PHYSICAL MODELING
OF A
STORMWATER SEDIMENT REMOVAL BOX

FINAL REPORT

Submitted to
Brevard County, Florida, and the National Estuary Program

by

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EXECUTIVE SUMMARY

Sediment removal efficiency of a typical stormwater sediment removal box (also known as baffle box) was investigated in the laboratory using a hydraulic scale model. The standard design currently being used divides the box into three chambers by two barriers or baffles. The baffles slow the flow of water and allow the sediments to settle in the box. These type of sediment traps are currently being used as one of the stormwater management practices in Brevard County, Florida.

The scale model was constructed using a length scale ratio of six, and principles of hydraulic similitude were used to relate the model results to prototype behavior. Sandy Clay and Fly Ash were used in the model to simulate the effect of coarse and fine sediments in stormwater, respectively. Experiments were conducted to determine sediment removal efficiencies of the box under varying flow conditions by measuring removal efficiencies for different entrance velocities, flow rates and sediment concentrations. Removal efficiency was defined as the ratio of the weight of sediment removed to the weight of sediment injected. Removal efficiencies of the standard, three chamber, sediment box were measured during 48 experiments (24 each for Fly Ash and Sandy Clay) which were designed to replicate field conditions. Thirty additional experiments (24 with Fly Ash and 6 with Sandy Clay) were conducted to determine the removal efficiqncy of the sediment box with modifications in the existing design. Modifications that were tested included sediment boxes with two, three, four or five chambers. The effect of raised baffles w4.5 also tested as part of the new designs. Finally, six experiments were conducted to simulate the effect of a shallower sediment trap, one that had half the depth of a normal box.

The effect of baffles in removing sediments could be seen visually; the sediment strikes the baffles and slides downward; some of it then recirculates and escapes into the next chamber or out of the box while the remainder remains trapped in the box. It was, therefore, felt that inclusion of more chambers would perhaps improve the overall removal efficiency of the box. This did not happen in most cases because more chambers meant that the individual chamber sizes were smaller and, therefore, less efficient in retaining the trapped sediment.

The average removal efficiency of the traditional, three chamber box, for experiments performed using coarse (Sandy Clay) and fine sediments (Fly Ash) were 89.8% and 27.8%, respectively. The removal efficiency of the box remained constant with inflow sediment concentration for coarse sediments, but increased with increase in inflow sediment concentration for fine sediments. In general, increase in flow rates and entrance velocities reduced the removal efficiency for both coarse and fine sediments. Removal efficiencies measured with new designs were not significantly higher or lower than the existing design'. However, further improvements which can reduce recirculation of sediment within chambers can probably improve the removal efficiencies especially in the case of fine sediments. Experiments with the raised bottom or shallower sediment box showed that the removal efficiencies were approximately 6 to 7 percent lower than the standard size box. One can, therefore, infer that a box which is deeper than the standard box might produce improved removal efficiencies.

It can be concluded from the experimental results that these type of sediment boxes are highly effective in removing coarse sediments in stormwater, but their efficiency in removing fine sediments '(approximately 30%) can be further improved with some modifications especially if these modifications can reduce recirculation within the chambers.

ACKNOWLEDGMENT

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Chapter 1

INTRODUCTION

1.1 Stormwater Management

In the last 25 years, stormwater management has become an important part of the general field of water resources engineering and management. A broad definition for the term 'stormwater management' could be: management of 'quantity' and 'quality' of stormwater. Stormwater management in urban watersheds is a challenge to the modern engineer as it involves blending existing methodologies with non-conventional techniques.

The traditional method of disposing stormwater in an urban area has been to drain it away as rapidly as possible. This is done by swales, gutters, and storm. sewers conveying runoff to the nearest receiving body of water. In recent years, however, environmental concerns have arisen and engineers and planners are beginning to question the impacts of the practice of rapid conveyance down stream on the receiving waters (Stahre, 1990).

The growing concern of the impact of stormwater, as a potential pollutant to waterbodies in the United States, has led to new rules and regulations being implemented by authorities. The 1972 Federal Water Pollution Control Act (FWPCA), also referred to as, the Clean Water Act (CWA), prohibits the discharge of any pollutant to waters of the United States from a point source unless the discharge is authorized by a National Pollutant Discharge Elimination System (NPDES) permit. In 1987, Congress amended the CWA to include municipalities that have separate stormwater sewer systems serving populations of 100,000 or more. In 1990, the Environmental Protection Agency (EPA) published (EPA, 1992) permit application requirements to implement these requirements.

1.2 Best Management Practices (BMPs)

Dischargers into the municipal separate storm sewer systems must comply with pollution standards set by the local authorities to obtain NPDES permits from the EPA. Effective management techniques must be adopted to remove pollutants in stormwater runoff prior to discharging into any water body. The various control measures that can be implemented to effectively, reduce pollutant loadings are sometimes termed as "Best Management Practices` (BMPs). Federal Code (Federal Regulations, 1976) defines a BMP as "a means of practice or combination of practices that is determined by a state (or designated area wide planning agency) after problem assessment, examination of alternative practices, and appropriate public participation to be the most effective practicable (including technological, economic, and institutional considerations) means of preventing or reducing the amount of pollution generated by non-point sources to a level compatible with water quality goals.

BMPs are broadly classified as Structural or Non-Structural controls. A brief overview of the types of BMPs is described in the following sections.

1.2.1 Non-Structural Controls

Non-structural practices to control stormwater runoff include street sweeping, controlled use of fertilizers, pesticides and de-icing compound, buffer strip preservation, and public education. Such control measures are effective and are recommended for new development (EPA, 1993). They may be included during the planning, site-selection, and development, stages. Non-structural practices usually prevent pollutants from entering the stage of concentrated flow and the are sometimes referred as 'Source Controls.,

1.2.2 Structural Controls

Structural practices to control stormwater runoff rely on three basic mechanisms: detention, infiltration and filtration.

Detention controls temporarily store stormwater runoff to control peak runoff rates and provide a reduction in pollutant concentrations by the gravitational settling of suspended solids and associated contaminants. Except for incidental losses due to evaporation and or percolation, essentially all the detained water is subsequently discharged to a surface water conveyance. The most common examples of detention practices are wet (retention) detention basins and extended detention basins.

Infiltration controls rely chiefly on absorption to treat stormwater discharges. In the ideal case, stormwater percolates through a porous medium and into native soils where filtration and biological action remove pollutants. Typical controls of this type include infiltration trenches, infiltration basins, filtration basins, porous pavements, concrete or block pavers. Filtration controls treat stormwater when it flows over the filtration media such as different types -of vegetation (also called as bio-filters). Generally, these controls are most effective before the flows become concentrated. After passing over the filtration media, the treated water is usually directed to a stream or a storm sewer.

1.2.3 Sediment Boxes

Sedimentation -basins have been part of treatment trains in the field of environmental engineering for many years. Now a BMP, known as a sediment box, which is similar in concept to a sedimentation basin is being used to treat stormwater. The box is divided into three compartments by two barriers, also' known as baffles, as shown in Figure 1.1. The barriers slow down the flow of water and allow the sediment to settle in the box. The design concept of a sediment box is similar to the design of a traditional three chamber water quality inlet also known as oil/grit separator. Sediment boxes, or baffle boxes, are also a type of detention control since pollution concentrations are reduced by the gravitational settling of suspended solids and associated contaminants. While it is certain that these type of sediment boxes remove sediments, their removal efficiency, under various field conditions, has not been determined either under field or laboratory conditions.

1.3 Objective of This, Study

The objective of this study was to establish the sediment removal efficiency of a typical sediment box under various field conditions. A laboratory scale model of a typical box was constructed, and experiments were performed using the model conforming to principles of hydraulic similitude. The overall removal efficiency, Em(O), of the model box for all experiments, in this investigation, is defined as the ratio of total mass of sediment trapped to the total mass of sediment injected during the experiment, expressed as a percentage. Similarly, efficiencies of chamber I (closest to the inlet pipe), chamber II (middle chamber) and chamber III (farthest from the inlet pipe), Em(I), Em(II), EM(III), are, respectively, defined as the ratio of the mass of sediment trapped by a chamber to **the total** mass of sediment injected during the experiment. The overall efficiency can therefore be computed as:

$$Em(O) = Em(I) + EM(II) + Em(III)$$

Experiments were conducted on the model box to determine the overall sediment removal efficiency, and the individual chamber removal efficiencies, of the box under various field conditions such as: varying entrance velocities, storm water flow rates, varying suspended solids concentrations in stormwater, and varying particle size distribution of suspended solids.

1.4 Background

Sediment boxes are being installed in several districts within Brevard County (Figure 1.2) where sediment loadings from storm water is a major threat to the water quality of the Indian River Lagoon. Approximately 15 boxes have been installed in submerged stormwater pipes in key locations within the county to remove sediments from stormwater. Photograph 1.1 shows field installation of a sediment box in Indialantic, Florida. Typical dimensions of a sediment box are shown in Figure 1.1. These boxes have proven to be highly successful in removing sediments; approximately 6,500 pounds of sediment was removed from a sediment box installed in the Indialantic, Florida, within 40 days after installation. It would be difficult and expensive to determine the removal efficiency of a sediment box from field data; both the mass of the sediment trapped by the box and the mass of the sediment having flown through the box are difficult quantities to measure in the field.

Numerous studies have identified Total Suspended Solids (TSS) as a major stormwater pollutant. Suspended solids (TSS) in stormwater can cause a significant increase in the turbidity of receiving water bodies.

Harper (1994) conducted a literature search of previous studies on. TSS concentrations in stormwater' runoff for - f selected land use categories in South and Central Florida. The search included publications by the South West Florida Water Management District (SWFWMD) , the South Florida Water Management district (SFWMD) , the St. Johns River Water Management district (SJRWMD) , the Florida Department of Environmental Protection (FDEP), U.S. Environmental Protection Agency (U.S. EPA), the U.S. Geological Survey (USGS), the University of Central Florida, the University of Florida and other applicable sources. From these publications certain studies were selected based on the availability of one year of continuous data, and wide range of rainfall and antecedent moisture conditions. The analysis by Harper (1994) included only those studies that were performed on homogenous watersheds were. Forty publications with information about TSS concentrations from stormwater runoff were chosen after screening, and the mean TSS, concentrations for various land use categories are summarized in Table

1.3. The range of TSS runoff concentrations in stormwater from this study is from 3 mg/l to 94 mg/l. The findings of the NURP study, and Harper (1994), show that there is wide range in TSS EMCs, although the EMCs from Florida stormwater tend to be on the lower side.

Table 13: Summary of Literature-Based Mean TSS Runoff Concentrations
for Selected Land U~, Categories in Central and South Florida.
(Harper, 1994)

Land Use Category	Percent Impervious	Mean TSS Runoff Concentration (mg/1)	
1. Low Density Residential	14.7	19.1	
2. Single Family	27.8	27.0	
3. Multi-Family	67.0	71.7	
4. Low Intensity Commercial	91.0	81.0	
5. High Intensity Commercial	97.5	94.3	
6. Industrial	86.8	93.9	
7. Highway	85.0	50.3	
8. Agricultural			
Pasture	0.0	94.3	
Citrus	0.0	16.3	
General Agriculture	0.0	55.3	
9. Recreational/Open Space	1.5	11.1	
10. Mining		23.0	93.9
11. Wetland	0.0	10.2	
12. Open Water/Lake	100.0	3.1	

1.4.2 Particle Size Distribution of TSS

Settleable or suspended solids generally consist of particles that have a grain size greater than 10 micrometers (0.01 mm). These include silts or clays (grain size between 10 to 75 micrometers or 0.01 mm to 0.075 mm.); fine to very coarse sands (grain size between 75 to 5000 micrometers or 0.075 mm to 5.0 mm); and gravel (grain size greater than 5000 micrometers or 5.0 mm) Stahre (1990) conducted particle size studies on stormwater samples in Sweden, after separating coarse sediments by five minutes of sedimentation. The studies were performed using a light blocking instrument which could measure 15 different TSS size intervals ranging from 2 to 500 micrometer. Stahre's findings are shown in the bar graph in Figure 1.4. As seen in the figure the number of particles are ,greatest in the 10 to 20 micrometer range. The number of particles larger than 40 micrometer were less than 10 particles per milliliter of the stormwater samples, and hence do not appear in Figure 1.4. A microscopic study of the particles revealed that, for most part, the particles were spherical in shape. The particles size distribution was, therefore, transformed into particle volume distribution using this assumption. Figure 1.4 also shows the particle volume distribution for various particle sizes. An examination of Figure 1.4 reveals that, for these samples, the 10 to 35 micrometer sized particles account for 90% of the TSS volume, i.e., most of the suspended solids in Stahre's samples consisted of silts and clays

Laboratory analysis conducted on storm water samples by Rinella and Mckenzie (1982) in Portland, Oregon, showed that 70% of the particles had a diameter of less than 32 micrometers. The study was similar to the studies by Stahre (1990) but used different instrumentation. Coarse sediments were not separated by sedimentation before the tests were performed. A study, similar to Rinella and Mckenzie (1982), conducted by Randall et al. (1982) in Virginia, showed that 80% of the particles by weight were less than 25 micrometers. These studies supported the findings of Sartor and Boyd (1977) that most suspended solids in storm water are associated with smaller particles. Ellis (1977) performed a study which included characterization of particulate solids from street surface contaminants on a catchment in London, England. He reported that particle sizes of TSS from street surfaces ranged between 10 micrometers to 10,000 micrometers, although 90% of the TSS had grain sizes less than 100 micrometers.

Laboratory tests were conducted at Florida Tech on sediment samples extracted from a sediment box in Indialantic, Florida. A small hand held siphon plunger pump, with tubing, was inserted into the box through the manholes to extract the samples. Three samples were obtained from each chamber of the sediment box. These samples were dried by placing them in pans and exposing the pans to sun light; the samples were not oven dried to ensure retention of organics during the drying process. Sieve analyses were performed on the dried samples using a set of 7 sieves with openings varying from 2 mm to 0.075 mm. The particle size distribution graphs from the sieve analysis results for each chamber of the box are shown in Figure 1.5. These graphs indicate that coarser particles tend to settle in the compartment nearest to the inlet pipe while the finest particles settle in the compartment farthest from the inlet pipe.

Sieve analysis results on the sediments trapped in the Indialantic sediment box tend to indicate that a large percentage of the sediments trapped are much larger in size compared to the TSS sizes typically found in the literature (5 to 80 micrometers). For example, only 20% of the particles trapped by Chamber III (Figure 1.5) are less than 0.1 mm(100 micrometers). This could be due to the following reasons: 1) the sediment load from the Indialantic watershed consists primarily of coarse particles, or 2) the sediment box is unable to trap much of the fine sediments in stormwater.

1.4.3 Density of TSS

Density of solids for most soils range from 2500 to 2800 kg/m3 (Holtz, 1981). Stahre (1990) performed a number of studies to determine particle densities of TSS in stormwater. His findings suggested that particle densities are most affected by particle size, the pH of water, and the content of heavy metals in water. The exact variation of density with these factors were not clarified. Stahre found that it helps to describe the variation in densities if the particles were separated into two groups, viz, light particles having densities of 1000 to 1160 kg/m3 and heavy particles having densities grater than 1160 kg/m3. Figure 1.6 illustrates how the density distribution varies with particle size for the two density groups. Figure 1.6 shows that the proportion of heavier density particles declines with increasing particle size, and the proportion of lighter particles increase with particle size. In general, Stahre's (1990) findings conclude that light particles in stormwater have an average density of 1300 kg/m3. This shows that the suspended particles are only slightly denser than water which has a density of 1000 kg/m3 at a temperature of 20 degrees Celsius. One reason for the relatively small densities could be the presence of organics in the suspended solids. Similar total suspended solids (TSS) particle densities were reported by Bondurant et al. (1975).

Laboratory tests were conducted, at Florida Tech, on samples extracted from the sediment box in Indialantic, Florida, to determine the density of solids. Samples used for sieve analysis (described earlier) were saved and used for density tests. Tests were conducted on samples from all the chambers according to the procedure outlined in Das (1989). Samples were de-aired in the volumetric flask using an aspirator. Densities were computed by measuring the volume of water replaced by a known-weight of dry sediment. Results obtained from these tests are summarized in Table 1.4.

Table 1.4: Density of Sediments for Samples Obtained From Sediment Box in Indialantic, Florida.

Chamber #	Density(kg/m3)
Chamber I (closest to inlet)	2680
Chamber II	2570
Chamber III (farthest from inlet)	2380

The density of sediments for the sample from the box, as shown in Table 1.4, are on the higher side when compared to the findings of Stahre (1990) and Bondurant et al. (1975). This could be attributed to either, or both, the following reasons: 1) the watershed contributing to this box consists primarily of medium to coarse sand, and 2) the inability of the box in trapping light particles associated with stormwater. The presence of a large proportion of organics in the samples, as was visually observed during the tests, could have reduced the density to the lower end of the density range for sands.

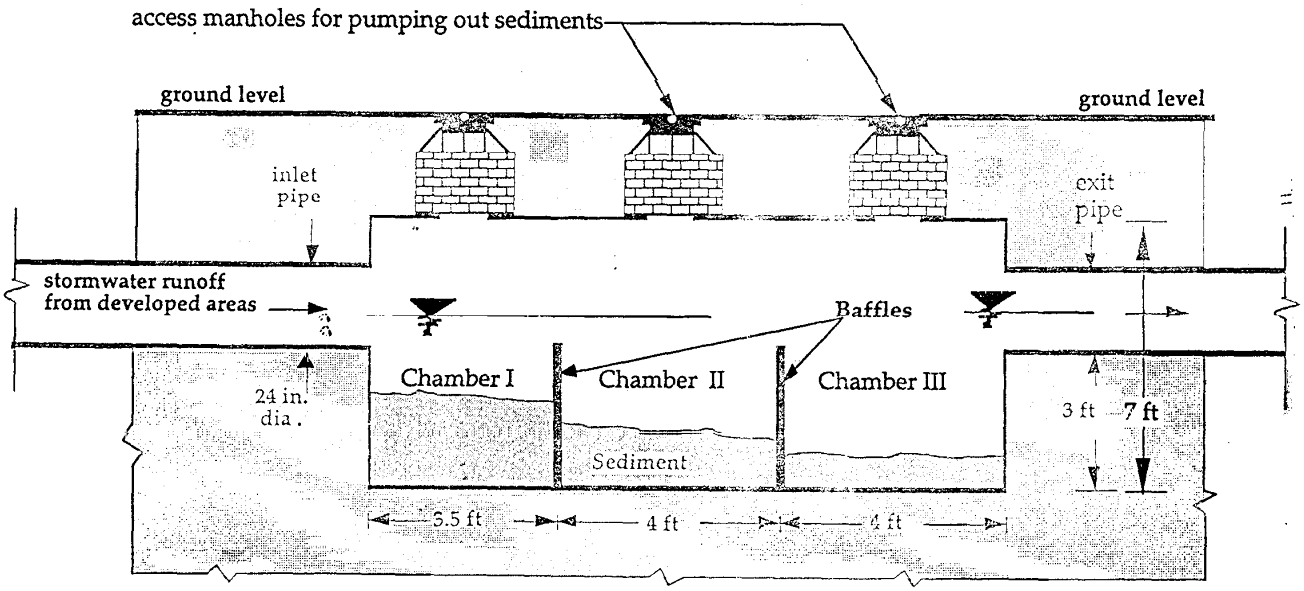

Figure 1.1: Elevation View of a Sediment Box Used for Removing Sediments from Stormwater

Chapter 4

DESIGN OF EXPERIMENTS

It was expected, based on literature reviewed, that the removal efficiency of the sediment box would be dependent on the soil properties (particle size distribution, particle density etc.), the inflow sediment concentration, volumetric flow rate, and the inlet (or entrance) velocity. It was also possible that the efficiency was a function of the duration of the experiment since the efficiency of the box could decrease or increase with time as the box began to fill up with sediments. Therefore, experiments were designed with emphasis on these parameters..

4.1 Sediment Modeling Materials

Eight soils, or materials representing soils, such as Rounded Sand, ASTM 20-30 Silica Sand, Light Weight Aggregate, Yellow Silica Sand, Fly Ash and Sandy Clay were considered for testing. Particle size distribution of these materials were determined in the laboratory using sieve analysis and the resulting curves are shown in Figure 4.1. Some significant properties such as density, specific gravity, d50 (diameter of 50% finer by weight) and d9o (diameter of 90% finer by weight) are shown in Table 4.1. Sandy Clay and Fly Ash were selected for further testing since their particle size distribution graphs represented a wide range of soils. Particle size distribution curves of Sandy Clay and Fly Ash are shown separately shown in Figure 4.2. Photographs 4.1 and 4.2 show, the texture and color of Sandy Clay and Fly Ash.

4.2 Description of Experiments

A list of 24 experiments, described in Table 4.2, were designed to examine the effect of variables, such as inflow sediment concentration, volumetric flow rate, and entrance velocity, on the removal efficiency of the box. Table 4.2 also shows the corresponding values of the prototype flow rates and entrance velocities which were computed by Equations 2.4 and 2.3, respectively. The entire set of 24 experiments were performed for both fly ash and sandy clay, for a total of 48 experiments.

Experiments were. designed to have inflow sediment concentrations ranging from 50, 200, 500 and 1000 mg/l to simulate the range of TSS concentrations, listed in the literature.

Table 4.2 Design of Experiments: Model and Prototype Parameters

Exp #	Inflow Sediment Concentration	Duration of Experiment	Model Flow Rate		Prototype Flow Rate*		Model Entrance Velocity		Prototype Entrance Velocity*		Mass of Sediment Injected
	Cm mg/I	tm. minutes	Qm gpm	Qm liters/sec	Qp cfs	QP liters/sec	vm f t/s	vm m/s	vp ft/s	vp m/S	grams
I	50	60	5	0315	0.98	27.82	0.902	0.275	2.21	0.67	56.8
2	50	60	5	0.315	0.98	27.82	0.984	0.300	2.41	0.74	56.8
3	50	60	5	0.315	0.98	27.82	1.723	0.525	4.22	1.29	56.8
4	50	60	7	0.442	1.38	38.95	1.050	0.320	2.57	0.78	79.5
5	50	60	7	0.442	1.38	38.95	1.706	0.520	4.18	1.27	79.5
6	50	60	7	0.442	1.38	38.95	2.461	0.750	6.03	1.84	79.5
7	200	30	5	0.315	0.98	27.82	0.902	0.275	2.21	0.67	113.6
8	200	30	5	0.315	0.98	27.82	0.984	0.300	2-41	0.74	113.6
9	200	30	5	0.315	0.98	27.82	1.723	0.525	4.22	1.29	113.6
10	200	3Q	7	0.442	1.38	38.95	1.050	0.320	2.57	0.78	159.0
11	200	30	7	0.442	1.38	38.95	1.706	0.520	4.18	1.27	159.0
12	200	30	7	0.442	1.38	38.95	2.461	0.750	6.03	1.84	159.0
13	500	30	5	0.315	0.98	27.82	0.902	0.275	2.21	0.67	283.9
14	500	30	5	0.315	0.98	27.82	0.9&4	0.300	2.41	0.74	283.9
15	500	30	5	0.315	0.98	27.82	1.723	0.525	4.22	1.29	283.9
16	500	30	7	0.442	1.38	38.95	1.050	0,320	2.57	0.78	397.4
17	500	30	7	0.442	1.38	38.95	1.706	0.520	4.18	1.27	397.4
18	500	30	7	0.442	1,38	38.95	2.461	0.750	6.03	1.84	397.4
19	1000	30	5	0.315	0.98	27.82	0.902	0.275	2.21	0.67	567.8
20	1000	30	5	0.315	0.98	27.82	0.984	0.300	2.41	0.74	567.8
21	1000	30	5	0.315	0.98	27.82	1.723	0.525	4.22	1.29	567.8
22	1000	30	7	0.442	1.38	38.95	1.050	0.320	2.57	0.78	794.9
23	1000	30	7	0.442	1.38	38.95	1.706	0.520	4.18	1.27	794.9
24	1000	30	7	0.442	1.38	38.95	2.461	0.750	6.03	1.84	794.9

*corresponding values in the full size sediment box (Fig. 1.1), based on which the model was scaled, computed using Froude Number modeling theory

5.2 Coarse Sediments

The results of the 24 experiments performed on Sandy Clay are shown in Table 5.2 and Table 5.3; these tables show the mass of sediment trapped by each chamber, the removal efficiency of each chamber, and the overall removal efficiency of the box for each experiment. Average efficiency of each chamber, and the average overall removal efficiency, for experiments performed with the same concentration and flow rates are also shown in Tables 5.2 and 5.3. Several averages, for example, average chamber removal efficiencies for Experiments 1 to 3 and Experiments I to 6 etc. are also shown in these tables.

.The effect of baffles in removing sediment, in the experiments with Sandy Clay, is shown in Photographs 5.1 to 5.3. It was observed during the experiments that the finer soil particles enter the box fairly quickly while the coarse particles remain in the pipe for a longer duration. Some of the fine particles hit the first baffle and slide downwards (Photograph 5.1), while others escape to chambers II and III. (Photographs 5.2 and 5.3). A fraction of these particles hit the bottom of the chamber and get trapped while others recirculate upwards. The same phenomenon occurs in all the chambers. The coarse particles, on the other hand, roll along the entrance pipe and fall into chamber I, near the entrance. This is especially visible Photograph 5.2. As a result of this a mound of coarse particles could be observed in Chamber 1, close to the entrance pipe, at the end of most experiments. At higher entrance velocities (such as in Experiments 6, 12, 18 and 24), a large fraction of coarse particles escaped Chamber I and were trapped in Chambers II or III.

5.2.1 Average Efficiencies

The overall removal efficiency and chamber removal efficiencies, for each experiment, are shown in Figure 5.2. By examining the individual chamber removal efficiencies of Experiments 1 to 3, 4 to 6, 7 to 9 and 10 to 12 it can be observed from this figure that the removal efficiency of Chamber I decreases at higher entrance velocities, although not by much when Cm=1000 mg/l. Similarly, one can observe that the removal efficiencies of chambers H and III increase at higher entrance velocities. This is primarily because particles not removed by Chamber I are now removed in chambers II and III. Furthermore, observing the overall efficiencies for same sets of experiments shows that the overall removal efficiency decreases at high entrance velocities when sediment concentrations are 50 mg/l. At high inflow sediment concentrations (200 mg/l to 1000 mg/1) the overall efficiency is not greatly affected by entrance velocity,

'The average removal efficiencies, for chambers I, II and I[II, were 65.3%, 2 1.8% and 2.6% respectively, and the average overall efficiency for the 24 experiments was found to be 89.8%. The normality of the data was checked by plotting the respective efficiencies against the standard normal deviates (Figures A4 to - A.7). Sample computations for the data needed to plot Figure AA are shown in Table AA. The straight line variation in all these graphs establishes the closeness of the data sets to a normal distribution. The 95% confidence limits for the means were again computed by using the student t-distribution. The summary of the statistical computations are shown in Table 5.4

5.2.2 Efficiency (Em) versus Inflow Sediment Concentration (Cm)

The variation of overall efficiency, and the efficiency of each chamber, with, the inflow sediment concentration of Sandy Clay is shown in Figure 5.3. Each data point on the graph represents the average of 6 experiments performed for the same concentration. These average values were computed in Tables 5.2

and 5.3. The best, fit equations based on linear regression analysis and their respective coefficients of determination, r2, are:

Em(O) = 89.78 - 3.5 x 10-3 Cm (r2 = 0.001)
Em(l). = 64.24 + 2.4 x 10-3 Cm (r2 = 0.85)
Em(II) 2.31 + 7.3 x 10-4 Cm (r2 = 0.78)
EM(III) 23.22 - 3.1 x 10-3 Cm (r2 = 0.84)

Table 5.4: Summary of the Statistical Computations on the Results of 24 Experiments Performed Using Sandy Clay

Parameters	Overall Efficiency	Chamber I Efficiency	Chamber II Efficiency	Chamber III Efficiency
Mean Efficiency	89.8	65.3	21.8	2.6
Standard Deviation (+/-)	2.3	14.1	11.6	1.8
Upper 95% Confidence Limit	90.7	71.2	26.7	3.4
Lower 95% Confidence Limit	88.8	59.3	17.0	1.9

and the resulting curves are shown in Figure 4.1. Some significant properties such as density, specific gravity, d50 (diameter of 50% finer by weight) and d9o (diameter of 90% finer by weight) are shown in Table 4.1. Sandy Clay and Fly Ash were selected for further testing since their particle size distribution graphs represented a wide range of soils. Particle size distribution curves of Sandy Clay and Fly Ash are shown separately shown in Figure 4.2. Photographs 4.1 and 4.2 show the texture and color of Sandy Clay and Fly Ash.

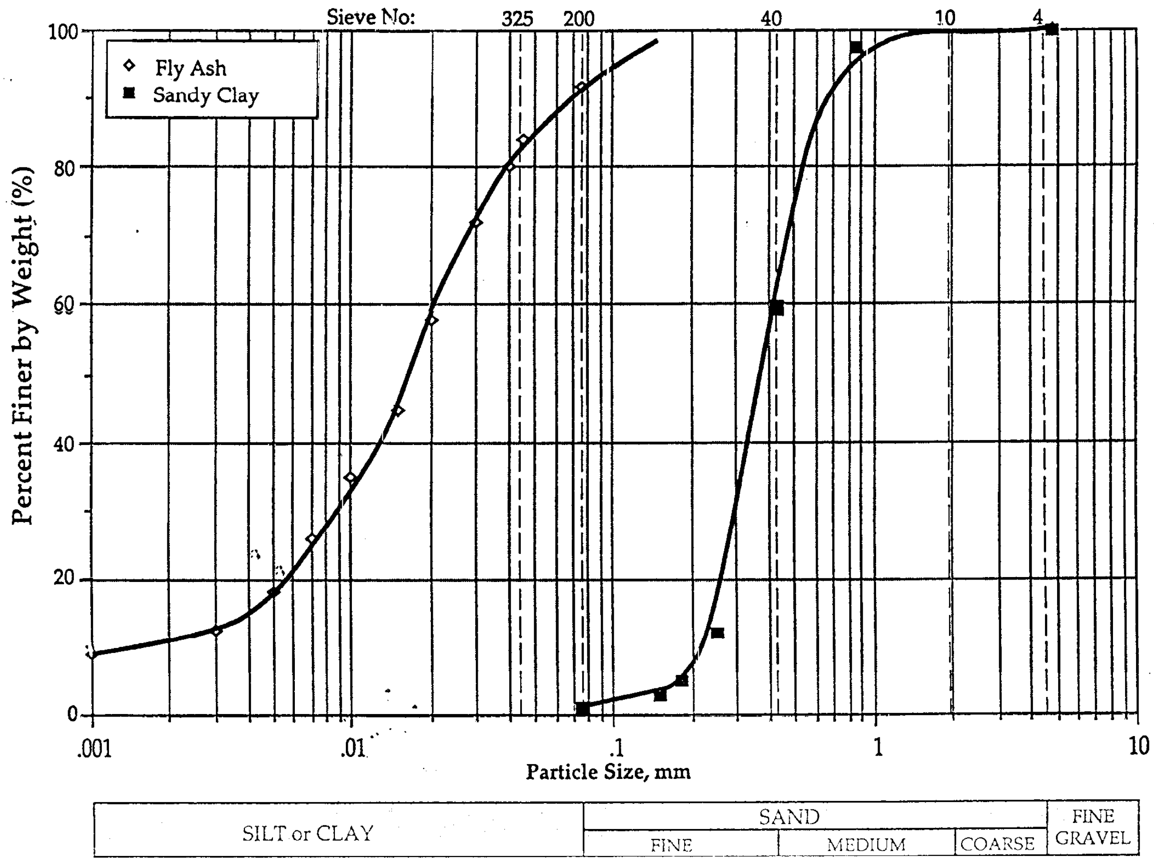

Figure 4.2: Grain Size Distribution Curves of Chosen Sediments for Model Study.

5.3 Fine Sediments

The results of the 24 experiments performed on Fly Ash are shown in Tables 5.5 and 5.6; these tables show the mass of sediment trapped by each chamber, the removal efficiency of each chamber, and the overall removal efficiency of the box for each experiment. Average efficiency of each chamber, and the average overall removal efficiency, for experiments performed with the same concentration and flow rates are also shown in Tables 5.5 and 5.6. Several averages, for example, average chamber removal efficiencies for Experiments 1 to 3 and Experiments 1 to 6 etc. are also shown in these tables.

The effect of the baffles in removing fine sediments is shown in Photographs 5.4 to 5.7. It is clear from these photographs that the particles of fly ash slide down the baffles upon hitting them. While some of these particles remain trapped, others are caught in an upward current and begin a recirculation process. The effect of recirculation on the removal efficiency of fine sediments could not be determined through experiments but it is apparent that it could be a significant factor.

5.3.1 Average Efficiencies

The overall removal efficiency and chamber removal efficiencies, for each experiment, are shown in Figure 5.6. By examining the individual chamber removal efficiencies of Experiments 1 to 3, 4 to 6, 7 to 9 and 10 to 12 it can be observed from this figure that the overall removal efficiency decreases at higher entrance velocities. A corresponding decrease can be observed in the chamber I removal efficiency.

The average removal efficiencies, for chambers I, II and III, were 10.8%, 9.9% and 7.1% respectively, and the average overall efficiency for the 24 experiments was found to be 27.8%. The normality of the data was checked by plotting the respective efficiencies against the standard normal deviates (Figures A.8 to A.12). The straight line variation in all these graphs establishes the closeness of the data sets to a normal distribution, The 95% confidence limits for the means were again computed by using the student t distribution. The summary of the statistical computations are shown in Table 5.7.

5.3.5 Reduction in Capacity of the Sediment Box

Sediment Boxes, installed in the field, get filled up with sediments over a period of time. Periodically the sediments are pumped out through the manholes. As these boxes get filled up with sediments, the capacity of the chambers reduce and this could be factor that affects the removal efficiency of the box. To investigate the effect on removal efficiency of the box at 50% reduced capacity, the model was modified by raising the
bottom of all the chambers 76 mm (3.0 inches). The construction details of the box with 50% capacity is shown in Figure 5.10. A slug of red colored dye was injected in the box to check for any leaks below the acrylic plates (Photograph 5.8). Photographs 5.9, 5.10 and 5.11 show the removal mechanism of fly ash in box with reduced capacity. These photographs show that recirculation begins very early in Chamber I.

Six experiments were performed using Fly Ash, at inflow sediment concentration of 200 mg/l, on the model box at 50% reduced capacity. The results of the 6 experiments are shown in Table 5.8. Table 5.8 shows the mass of sediment trapped by each chamber, the removal efficiency of each chamber, and the overall removal efficiency of the box for each experiment. Average efficiency of each chamber, and the average overall removal efficiency, for experiments performed with the same concentration and flow rates are also shown in Table 5.8. Average efficiency for each chamber, and the overall removal efficiency, for

experiments performed with the same flow rates are as shown in this table.

Figure 5.11 compares the overall efficiency of the box for the six experiments with 50% reduced capacity, with the overall efficiency of the box for the same experiments at full capacity. The trend, observed earlier for the experiments on full capacity, were reflected in the experiments on reduced capacity; overall efficiency reduced at higher entrance velocities. Comparison of the same experiments using the full capacity box and reduced capacity box show that there was a reduction in overall efficiency as the capacity was reduced by 50%, which varied from about 2% to 7%.

Chapter 6

RESULTS & ANALYSIS WITH NEW DESIGNS

6.1 Background

Some new baffle box designs, with two, three, four and five chambers, were also tested and their efficiency in removing Fly Ash as well as Sandy Clay were experimentally determined in the laboratory. A new sediment box was constructed to allow experimentation with four or five chambers. This new box had the exact inner and outer dimensions of the previous box. Four baffles could be placed at equal distances within the box creating five chambers 105 cm long.

6.2 Removal Efficiencies with Two Chambers

Two chambers were created by either removing the first baffle (the baffle closest to the entrance pipe) or the second baffle (the baffle closest to the exit pipe) from the standard three chamber box described earlier,

6.2.1 First Baffle Removed

Removal of the first baffle created a 381 cm chamber near the inlet pipe and a 203 cm chamber adjacent to the exit pipe. Six experiments, Experiments 7 through 12, were repeated with this design using fly ash and two experiments, Experiments 7 and 8, were also conducted with coarse sand. The sediment box removal efficiencies during these experiments are shown in Table 6.1. Comparisons of removal efficiencies for Fly Ash with those found with the standard three chambers (Table 5.5), shows that removal of the first baffle caused a reduction in removal efficiencies under all flow conditions, and the mean removal efficiency reduced by approximately five percent. Comparisons of removal efficiencies for Sandy Clay with those found with the standard three chambers (Table 5.2), shows that removal of the first baffle caused a reduction in removal efficiencies during Experiment 7 but an increase in removal efficiency during Experiment 8.

6.2.2 Second Baffle Removed

Removal of the second baffle created a 178 cm chamber near the inlet pipe and a 406 cm chamber adjacent to the exit pipe. Six experiments, Experiments 7 through 12, were repeated with this design using fly ash and two experiments, Experiments 7 and 8, were also conducted with coarse sand. The sediment box removal efficiencies during these experiments are shown in Table 6.2. Comparisons of removal efficiencies for Fly Ash with those found with the standard three chambers (Table 5.5), shows that removal of the second baffle caused a reduction in removal efficiencies at lower entrance velocities (Experiments 7, 8, 10, and 11) but the removal efficiency increased slightly at higher entrance velocities (Experiments 9 and 12). Comparisons of removal efficiencies for sandy clay with those found with the standard three chambers (Table 5.2), shows that removal of the second baffle caused a slight increase in removal efficiency during Experiments 7 and 8. Comparisons of the results shown in Tables 6.1 and 6.2 indicates that the removal of the second baffle provides similar or better results under the flow conditions tested in the experiments.

6.3 Removal Efficiencies with Four Chambers

Four chambers were created by placing only three baffles in the new box. Experiment 7 was conducted twice in the new sediment box; first after removing the baffle closest to the exit pipe (Experiment 7a), and then after removing the baffle closest to the in-let pipe (Experiment 7b). Thus, in Experiment 7a, the sizes of the four chambers (Chamber 1 being closest to the inlet pipe) Were 105 cm, 105 cm, 105 cm, and 210 cm, respectively, while in Experiment 7b, the sizes of the four chambers (Chamber 1 being closest to the inlet pipe) were 210 cm, 105 cm, 105 cm, and 105 cm, respectively. The sediment box removal efficiencies during these experiments are shown in Table 6.3. Comparisons -of removal efficiencies for Fly Ash with those found. in previous experiments showed that they were similar to those found With two chambers (Tables 6.1 and 6.2) but slightly lower than those with standard three chambers (Table 5.5). The removal efficiency in Experiment 7b, in which Chamber 1 was longer than the other chambers, was slightly higher than in Experiment 7a.

6.4 Removal Efficiencies with Five Chambers

Five chambers. were created by placing all four baffles in the new box, thus creating five 105 cm chambers. The sediment box removal. efficiencies during these experiments are shown in Table 6.4. Comparisons of removal efficiencies for Fly Ash with those found in previous experiments showed that they were slightly higher to those found with two chambers and four chambers but lower than those with standard three chambers.

6.5 Removal Efficiencies with Three Chambers

The removal efficiency of the sediment box improves presumably because sediment strikes the baffles and slides down thus getting trapped. It was surmised that raising the height of the baffles would, therefore, cause more sediment to be trapped within the box. In all of the previously described experiments, the height of the baffles was 152 cm coinciding with the height of the inlet pipe. However, in the following experiments, Experiments 7 and 8 were repeated by raising the baffles to coincide with the center line of the inlet and exit pipes. These experiments were conducted with two baffles and three chambers; first by raising the baffle closest to the inlet pipe (the other baffle remained at its normal height), and second by raising only the baffle closest to the outlet pipe. In general, it was noticed that raising the baffles caused the water level in the inlet pipe and the box itself to rise.

6.5.1 First Baffle Raised

Experiments 7 through 12, were repeated with this design using Fly Ash and the measured removal efficiencies are shown in Table 6.5. Raising .the baffle left a gap at the bottom of the baffle and allowed sediment to enter Chamber 2 from the bottom of Chamber 1. Comparisons of removal efficiencies for Fly Ash with those found, with the standard three chambers (Table 5.5), shows that raising the baffle caused a slight reduction in removal efficiencies at lower entrance velocities (Experiments 7, 8, 10, and 11), and a slight increase in removal efficiencies at higher entrance velocities (Experiments 9 and 12). More Fly Ash was trapped in Chamber 2 than Chamber 1 in Experiments 9 and 12.

6.5.2 Second Baffle Raised

Experiments 7 and 8 were repeated with this design using both Fly Ash and Sandy Clay, and the measured removal efficiencies are shown in Table 6.6. Raising the baffle left a gap at the bottom of the baffle and allowed sediment to enter Chamber 3 from the bottom of Chamber 2. In all of the raised baffle experiments conducted with Fly Ash, a considerable amount of sediment was observed moving through the bottom of the baffles into the adjacent chamber. Comparisons of removal efficiencies for Fly Ash with those found with the standard three chambers (Table 5.5), shows that raising the baffle caused a reduction in removal efficiencies. More Fly Ash was trapped in Chamber 2 than Chamber 1 in Experiments 9 and 12. On the other hand, comparisons of removal efficiencies for sandy clay with those found with the standard three chambers (Table 5.2), shows that raising the baffle caused an increase in removal efficiencies. Raising the second baffle caused all three chambers to remove fly ash in an equally efficient manner. This could be important because it Would allow all three chambers to fill at an equal rate and may improve the long-term (over a combination of several storms) removal efficiency of the sediment box.

Chapter 7

CONCLUSIONS & RECOMMENDATIONS

7.1 Conclusions

The objective of this study was to determine the sediment removal efficiency of a typical three chamber sediment removal box under a variety of flow conditions using a hydraulic model of a sediment box 3.51m. x 2.13m x 2.13m. The study was conducted on a hydraulic scale model which had a scale ratio, Lr, equal to six. Two soils, Fly Ash and red "baseball" sand or Sandy Clay were selected to respectively represent the fine and coarse sediments found in stormwater runoff. Twenty four experiments each were performed using sandy clay and fly ash for a total of 48 experiments to investigate the removal efficiency of the box under various field conditions. An additional thirty experiments were conducted to test new designs or modifications in the existing design, and six experiments were conducted to test a shallower sediment box 3.51m x 2.13m x 1.06m.

The following conclusions may be drawn from the experiments performed on the model sediment removal box.

1. Experiments repeated under identical flow conditions showed consistent results. Experiment number seven was repeated six times with fly ash and the removal efficiencies were measured in the narrow range of 33.3% to 34.1%.
2. Removal efficiencies of the box, for coarse sediments ranged from 86% to 96% with an average removal efficiency of approximately 90%

3. Removal efficiencies of the box, for fine sediments ranged from 26% to 30% with an average removal efficiency of approximately 28%.

4. Removal efficiency of the box for coarse sediments remained fairly constant even when the inflow sediment concentration was raised from 50 mg/l to 1000 mg/l. For fine sediments. the removal efficiency increased with inflow sediment concentration indicating that the box will remove "dirty" water more efficiently than "clean" water if the sediment consists of fine particles.

5. Removal efficiency of the box for coarse sediments reduced marginally as the entrance velocity was increased. For fine sediments the removal

efficiency of the box reduced significantly as the entrance velocity was increased.

6. Experiments performed by raising the bottom of the box to simulate a shallower box showed reduction in efficiency of about 2% to 5% when compared to the same experiments with the normal size box. These results may also be interpreted as follows: as the box gets filled with sediments and the box capacity reduces by half, the removal efficiency reduces. This phenomena could also be visually observed as the raised bottom caused more recirculation within the chambers
7. Coarse sediments get trapped in the pipe at relatively low velocities; however, they are flushed out when the next "storm" is simulated.
8. A hydraulic jump forms just upstream of the entrance at high velocities which may be expected during intense storms. The hydraulic. jump helps in mixing the sediments. and flushing the pipe.
9. Baffles appear to play a key role in sediment removal. Sediment hits the baffle and drops down. Some sediment is, however, lost due to recirculation within the chambers This is especially true with fine sediments.

10. Removal efficiencies measured with new designs were not significantly higher or lower than the existing design. However, further improvements which can reduce recirculation of sediment within chambers can probably improve the removal efficiencies especially in the case of fine sediments.

7.2 Recommendations for Further Investigation

1. New designs, or design modifications, which can cause a reduction of recirculation within chambers should be tested under high flow rates and entrance velocities with fine sediments such as Fly Ash.

A thorough understanding the flow patterns within the box would enhance the understanding of the sediment removal process and ,provide ideas for reducing recirculation within chambers. The flow patterns inside the box may be investigated by, developing velocity profiles at different locations using laser doppler velocimetry technique

3. Experiments may be performed by changing the baffle configuration, viz. increasing /decreasing the number of baffles, and changing the spacing between the baffles. This will help in identifying the optimum number of baffles and optimum baffle spacing for an improved