 was selected. The model was constructed using a vermiculite concrete slurry, wire mesh, and plywood templates housed in a 16' x 4' x 2' box made from half inch plywood. Using the contour map created from the field survey, cross-sections were drawn at 15 foot intervals. Elevations were then determined at intervals that were sufficient to define the basin topography. After each cross-section had been converted to scale they were traced onto plywood and cut into templates . These templates were placed at one foot intervals (corresponding to the 15 foot intervals from contour map) in the plywood box, thus defining the shape of the basin. A #900 wire mesh was tacked to the templates and acted as a support for a 4:1 vermiculite:concrete slurry. After drying, the vermiculite mix was covered with a concrete slurry to minimize roughness. Outfall pipes were positioned at the appropriate elevation within the basin and were made of 2" schedule 30 PVC piping. The outfall pipes were sealed with silicone to minimize leakage between the concrete and pipe wall. A schematic representation of the basin is shown in Figure 5.

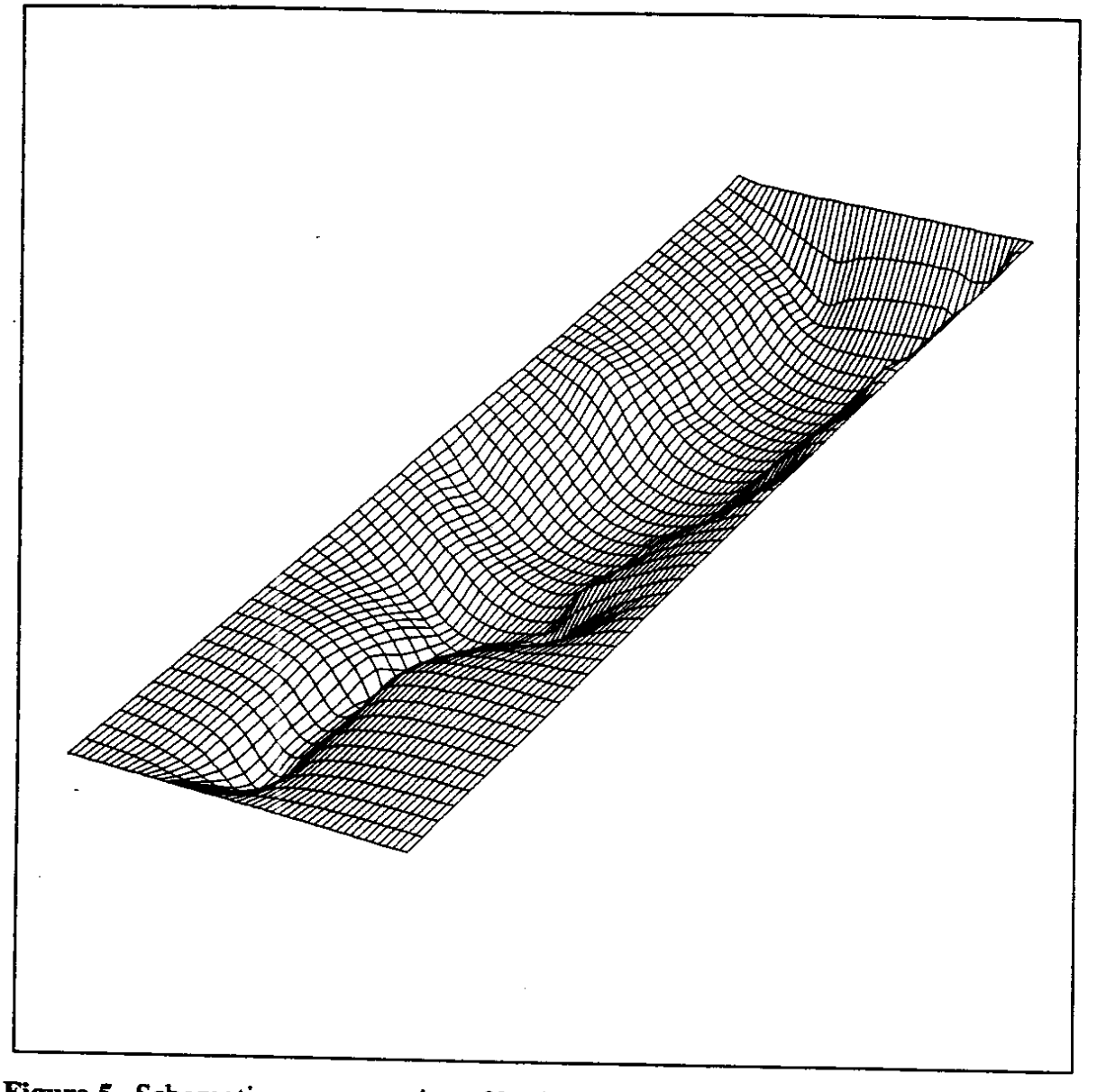

Figure 5. Schematic representation of basin.

Scale Model Configuration

Simulation of Prototype Configuration

Determining the removal rates for the prototype configuration was necessary so that the effects of piping configuration modification could be determined. For this phase of the study, the basin inflow and outflow pipes were positioned at the

same locations and elevations as in the prototype. Flows for each pipe were determined by personal communication with WSDOT as percentage of total flow and adjusted for each flow rate. The configuration is represented in Figure 6.

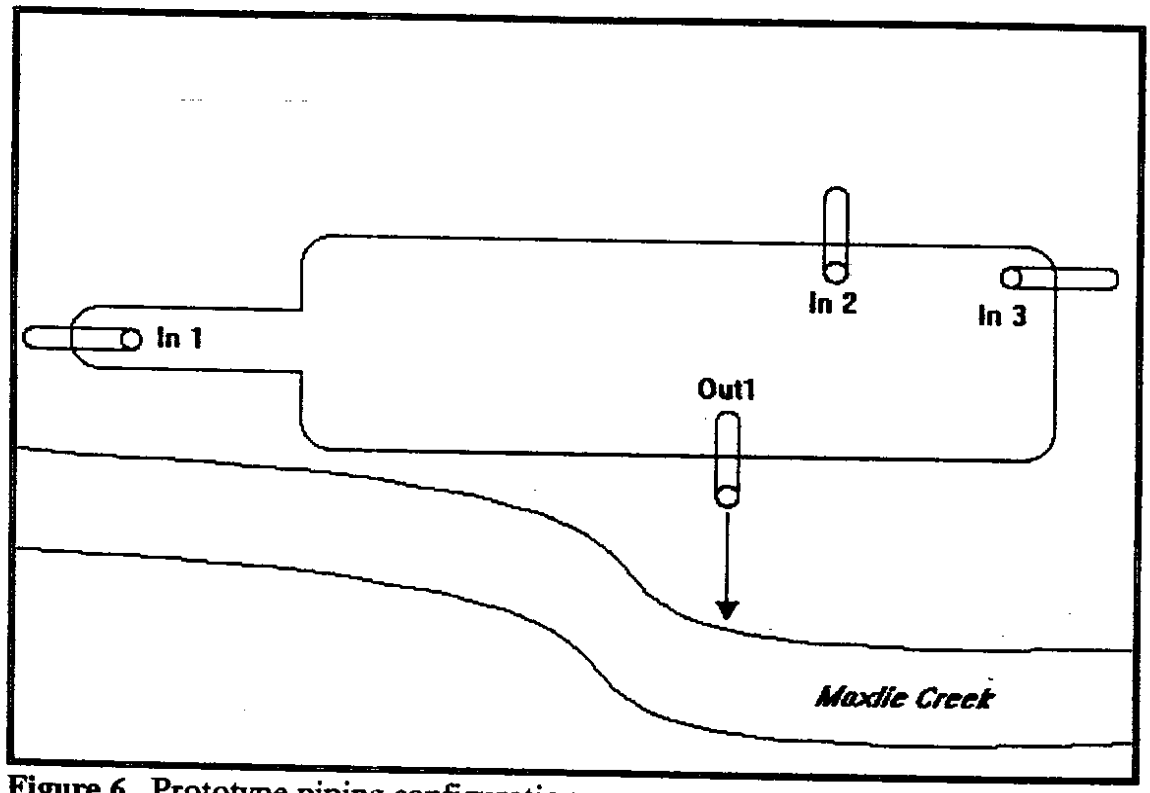

Figure 6. Prototype piping configuration.

The percentage of total flow for each pipe was

In1 = 20%
In2 = 20%
In3 = 60%

Optimum configuration

The influence of piping reconfiguration on sediment removal efficiency was investigated by performing a series of tests using the model represented in Figure 7. The piping configuration was intuitively based; utilizing the full length of the

basin and potentially reducing short-circuiting. To optimize the removal rates, short-circuiting of flow should be eliminated. The basin was configured as in Figure 7 to take advantage of basin dimensions and to minimize short circuiting occurring when inflow and outflow pipes are placed in close proximity.

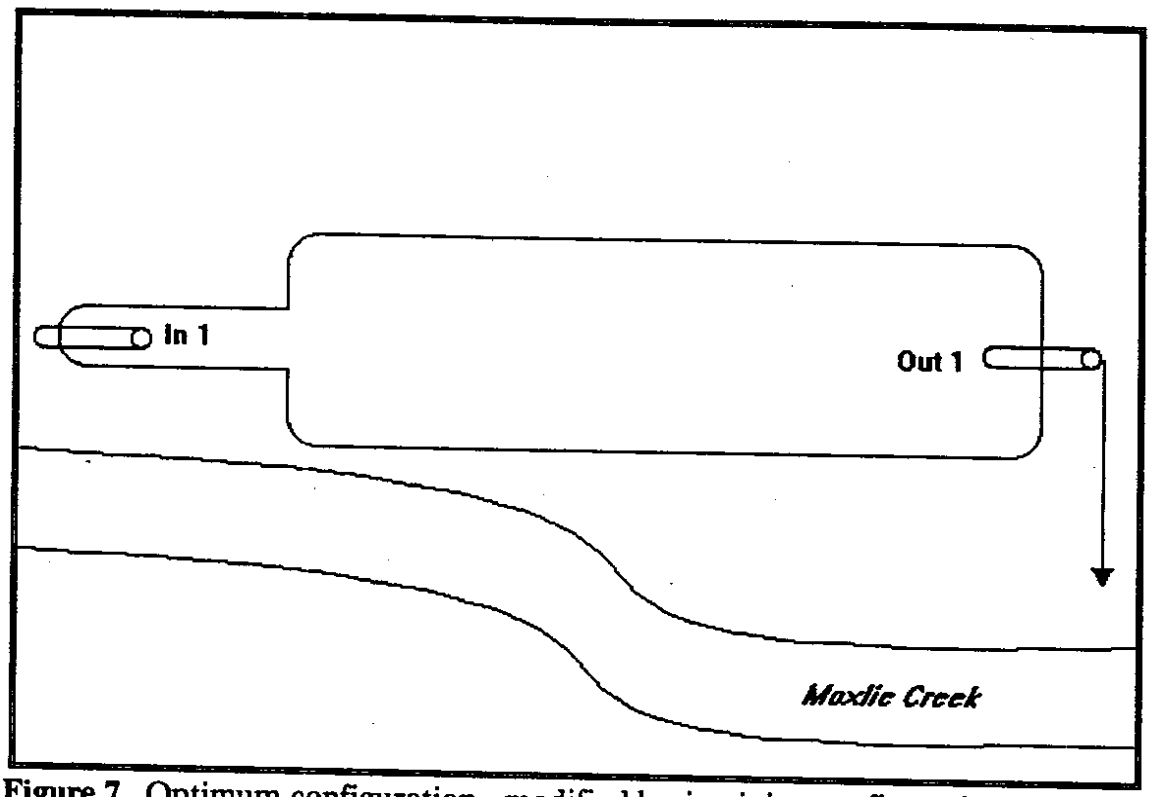

Figure 7. Optimum configuration - modified basin piping configuration

Wet Testing

After the concrete set, wet testing was initiated. The basin was configured as in Figure 6. Tap water was pumped into the basin at the highest flow rate; 12 GPM used in this study.

The main objectives of the initial wet test were to:

1. Check for leakage within the basin.
2. Confirm that actual volume and HRT data corresponded with design values.
3. Confirm the equivalency of SOR between the model and prototype.

Selection of Contaminant Concentrations for Simulated Storm Water

A comprehensive literature review was conducted to determine average TSS and metals concentration in highway runoff. The results of this search are summarized below:

Table 5. Highway runoff constituents reported as ranges of values [27, 28].

	Cadmium (mg/L)	**Copper (mg/L)**	**Lead (mg/L)**	**Zinc (mg/L)**	**TSS (mg/L)**
Range (High)	0.05	0.65	5.02	2.89	1274
Range (Low)	0.001	0.005	0.01	0.01	9

Preliminary calculations showed that removal efficiencies within the basin would range from 65-80 percent. Consequently, a TSS concentration of 500 mg/l was used in all removal experiments to ensure that there were sufficient solids in the effluent to accurately define removal efficiencies and accurately assess the effects of flow and basin modification on changes in removal efficiencies.

The simulated storm water (SSW) metals concentrations were based on the national averages listed in Table 5. Preliminary experiments showed high levels of variability in liquid and solid phase equilibrium concentrations for lead and copper at the levels indicated for national averages. To maintain liquid phase concentrations above the lower detectable limit and minimize the variability of lead and copper concentrations, the upper end of the observed range for suspended solids and metal concentrations was used in this work. These concentrations were 0.06, 0.18, 1.8, 1.3 mg/L for cadmium, copper, lead, and zinc, respectively.

Metal Sorption Internal to System

Unintentional loss of heavy metals due to sorption on the feed system components, the basin, and/or the inlet and outlet structures was evaluated by a series of experiments utilizing tap water containing lead, copper, and cadmium. The data in Table 6 summarizes the selected metal concentrations.

Table 6. Initial metals concentration for internal sorption test.

Metal	Concentration (μg/L)
Lead	100
Copper	35
Cadmium	4

The lowest experimental flow rate, 5 gpm, was selected to maximize the contact time within the system. Influent and effluent samples were taken every five

to define the particle size distribution. The hydrometer analysis procedure used was - ASTM (1980), Designation D 422 .

Simulated Storm Water Mixing and Introduction to Basin

Due to the particles tendency to settle within the 1000 gallon Nalgene holding

minutes over the course of one hour. These samples were analyzed using the methods detailed in Metals Quantification to allow comparisons to be made between basin influent and effluent concentrations.

Sediment used in SSW

The sediment used in the SSW was obtained at Wallowa lake in Eastern Oregon. This site was selected to minimize the background metal contamination level as there is no known upstream road access. The sediment was transported to the laboratory and stockpiled on a tarp at a depth of approximately 0.5 feet and air dried. The soil was undisturbed during drying to minimize unintentional stratification. From the stockpile a 1 ft^2 block was collected and dried at 103° for 24 hours. The dried sediment was shaken on a US standard #28 sieve using a Soiltest hammer type shaker for 15 minutes to remove larger size fractions (pebbles, sticks, bark, etc.). The fraction passing through the US standard #28 sieve was then ground on a Cincinnati muller type grinder for 30 minutes to reduce the sediment to elementary particles. After grinding, the soil was put on the sieve shaker for 30 minutes and all sediment that passed the 200 series sieve (75 microns) was used for preparing the SSW.

Particle size fractions are determined by two methods, sieve analysis and hydrometer analysis. The sieve analysis is used for particles with a diameter greater than 75 microns. Particles whose diameters are less than 75 microns are evaluated using hydrometer analysis. This test is based on Stokes law for falling spheres in a viscous fluid. No particles larger than 75 microns were used for removal efficiency determinations. Consequently hydrometer analyses were used

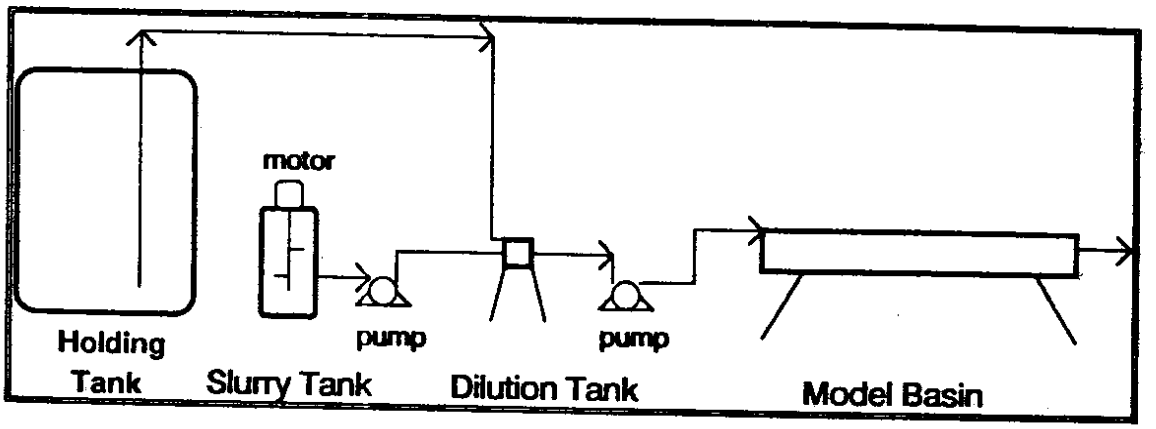

Figure 8. Schematic of SSW introduction to basin.

Preliminary mixing tests indicated that impeller placement toward the bottom of the tank minimized air entrainment and maintained a homogeneous solution. Air entrainment within the CSSW tank had to be avoided to maintain a constant influent flow rate and sediment concentration. The dilution tank was a 4 L plexiglass tank placed on a magnetic stirrer with a 3" Teflon coated stir bar.

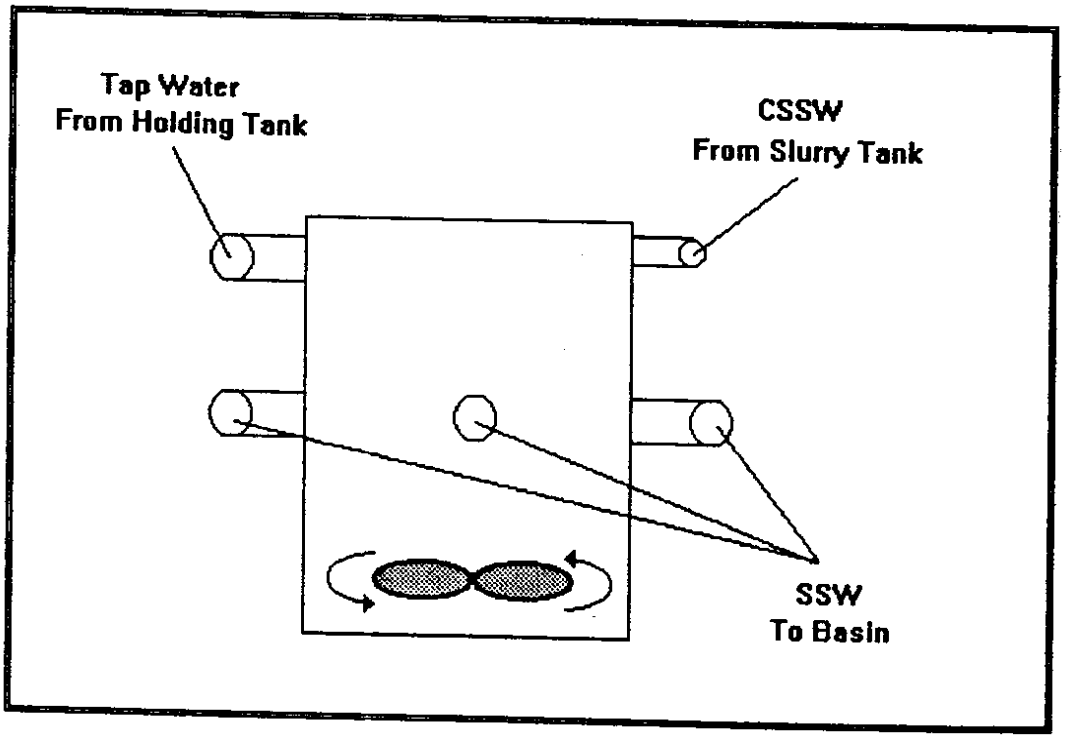

Figure 9. Schematic of dilution tank used for preparation of SSW.

All outlet ports on the dilution tank were located at equal distances from the bottom of the tank to maintain equivalent concentrations in all exit hoses. It is significant to have all influent concentrations equal so that accurate flow adjustments will give the desired loading rates. Sedimentation in the tubing was prevented by use of 0.25 inch tubing which maintained sufficient flow through velocity.

Flow Measurement

The flow was measured for the influent hoses using a graduated cylinder and stopwatch. Each flow was adjusted until the flow was stabilized, and measurements could be triplicated over a period of two minutes. The CSSW hose going into the dilution chamber was connected via a flow splitter so that the head of the holding tank would not affect the flow measurement. The CSSW flow was then measured with a graduated cylinder and a stopwatch following the same procedure described above.

Suspended Solids Percent Removal Determinations

To eliminate the loss of volume due to sludge accumulation, the basin was cleaned of all sediment following the termination of each run. In addition, the CSSW tank was emptied. An appropriate amount of soil was added to the CSSW tank that resulted in a concentration of 16.2 g/l, and the volume was adjusted to 30 gallons. Dilution water flow rate from the holding tank was then adjusted. During this adjustment period the scale model was filled with clean water. A hose used to fill the holding tank was adjusted to the corresponding basin flow rate so that a constant head would be achieved. A solids mass balance

was used to determine the flow rate for the CSSW to the dilution tank to achieve 500 mg/L solids concentration. Following CSSW flow rate adjustment the basin inflow was allowed to run for a time equal to four HRTs to approach steady state conditions. To prevent air entrainment, adequate amounts of water and soil were added to the slurry tank so that the level of CSSW in the tank remained at or above half capacity. Sampling was initiated following the four HRT time period. The sampling scheme followed during each test is illustrated in Table 7

Table 7. Sampling scheme used for removal efficiency determinations.

Sample	Time	Volume	Purpose	Type
In1	4HRT	300 mls	Solids Analysis	Grab
In2	5HRT	300 mls	Solids Analysis	Grab
Out1	5HRT	300 mls	Solids Analysis	Grab
In3	6HRT	300 mls	Solids Analysis	Grab
Out2	6HRT	300 mls	Solids Analysis	Grab
Out3	7HRT	300 mls	Solids Analysis	Grab
LM1	4HRT	150 mls	Liquid phase metals analysis	Composite
LM2	4HRT + 1min	150 mls	Liquid phase metals analysis	Composite
TM1	4HRT	150 mls	Total Metal Analysis	Composite
TM2	4HRT+1min	150 mls	Total Metal Analysis	Composite

Metals Percent Removal Determinations

The same procedure was followed for the metals runs as in the suspended solids runs with the following exceptions. Before the run was started the metals were added to the CSSW tank and allowed to equilibrate with sediment for 24 hours. After 24 hours the run was started as in the previous procedure. The liquid phase samples were collected in 150 mL Nalgene bottles, filtered immediately, and preserved with an appropriate amount of concentrated acid to make a 1 N solution.

The total metals samples were collected in a similar manner to the liquid phase samples, instead of filtering they were digested according to the procedure outlined in Metals Quantification.

The method used for collection of the composite samples for liquid and solid phase was the same. The effluent was collected in a 3.5 gallon bucket. The contents of the bucket were completely mixed and a sample taken.

Sufficient salts of the metals were added to the slurry tank to result in metal concentrations of 2, 6, 60, and 40 mg/l for cadmium, copper, lead, and zinc, respectively. The sediment concentration in the slurry tank of 16.2 g/L was identical to previous sediment removal experiments. Three replicates metal removal experiments were performed at a flow rate of 9 GPM and optimum configuration.

TSS Analysis

Preliminary tests showed that repeatability of TSS analysis could be enhanced by modifying the Standard Methods procedures. This modification was necessary to maintain a homogeneous suspension during pippetting. The modifications include shaking the sample thoroughly and transferring to a baffled 500 mL beaker. 100 mL aliquots were taken from the beaker and filtered through a Whatman 47 mm glass fiber filter.

Metals Quantification

Investigations were conducted to determine a digestion procedure which removed partitioned metals without damaging the mineral structure of the sediment. A 1N nitric acid digestion was shown to produce the best results. The sample taken from the basin was mixed and an aliquot was removed from the sample bottle and transported to another sample bottle that contained an appropriate amount of concentrated nitric acid to make a 1N solution. The sample bottle was placed on a wrist shaker at a speed sufficient to keep particles in suspension. The samples were allowed to digest for thirty minutes. At the completion of the digestion the samples were gravity filtered through a Whatman 47 mm glass fiber filter and the filtrate used for analysis on the Atomic Adsorption Spectrophotometer.

The Atomic Adsorption methods used were *Standard Methods* - 3111 B. for flame analysis and *Standard Methods* - 3113 B for flameless Atomic Adsorption analysis when greater sensitivity was necessary.

An exception to *Standard Methods* procedure for preservation of samples was made to minimize matrix effects observed in flameless Atomic Adsorption analysis. The samples were preserved with 1N nitric acid.

In all cases blanks were run to check for contamination within sample bottles, stock solutions (metals and acid), filter paper, and all glassware.

CHAPTER 4

INTERPRETATION, APPRAISAL, AND APPLICATION

INTERPRETATION, APPRAISAL, AND APPLICATION

Particle Size Defined

Hydrometer tests were run on several different samples collected from different locations within the sediment stockpile to evaluate the homogeneity of the stockpile. Five samples from the stockpile were analyzed and compared. The results of the five samples produced similar particle size distributions. The results from all tests were averaged to give a particle size distribution used for application in Camp's theory. This distribution is shown in Figure 10 .

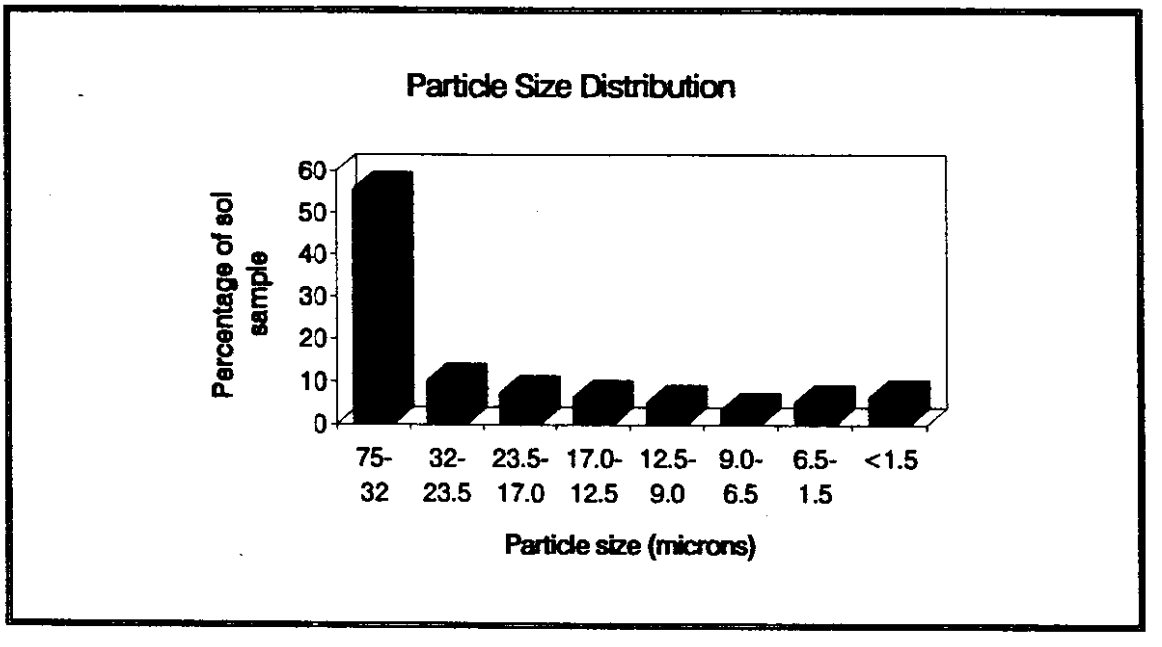

Figure 10. Particle size distribution for sediment used in removal experiments.

Settling Velocity Distribution

After determining a particle size distribution for the sediment used in the SSW a Type 1 settling curve was constructed using Stokes law, Equation 1.

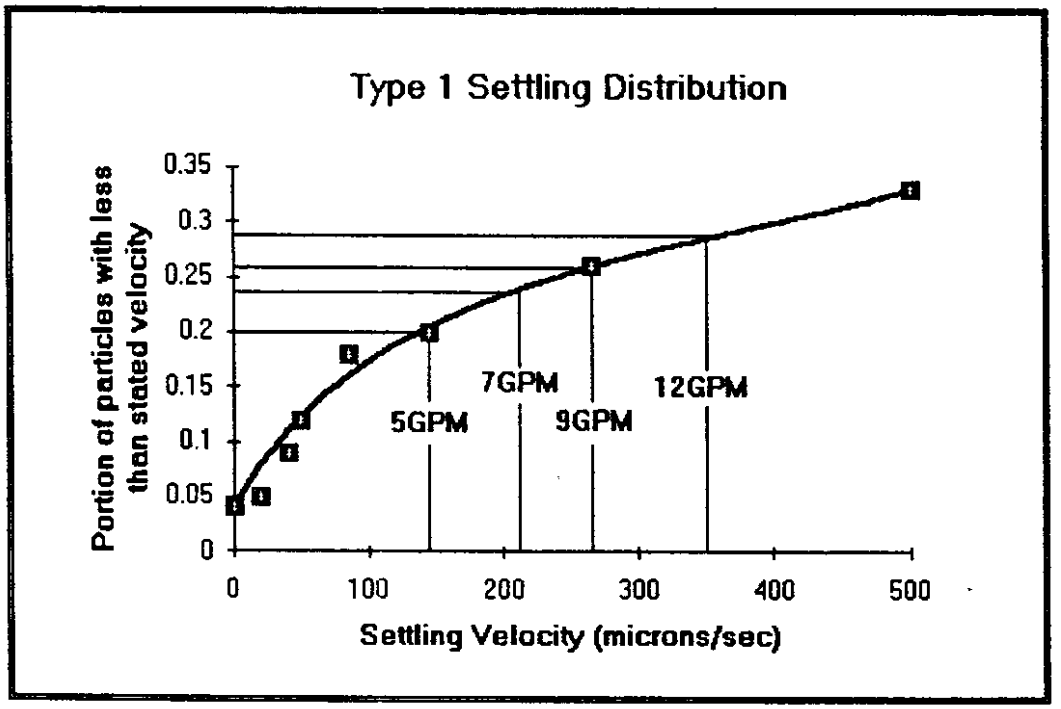

Figure 11. Type 1 settling curve with SOR indicated for given experimental flow rates.

Figure 10 shows 55% of the particles were determined to be larger than 32 μms. From Figure 11 it can seen that the largest SOR was 354 μms/sec corresponding to a settling velocity for a particle 19.9 μm in diameter. Therefore it was not necessary to define the particle size distribution for the particles above 19.9 μm in diameter since these particles are 100 percent removed at the highest SOR and all subsequent lower SORs. The particles with a diameter less than 19.9 μm will be the particles partially discharged in the effluent. The percentage of these

particles discharged in the effluent can be determined by evaluating the second term of Equation 2. For the experimental SORs used and the particle size distribution of the sediment used in the SSW, this contribution to the overall percentage removal was negligible.

Figure 12 shows an interpretation of the entire settling velocity distribution for the sediment used in the SSW.

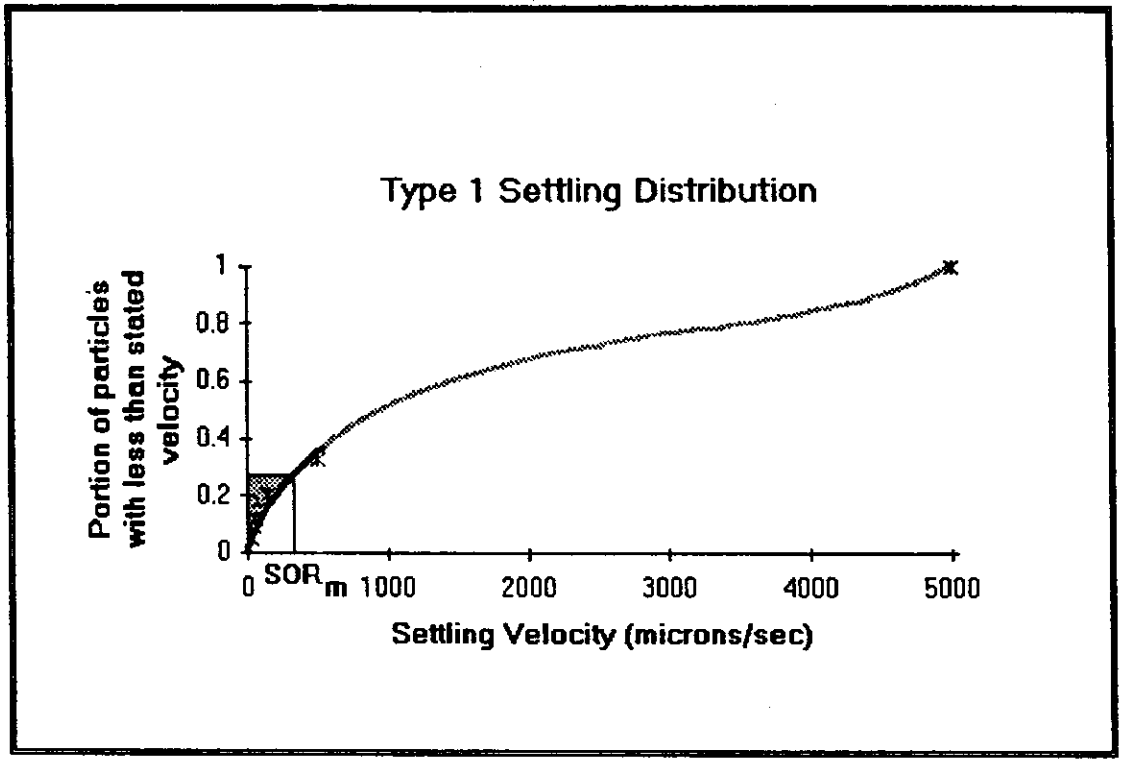

Figure 12. Settling velocity distribution for 100 percent of particles

The dark portion of the curve represents the portion for which values were obtained from the hydrometer tests. The dotted line is an interpretation of the best fit between the two points. The highest experimental surface overflow rate corresponding to a model basin flow rate of 12 GPM is indicated in Figure 12.

The shaded area above the curve is the area to be integrated as indicated in the second term of Equation 2. The removal calculated by this term contributes only 0.078% to the overall removal of 80% *see* Table 8. This indicates that the second term of Equation 2 is not significant for the system studied. Camp's theory indicates that a portion of those particles with less than stated SOR will be removed due to their position upon entering the basin. For this system that portion is low with respect to total removal. Table 8 shows the total removal determined by Camp's approximation including the portion contributed by both term of Equation 2. In addition, the surface overflow rate expressed as a velocity is shown for each experimental flow rate.

Table 8. Calculated removal efficiencies.

Flow Rate [L/min]/[GPM]	**SOR (μms/sec)**	**Removal ($1-X_0$)**	**Integral 2nd Term**	**Total Removal**
18.93/5	147	80	0.078	80.1
26.50/7	207	76	0.088	76.1
34.07/9	265	74	0.103	74.1
45.42/12	354	71	0.11	71.1

Suspended Solids Percent Removal Determinations

Prototype configuration

Table 9. Experimental removal determinations for prototype configuration.

Flow Rate [L/min]/[GPM]	Trial #1 (% removal)	Trial #2 (% removal)	Trial #3 (% removal)
18.93/5	78.73	76.12	n/a
26.50/7	76.62	76.5	n/a
34.07/9	67.12	66.45	n/a
45.42/12	64.22	65.16	66.86

Optimum configuration

Table 10. Experimental removal determinations for optimum configuration.

Flow Rate [L/min]/GPM]	Trial #1 (% removal)	Trial #2 (% removal)	Trial #3 (% removal)
18.93/5	76.91	72.31	n/a
26.50/7	73.68	75.64	78.09
34.07/9	71.22	67.73	n/a
45.42/12	69.55	66.45	n/a

As expected the higher flow rates produced a lower percentage removal of suspended solids due to increased SORs.

Comparison of Experimental Values with Camp's Theory Predicted Values

Average experimental values for prototype and optimum configurations are compared to removal predictions made by application of Camp's Theory in Table 11.

Table 11. Comparison of experimental results to theoretical predictions.

Flow Rate [L/min]/[GPM]	Prototype (% removal)	Optimum (% removal)	Predicted Values (% removal)
18.93/5	77.4	74.6	80.1
26.50/7	76.6	75.8	76.1
34.07/9	66.8	69.5	74.1
45.42/12	65.4	68.0	71.1

The effects of altering piping configuration to minimize short-circuiting did not show a significant increase in removal efficiencies. This may be due in part to the flow pattern established in the scale model basin at prototype piping configuration. The flow pattern qualitatively determined from visual observations is shown in Figure 13.

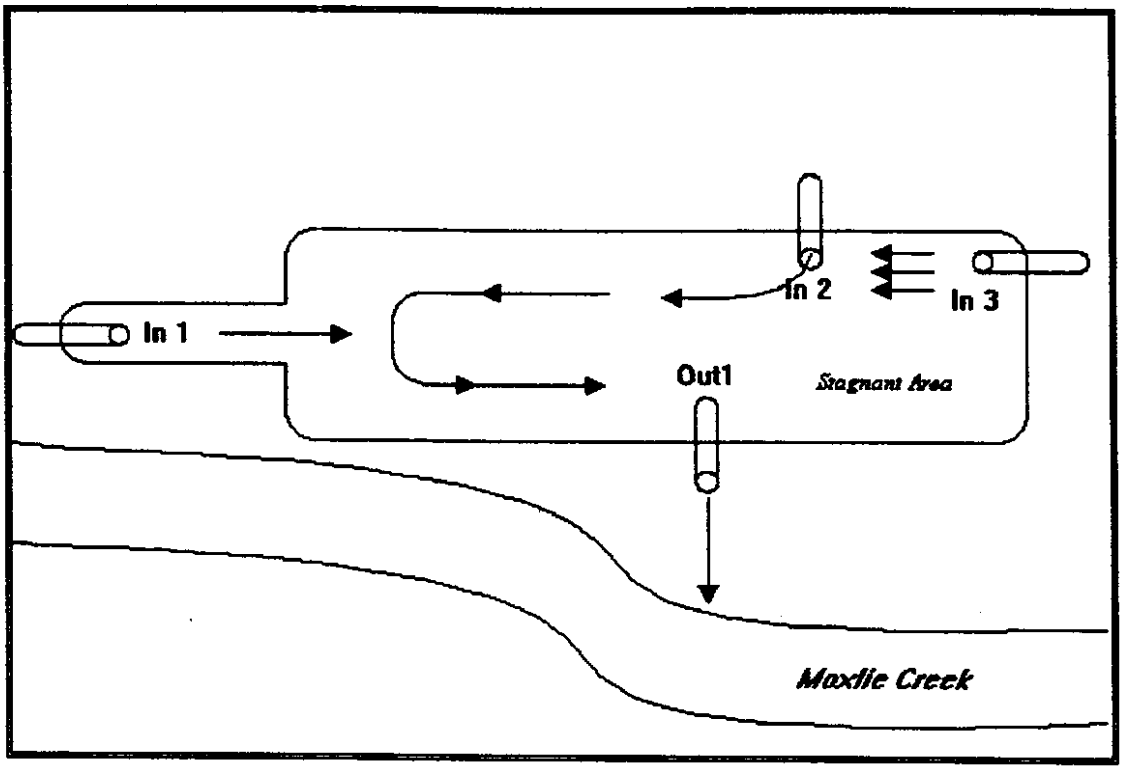

Figure 13. Flow pattern for prototype configuration.

The flow pattern established may be preventing short-circuiting of flow from In2 to Out1 . As a result, solids entering the system at In 2 are not transported directly to the outfall but are given the opportunity to settle due to increased residence time in the basin dictated by the established flow pattern. This would suggest that the basin is approximating ideal conditions as described by Camp for both configurations studied. However predictions for flow patterns established in the prototype cannot be made because the model study was not designed in accordance with Froude number similarity criteria.

Metals Removal

The percentage removal determinations based on total metals analysis are presented in Table 12. The total metals are defined as the sum of metals partitioned to sediment and the metals remaining in the liquid phase after equilibrium was established. The results of two separate experiments (Trial 1 and Trial 2) are presented in Table 12.

Table 12. Percent removal of total metals at 9 GPM.

Metal	Trial 1 percent removal	Trial 2 percent removal
Lead	34.6	35.3
Zinc	33.8	33.1
Cadmium	40.0	32.5
Copper	37.5	28.2

The solids percentage removal for Trial 1 and Trial 2 was 74.8 % and 71.0 %, respectively. Clearly, the total metals removal is not as good as solids removal.

By calculating the solid phase removal it becomes clear that removal of the smaller particles is necessary to achieve higher removal efficiencies for metals. The solid phase is defined by the difference of total analysis and liquid phase analysis.

Table 13. Percent removal of solid phase metals at 9 GPM.

Metal	Trial 1 percent removal	Trial 2 percent removal
Lead	36.1	35.4
Zinc	40.3	35.8
Cadmium	41.7	25.0
Copper	36.8	33.3

Liquid phase analysis showed that more than 80 percent of the cadmium and zinc had partitioned to the sediment after equilibrium. While, lead and copper had greater than 93% in the solid phase. An average of 27.1% of the solids that were not removed in the basin had adsorbed greater than 58% of the available cadmium and 64% of the available lead.

The liquid phase analysis suggest that better removal of solids could result in metals removal as high as >93% removal for lead and copper and >80% removal for cadmium and zinc. Research is currently being conducted at Washington State University that is investigating increased removal potential of chemical addition to enhance settling. Preliminary results indicate that chemical addition will increase the removal rates of suspended solids.

CHAPTER 5

CONCLUSIONS AND RECOMENDATIONS

CONCLUSIONS AND RECOMENDATIONS

Sediment Removal

The removal efficiency of suspended solids from highway runoff can be reasonably predicted using Camp's Theory for discrete particle settling under the simulated field conditions studied. Measured percent removals ranged from 65 percent to 77 percent while calculated percent removals ranged from 71 percent to 80 percent over the four flow rates studied. This is a reasonable degree of predictive accuracy, indicating that Camp's Theory for type I sedimentation could be used to predict sediment removal in full scale systems.

It should be noted that basin scaling was based upon surface overflow rate (SOR) equivalency between the prototype and scale model. This scaling procedure was selected based on experimental requirements regarding contaminant partitioning (the relationship between liquid and solid phase contaminant concentration). Normally, when predicting the hydraulic responses of a particular system, the ratio of forces in the prototype and model are kept constant. In a free surface hydraulic model, such as the one considered in this study, the dimensionless force ratio used to accomplish dynamic similitude is the Froude number. This approach would result in model flow rates different from those used in this study. In addition, the sediment particle size and/or density would have to be modified. Modification of the sediment would directly affect the contaminant partitioning ratio and the impact of coagulant addition on sediment and contaminant removal. In turn, these changes would invalidate any relationship between metal removal in the model and prototype. It is felt, however, that percent removal predictions based on type I sedimentation theory could be utilized for estimation

purposes for sediment particle sizes and SOR's studied in this project. Prediction inaccuracies would be expected to increase as particle size decreased and flow rate increased.

Data from the preliminary metal removal studies indicated an average total metal removal of 34% compared to 67% sediment removal at a flow of 9 gpm. This was a result of the inverse relationship between the degree of metal partitioning and particle size. Consequently, a failure to remove smaller particles could result in significant levels of total metals in the basin effluent, even though sediment removal efficiency is relatively high.

Small particle removal could be enhanced by lowering the SOR of the basin, minimizing short circuiting, and the addition of coagulants. Surface overflow rate could be lowered by decreasing the basin flow by adding additional basins to a given drainage area or by increasing basin surface area (enlarging the structure). This alternative is often limited by both cost and space constraints and alternative solutions may be more applicable. A possible solution could be the addition of grassy swales between the basin and the receiving water to polish the effluent. Another alternative would be to add coagulants to the basin influent to enhance small particle and metal removal.

Short-circuiting can be minimized by optimum placement of inlet and outlet piping configurations. If this is not possible during construction or if existing basins cannot be effectively reconfigured, short-circuiting could be decreased by installing baffles.

CHAPTER 6

IMPLEMENTATION

IMPLEMENTATION

The data presented in this report indicate that Type I sedimentation theory could be used to estimate sediment removal in existing storm detention basins under conditions of similar surface overflow rates and particle size distributions. In addition, accurate predictions would be expected over the range of flows studied for particles larger than those studied. Care should be taken if removal predictions of particles with diameters less than approximately 20 μ are required, if surface overflow rates are greater than those applied in this study, and if there is reason to believe significant short circuiting is occurring. In addition, this predictive method does not consider bottom scouring and consequently, basin depth should be maintained at levels to maintain horizontal flow through velocities less than 1 - 2 fps.

If system conditions are within the bounds of the aforementioned criteria, sediment removal prediction can be made by defining the following parameters.

- particle size distribution and density
- basin surface area
- flow rate

Application of these parameters to the basin system of interest can then be used in combination with the procedure outlined in the Research Approach chapter to estimate percent sediment removal.

CHAPTER 7

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LITERATURE CITED

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