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ELIMINATING SCOUR AND EXCESSIVE VOLUMES IN SETTLING TANKS USING INCLINED PLATES

by

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This thesis is dedicated to my family and husband

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ABSTRACT

The main objective of this study was to compare the total suspended solids (TSS) removal efficiency of a modified sedimentation tank to that of a conventional tank. The experimental tank was designed for flow to pass over a series of inclined plates. It had a much shallower flow through zone and the inclined plates were situated just below this zone. The inclined plates were added to provide a quiescent settling zone for the falling particles and to act as a barrier to prevent scour of settled particles. A conventional horizontal flow sedimentation tank was also used in this study. The two designs were run in parallel and a highly concentrated clay suspension was passed through both tanks. The TSS concentrations of both the influent and effluent streams were measured. The response of both designs to different parameters such as sampling time, depth over the inclined plates, flowrate, inclined plates spacing and inlet TSS concentration was observed. The tank with the inclined plates (at the smallest spacing) proved to have an equal to slightly higher removal efficiency and a slightly better reaction to the change of parameters. This tank also proved to have less dead volume than the control tank. Since the reduction in flow through volume proved to be as good and slightly better than the control tank, the concept deserves further research. It has the potential to permit considerable tank depth reductions while retaining efficiency.

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GLOSSARY

a	plan area, m^2
A	cross-sectional area, m^2
A_t	area required for thickening, m_2
C	capacity, lb/ft^2-h
C_i	rhodamine WT dye concentration of stream at a certain time, mg/L
C, C_1, C_2	total suspended solids concentration in specified stream, mg/L (1 - influent stream, 2 - effluent stream)
C_u	underflow concentration, mg/L
d	depth, m
D	diameter, m
d_n	depth between isoremoval curves, mm
D_p	consistency of discharge pulp, ft^3/lb
d_t	total depth, mm
d_x	depth of interface, mm
F	initial pulp consistency, ft^3/lb
Fr_i	densimetric Froude number, [0]
$F(V_s)$	velocity distribution
g	acceleration of gravity, 9.8 m/s^2
h, h_i	depth of water (i - at inlet), m
H_i	total height of liquid in column at time of sampling, mm
H_o	initial liquid level in column, m
H_p	height of the sampling port, mm
P	perimeter, m
Q	flowrate, L/min
Q/A	upflow rate, m^3/m^2d
R	settling rate, ft/h
Re	Reynolds number, [0]
R_h	hydraulic radius, m
R_n, R_{n+1}	removal percent of isoremoval curve n or n+1, %
S	particle flux, kg/m^2-h
s.g.	specific gravity of solid particles in suspension, [0]
t_d	detention time, min
t_i	elapsed time, min
t_u	time required to reach desired underflow concentration, hr
U	average underflow velocity caused by removal of sludge, m/s
v	flow velocity, m/d
V	volume, m^3
V_i	settling velocity of solids of concentration C_i, m/s
V_o	overflow rate, m/s
V_s	particle settling velocity, mm/min

w	total amount of sediment held in suspension per unit horizontal area, mg/m^2
θ	relative overflow rate, [0]
ξ	dimensionless height, [0]
φ	fractional density difference, [0]
ρ_i	density of influent suspension, kg/m^3
ρ_t	density of water in basin, kg/m^3
ρ_r	density of water, 1 kg/m^3
μ	viscosity, kg/m-s

CHAPTER 1

INTRODUCTION

Sedimentation involves the removal from water of suspended particles, by gravity. Sedimentation basins or clarifiers are an integral part of any water and wastewater treatment plant and they have been used for over one hundred years. A secondary sedimentation basin for activated sludge consists of the last process before the effluent is released or discharged into a receiving body of water. Though the principle behind them is similar, their design has not changed significantly.

One of the first works published on sedimentation by Hazen in 1904 revealed that the removal of solids from a suspension depends upon the available surface area and is completely independent of the volume or depth of the basin. The majority of conventional clarifiers are presently designed using an upflow rate design criterion which takes this fact into consideration or using a detention time criteria which gives a resulting volume and does not specify area or depth.

Clarifiers can be rectangular with horizontal flow or circular where an upflow pattern results. Most common circular basins have a diameter ranging from 10 to 40 m, some can be as large as 60 m (Metcalf & Eddy, 1991). The feed to the circular basins can be located at the center or around the perimeter and the incoming stream's energy is dissipated by baffles. The influent discharge is a submerged jet and is either located at the bottom or directed towards the bottom. The design assumes that the entire volume of the basin is used and that the flow disperses uniformly over the entire surface area of the clarifier to then rise upward. It is finally collected in overflow weirs or launders located along the top perimeter. Sludge collection mechanisms comprise either a rotating sludge scraping arm directing the sludge to the bottom sludge collection hopper or of a series of pipes using suction to collect the settled sludge.

Rectangular basins typically have the influent entering the basin at the inlet end and horizontally flowing to the opposing end of the basin to the outlet. Energy dissipation devices such as baffles are located at the inlet end. The flow has to travel through the length of the basins. Lengths can measure up to 90 m (Metcalf & Eddy, 1991). There is less chance for short-circuiting problems in rectangular basins (WPCF, 1985) however the flow does not necessarily utilize the available depth or width of the basin. Sludge removal can either be accomplished by a chain and flight mechanism that scrapes the settled sludge to the sludge collection hopper or a traveling bridge unit that either scrapes or suctions the sludge.

Both circular and rectangular basins can be used as secondary clarifiers. Circular upflow clarifiers are the most frequent choice. This study's major focus was on secondary clarification for activated sludge streams or other highly concentrated suspensions.

The conventionally designed rectangular and circular basins are very expensive because of real estate and construction costs. They are usually very large and deep. They are being designed larger and deeper to ensure good treatment end results and compliance to set regulations. This increase in size and depth may not be necessary to rectify improper flow distribution or hydraulic conditions. Short-circuiting and dead volume reduce a basin's efficiency by decreasing the utilization of the surface area of the basin. Increasing the depth of the basin allows the flow to ultimately distribute over the surface area. The addition of excessive depth to combat flow problems is costly. To utilize the design criterion of increasing the available surface area to increase the removal efficiency becomes an inappropriate solution when only a fraction of the entire available surface area is not completely utilized.

The assumption that the flow is evenly distributed over the entire available surface area becomes untenable when the actual flow pattern is monitored with a tracer. The influent jet of a center feed clarifier seems to be directed radially outward along the clarifier bottom. At the side walls, the flow moves upward. Actual hydraulic conditions in settling basins have been modeled to behave as described above through hydrodynamic analysis (McCorquodale et al., 1988). This problem reduces the basin's efficiency. This flow behavior produces an additional problem of settled solids resuspension or scour along the basin bottom. The following diagram displays the actual observed hydraulic behavior.

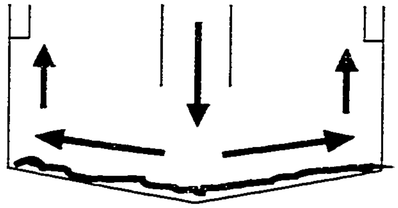

Figure 1.1 Common flow pattern in conventional clarifiers

This particular flow pattern causes practical problems. The flow is confined to a relatively shallow zone above the basin floor. The flow then has a greater velocity and becomes turbulent. The turbulence reduces the effective settling velocity of the particles in the suspension. This turbulence along the clarifier bottom also causes the resuspension of settled particles in the sludge blanket. These are clearly realistic drawbacks for sedimentation basins.

Several variations on design have been applied to improve the removal efficiencies, to increase the hydraulic loading, to reduce turbulence and resuspension and to reduce the size and cost of the basins. Such variations include tube and lamella clarifiers. The flow in these types of basins is directed through a series of long parallel tubes or plates (lamella). They are based on the principle that removal efficiency depends on available surface area and they do reduce turbulence. These tubes and lamella significantly increase the available surface area. The problem with these devices is that no concrete solution to the question of clogging of the tubes or plates by biological growth has been found. The clarification of highly concentrated biological streams such as activated sludge is prone to such clogging problems.

Research to improve sedimentation basin design and performance has been ongoing for almost a century. The research in this thesis has focused on using this short-circuiting problem as part of the solution. It eliminates the wasted basin volume and places the remainder of the volume to better use. The potential elimination of wasted volume could reduce construction costs significantly.

Basin configuration modifications to overcome these problems were tested in this research. The purpose of the investigation was to evaluate the usefulness of adding inclined parallel plates in the settling zone of a rectangular sedimentation basin. The flow was directed horizontally above the zone containing inclined plates. No reduction in turbulence is gained in the flow through area compared to actual conditions in conventional clarifiers. Flow was not expected to move through the plates.

The advantage of directing the flow over the plates was to let solids settle into the confines of the plates and not subject them to scour or turbulence. The plates provide a quiescent settling zone and prevent any currents from forming along the bottom of the basin that could cause scour. The plates also create a barrier and prevent the particles which are lifted upwards from reaching the moving water above and being carried away to the effluent stream. The proposed modifications do not simulate a lamella or a tube clarifier. The plate spacing for this suggested configuration is much larger than the spacing between lamella in lamella clarifiers and the diameters of tubes in tube clarifiers. The flow is directed over the plates as opposed to through them as in lamella or tube clarifier configurations.

Since the flow is confined to the top layer of the basin over the inclined plates, the flow is more turbulent. A balance must be found between the negative effects of a turbulent more shallow layer of flow on settling and the scour of settled solids. Turbulence is already present in conventional clarifiers and scouring is often a result. The primary purpose of the inclined plates is to reduce or prevent scour and permit the tank to have an efficiency equivalent or better than a conventionally designed clarifier and help to fully utilize the precious available surface area.

The modified experimental basin had a rectangular shape and thus provided additional advantages. A rectangular geometry is less expensive to construct and requires less land than a circular geometry. The flow distribution in a shallow rectangular depth is more readily accomplished than flow distribution in a much deeper basin. The performance of this modified clarifier should equal or surpass that of conventional clarifiers.

The study compares the efficiency of a control sedimentation basin to that of an experimental set-up. The control basin will simulate current conventional clarifier design. The experimental basin will include the above-mentioned modifications to the conventional clarifier design.

The main objectives of this research include:

- determining the relative removal efficiency difference between a conventionally designed basin and basins including parallel inclined plates,

- determining the effect of the flowrate, the influent total suspended solids (TSS) concentration, the number of inclined plates, and the depth of flow on both the control and the experimental basins' removal efficiencies,

- determining the effect of the influent stream TSS concentration on the effluent TSS concentration,

- determining the fraction of the volume actually utilized in both basin configurations or which basin has less wasted volume,

- determining whether the proposed sedimentation basin modifications are beneficial, whether they enable the basin to give an equal or better solids removal efficiency and if a reduction in basin size is possible.

This research is to be carried out experimentally as opposed to a hydrodynamic modeling exercise. Experiments compare the experimental basin design's behavior with that of a control. Many uncontrollable factors are involved in sedimentation experiments of this size that necessitate a laboratory study.

CHAPTER 2

LITERATURE REVIEW

Sedimentation basins are one of the oldest methods available to separate solids from liquids. They are still one of the most commonly used processes in the fields of water and wastewater treatment. For this reason, it is important to review the early research. This will explain why and how sedimentation basins have changed. Most designs today still use concepts formulated several decades ago.

In 1904, Hazen published one of the first studies on sedimentation. Hazen's analysis showed that the settling of particles from water depends on the available surface area and not volume. This was a very important fundamental result that remains true and is still utilized today. He also wrote that the depth of the basin, which will provide optimal results, is obtained when the solids containing influent is not mixed with the clarified effluent. This means that plug flow hydraulics would be preferred.

Hazen derived an equation for calculating the solids removal under the following conditions: discrete settling particles, a single solid particle settling velocity and no scour at the bottom of the basin. The equation is as follows:

$$r = \frac{V_s}{V_0} \qquad \text{when} \quad \frac{V_s}{V_0} \leq 1 \tag{2.1}$$

$$r = 1 \qquad \text{when} \quad 1 = \frac{V_s}{V_0}$$

where

where	r	removal
	V_s	particle settling velocity, m/s
	V_0	overflow rate, m/s

These assumptions enabled the solution of the problem but are often not applicable. The assumption that only a single particle settling velocity exists in a suspension is unrealistic and flocculation along with hindered settling usually occurs, especially in secondary clarifiers. His assumption that no scouring or settled particle resuspension was occurring is not appropriate. Scouring of solid particles is very much a problem today and it reduces a sedimentation basin's efficiency.

Hazen discussed his idea of an ideal sedimentation basin constructed with several superimposed horizontal trays at approximately an inch apart. With this concept, the surface area is increased, the depth in which the particles must settle is reduced which also increases the removal of solids in suspension. He concluded that this ideal basin, unfortunately, would have several logistic problems such as the settled sludge removal requirements being too frequent.

Hazen then concluded that best results would be obtained in plug flow conditions accomplished by dividing the basin in several compartments in series with baffles. The depth of the basin would then be sufficient to store settled sludge and sludge removal mechanisms.

Dobbins (1944) studied the sedimentation of discrete particles of uniform size in a stream with fully developed turbulence. He developed a general differential equation expressing the concentration changes during turbulent sedimentation in an infinitely wide stream. He also presented a solution for a simplified case. Turbulence complicates the problem, the analysis of secondary motion was combined with the analysis of coagulation phenomena.

In a sedimentation basin with horizontal flow, the suspended solids concentration increases toward the bottom of the basin. Settling particles create a downward flow. A flow in the opposing direction is then created for the less concentrated fluid. These opposing flows retard the rate of settling for the particles in the basin but increases the flocculation of particles. Turbulence will affect the upward flow carrying particles and lower the basin's efficiency and it will improve flocculation, increasing the basin's efficiency. The overall effect of turbulence, whether it will increase or decrease the basin's performance depends on the degree of turbulence and the relative magnitude of these effects. Only the negative effect of the upward flow is a factor in a discrete particle suspension.

Dobbins derived the following differential equation for sedimentation under turbulent conditions, discrete particle settling and confined to a two dimensional case corresponding to conditions of steady uniform flow in the central region of a wide channel.

$$\frac{dw}{dxdydz} = \varepsilon_y \frac{\partial^2 C}{\partial y^2} + \frac{\partial \varepsilon_x}{\partial y}\left(\frac{\partial C}{\partial y} + \frac{\partial^2 C}{\partial y^2}dy + \frac{\partial^2 C}{\partial x \partial y}\frac{dx}{2}\right) + \varepsilon_x \frac{\partial^2 C}{\partial x^2} + \frac{\partial \varepsilon_x}{\partial y}\frac{\partial^2 C}{\partial x^2}\frac{dy}{2} + w\frac{\partial C}{\partial y} - \left(v + \frac{\partial v}{\partial y}\frac{dy}{2}\right)\frac{\partial C}{\partial x} \tag{2.2}$$

where		
	w	total amount of sediment held in suspension per unit horizontal area, mg/m^2
	x	horizontal distance in the direction of the flow, m
	y	elevation above the surface of the bed material, m
	t	time of settling, s
	ε	kinematic turbulence coefficient, [0]
	C	concentration of sediment in suspension, mg/L
	v	horizontal velocity at a point, m/s

With several assumptions and boundary conditions, this equation can be solved and the concentration changes can be found. Dobbins solved this equation for a two dimensional case corresponding to the conditions of steady uniform flow in the central region of a wide stream and a solution with particles that have the same settling velocity under isotropic turbulence at a uniform initial concentration with no scouring. Therefore the assumptions include: steady state conditions, a velocity distribution following a parabolic law as opposed to a logarithmic law, no diffusion of suspended solids taking place in the x direction and V_s is constant throughout the depth. The concentration profile is as follows:

$$\frac{C}{C_0} = 4 \cdot Pe \cdot e^{Pe(1-\xi)} \sum_{n=1}^{\infty} \frac{\beta_n H_n Y_n e^{\frac{-(Pe^2+\beta_n^2)\theta}{2Pe}}}{(Pe^2 + \beta_n^2 + 2Pe)(Pe^2 + \beta_n^2)} \tag{2.3}$$

where $\xi = \frac{y}{h}$ (2.4) $\qquad Pe = \frac{V_s h}{2\xi_s}$ (2.5) $\qquad \theta = \frac{V_s}{V_0}$ (2.6)

$$2\cot\beta_n = \frac{\beta_n}{Pe} - \frac{Pe}{\beta_n} \tag{2.7}$$

$$H_n = \cos\beta_n + \frac{Pe}{\beta_n}\sin\beta_n \tag{2.8}$$

$$Y_n = \cos\beta_n x + \frac{Pe}{\beta_n}\sin\beta_n x \tag{2.9}$$

where:

C_0	concentration of sediment at t=0 and y=0, mg/L
h	total depth of fluid, m
β_n	proportionality factor, [0]
η	dimensionless height, [0]
θ	relative overflow rate, [0]

He concluded that experimental results followed those of the theoretical predictions quite closely.

The graph in Fig. 2.1 shows the removal ratios versus the kinematic turbulence coefficient for sedimentation generated by Dobbins' research. It shows that increasing turbulence has a decreasing effect on the removal ratio. As turbulence increases (or the kinematic turbulence coefficient decreases, moving to the left on the x-axis), the removal ratio decreases. As turbulence decreases (moving to the right on the x-axis), the removal ratio becomes equal to the ratio of the particle settling velocity and the upflow rate. A particle having a settling velocity greater or equal to the upflow rate will be removed. A particle having a settling velocity smaller than the upflow rate will be removed at a ratio equal to the ratio of its settling velocity divided by the upflow rate.

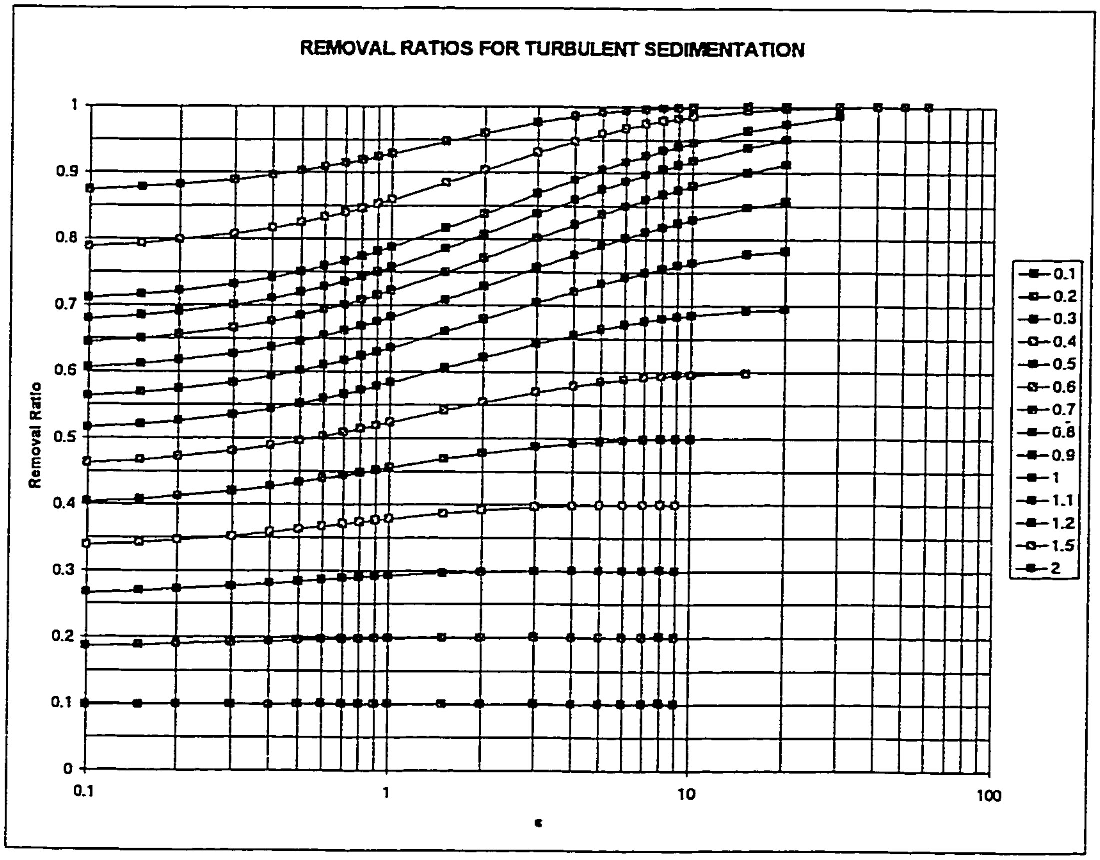

Figure 2.1 Removal ratios for turbulent sedimentation (the legend = V_s/V_o), (Dobbins, 1944)

The number values found in the legend of Fig. 2.1 represent the following expression:

$$\theta = \frac{V_s}{V_0} \tag{2.10}$$

Several conclusions were drawn from this work. One important conclusion states that the equilibrium concentration depends upon the amount of material available on the bottom up to the point of saturation and on the hydraulic conditions at the bed when the bottom is saturated with solids. Also, the equilibrium concentration at any level above the saturated bed is independent of the depth of fluid. If the bottom is saturated, for unsteady state, the rate of pick-up of solids is independent of the total amount of solids in suspension and depends only on the hydraulic conditions at the bed and the characteristics of the solids.

Dobbins extended Hazen's removal expression to include a suspension containing particles with different settling velocities. The removal for quiescent conditions of a suspension with many particle sizes which is more realistic and is as follows:

$$r = 1 - \frac{1}{V_0}\int_0^{V_0} F(V_s)\,dV_s \qquad (2.11)$$

where $F(V_s)$ settling velocity distribution

All the above mentioned removal equations assume ideal settling conditions and the maximum removal possible in these conditions. Actual settling in basins does not occur in ideal conditions. Therefore designs must reflect this non-ideal situation. The factors that affect ideal sedimentation are: flowrate, inlet TSS concentration, flocculation properties of suspension to settle, available surface area inlet baffling configuration, temperature of influent stream, density of influent stream and turbulence. When possible, these factors must be taken into consideration during the course of experimental research.

Camp (1946), brought together a compendium of known design principles on sedimentation basins. Several topics were covered. Once again, the fact that the removal of a solid in a suspension is a function of surface area and is independent of the depth of the bed or basin was mentioned. It also pointed out for a given overflow rate and fixed horizontal dimensions, the smallest depth possible without promoting scour should be chosen. This comment is very important. If one can significantly reduce scour in a basin by altering its configuration, the depth can be significantly reduced. It is then obvious that several advantages, including a reduction in cost would be incurred.

Short-circuiting is also mentioned in Camp's article (Camp, 1946). This phenomenon reduces the utilized surface area for sedimentation with a consequent reduction in overall solids removal. This is an unwanted predicament. Short-circuiting is brought on by high inlet velocity and temperature or density currents along with an ineffective inlet baffling configuration. If a different basin configuration can help minimize this effect, there would undoubtedly be increases in efficiency. A smaller basin depth would evidently reduce short-circuiting. Lateral movement would be restricted.

The conclusions of this article include a tentative sedimentation basin design based on all topics developed in the paper. It is similar to Hazen's initial suggestion in 1904. The suggested basin consists of several super-imposed horizontal trays with small height spacing. This configuration increases the total available surface area significantly and the depth is minimized. Short-circuiting is almost eliminated. The drawbacks to this proposed design are the tray spacing must be large enough to permit mechanical sludge removal and all other difficulties encountered involving cleaning of the trays. Obtaining a hydraulically stable flow distribution on all trays is also difficult.

Fisherstrom (1955) applied the tray settling principles with some success. In water treatment plants, he added reinforced concrete trays spaced at 5-6 feet intervals. He felt that a Reynolds number in the laminar flow range would be beneficial to solid particles settling. Horizontal trays have the following effects:

- decreasing the Reynolds number
- reducing the overflow rate
- reducing the distance through which a particle must drop
- decreasing the time to reach the bottom surface of the sedimentation basin

These effects all have obvious advantages. The size of sedimentation basins can thus be greatly reduced or a basin's loading can be increased. Cost and space savings are then incurred.

Fisherstrom considered that his tray configuration would require sludge removal and cleaning of the trays. He also felt that if the draining frequency exceeded once per week, it was too high for practical application. In addition, he argued that the quantity of water lost when draining would be too high if it occurred this frequently.

These types of sedimentation basins however, did not gain acceptance in the water and wastewater treatment industry. Hansen and Culp (1967) state that the reason for this resistance was due to unwillingness of design engineers to change their method of sizing and designing sedimentation basins. Shallow depth sedimentation with trays had a reputation of being well established theoretically; however, they still needed improvement on the practical application side. Such improvement was required for the flow distribution to the trays and again mechanical sludge removal between trays.

In 1967, Hansen and Culp applied the shallow depth sedimentation theory. They suggested using inclined tubes in basins. These tubes provide the same conditions as horizontal trays. Studies were conducted on different tube diameters [1.27 cm (1/2 in.), 2.54 cm (1 in.), 5.08 cm (2 in.), 10.16 cm

(4 in.)], lengths [0.61 m (2 ft), 1.22 m (4 ft), 2.44 m (8 ft)] as well as flowrates. Flow distribution problems were overcome with this basin configuration. Experimental tests showed that this configuration does provide shallow depth laminar flow conditions. It was found that the sludge did accumulate and clog the tubes. The sludge could be removed by periodically draining the tubes. This was made possible by slightly inclining the tubes (5°). They suggested that the tube cleaning take place at the same time as the backwash cycle of a following filter to avoid excessive water loss. It was suggested that a set of tubes can be added to existing sedimentation basins.

The apparatus used for the tube settling experiments included: a mechanical flocculator having a total volume of 307 L (81 gallons), a tube settler section and lastly a mixed media filter section. The tube settler section had a bottom inlet with a small open vertical channel that directed the fluid to the inlet of the tubes. The tubes were all attached together and oriented at an angle of 5° from the horizontal. The flow was forced to pass through the tubes. The outlet of the tubes directed the flow in another vertical channel open at the top. This led to the mixed media filter which had a pump draw off the bottom.

Hansen and Culp concluded that: "The tube settling process allows the long recognized advantages of shallow depth sedimentation to be applied in a practical manner." The drawback again was found in the fact that the tubes are difficult to clean and can clog when used with highly concentrated biological streams. These two problems depend on the conditions at hand for different situations. The following schematic displays the configuration of a tube clarifier. The direction of flow can be observed.

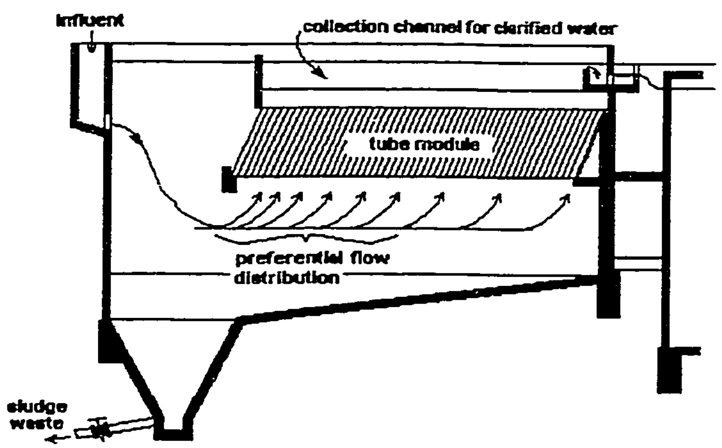

Figure 2.2 Tube clarifier

Lamella clarifiers have a configuration very similar to tube clarifiers. Instead of a tube module, a series of parallel plates separated by a few inches are added to the basin. The plates span the width of the basin and can have lengths similar to that of tubes.

Culp et al. (1968) performed a literature review on the subject. They concluded that the idea of inclined tube settlers was the best solution both practically and hydraulically. Laboratory scale, pilot scale and field tests demonstrated this method to improve the performance of conventional sedimentation basins at higher hydraulic loading. Full scale tests were conducted in an existing circular flocculator-clarifier at a water treatment plant. They installed several tube settler modules in this basin. These tests showed that the existing sedimentation basin's capacity had increased and its effluent quality had remained as good as it was before the addition of the tubes.

Yao (1970) studied high rate sedimentation. This refers to sedimentation basins with detention periods much shorter than detention times in conventional sedimentation basins. Particles are able to settle out of the suspension much faster. This is usually achieved through the use of shallow settlers such as tubes, parallel plates (lamella) or shallow open trays. The research compared all the different types. His theoretical study led him to conclude that:

- open shallow trays are generally impractical due to large area requirements and hydraulic conditions can be unstable,
- uniform inlet flow distribution is difficult to maintain in parallel plates,
- circular and square tubes both function well and square tubes use space better.

Yao found that these high rate settlers are theoretically proven to be as effective as conventional sedimentation basins however he admitted that the problem of sludge removal was not completely solved. The suggested sludge removal method was inclining the tubes at a steep angle. Sludge naturally slides down by its own weight. This method is not very practical given that, it reduces the settlers performance and a suggestion of future research on sludge removal was made. The settled particles which slide down the tubes counter-current to the flow may be mixed in the tube influent and carried up again.

Slechta and Conley (1971) applied settling tubes to existing sedimentation basins. Testing of the settling tubes was performed in primary and secondary clarifiers. Settling tubes used in primary clarifiers were found to be capable of improving the performance of a poorly operating unit and improving the loading of existing clarifiers. They found that settling tubes in secondary clarifiers treating activated sludge should only be considered as a device for protecting the clarifier against a severe loss of solids because of upsets in the system or during peak flow conditions.

Regular cleaning was mandatory. No cleaning method was specifically suggested or recommended. Again sludge removal became a problem in addition to the cleaning of the tubes that have a tendency to clog due to biological growth in secondary clarifiers.

Cordoba-Molina et al. (1978), showed that the Hazen and Camp and Dobbins models all led to analogous results. Considering turbulent settling of discrete particles with a velocity distribution as the basis, it was found that for either laminar or turbulent conditions the limiting removal for Hazen's and Dobbins' cases becomes:

$$r = 1 - e^{-v_s/v_o} \qquad (2.12)$$

This expression assumes no scour from the bottom. If too much turbulence exists at the bottom, settling will be difficult. The conditions at the bottom affect the basin's removal efficiency. It is therefore important that these conditions be carefully controlled. If several inclined barriers or plates are included, the turbulence or hydraulic movement would be greatly reduced. This is the concept behind the present research. The barriers produce conditions conducive to particle settling as opposed to resuspension.

Cordoba-Molina pointed out that settling under quiescent and turbulent conditions are the limiting theoretical cases for suspended solids removal. The expression for removal under quiescent conditions represents the upper limit and the turbulent condition case represents the lower limit of possible removal. Thus, the turbulent model becomes a dependable conservative design when using a quiescent settling velocity distribution.

Acrivos and Herbolzheimer (1979) discovered that parallel inclined plates (lamella) in a sedimentation basin have additional benefits. Not only do the trays reduce the turbulence and reduce the scour at the tank bottom, they also use the Boycott effect which accelerates the particle settling. Boycott, in 1920, observed: "I have noticed lately that if oxalated or defibrinated blood is put to stand in narrow tubes, the corpuscles sediment a good deal faster if the tube is inclined than when it is vertical."

Verhoff (1979), performed an investigation involving general research into the optimal design of high rate sedimentation devices (lamella in particular). He gave the following definition for high rate sedimentation: "High rate sedimentation usually means a reduction of the liquid retention time in the settling device by reducing the distance necessary for the flocculated particles to reach the bottom. These devices are normally tubes, parallel plates (lamella) or other shaped tubes placed horizontally or inclined at some angle" (Verhoff, 1979). The conclusions drawn from this research include minimizing the critical settling velocity. If a high rate sedimentation device reduces this critical settling velocity significantly, better removal will follow.

With all this research focused on lamella or tube clarifiers, there are in 1996 still considerable problems concerning clogging due to biological growth and settled sludge removal. Their problems still outweigh their theoretical advantages. In industry today, it is a known fact that a good portion of existing tube or lamella secondary clarifiers for domestic or industrial wastewater have clogging and cleaning problems (Stuart, 1996). Their use is very limited to certain specific cases and they are seldom used for secondary highly concentrated biological streams.

In the past few decades several researchers have studied different aspects of sedimentation basins, trying to render them more efficient as well as develop numerical models to describe their behavior. McCorquodale has produced several papers on this topic in the 1990's. For an example, McCorquodale (1992) concentrated on optimizing different designs to achieve better removal performances. He also studied the non-ideal behavior taking place in sedimentation basins and created models for these basins. He found for instance that a variation in temperature of ±2°C from the ambient temperature is sufficient to induce strong density currents (McCorquodale, 1991a, 1991b). This type of variation is common and due to variations in ambient temperature at wastewater treatment plants. Tracer studies show that a large portion of the volume of the basin is not used and strong evidence of short-circuiting and dead volume exists in both rectangular and circular basins (McCorquodale, 1987).

The problems, as mentioned previously, with the general theory are that conventional clarifier design follow certain assumptions that are questionable. They assume that the flow is evenly distributed throughout the basin and also that the entire surface area is utilized.

These assumptions are being questioned because, tracer studies show that the flow suffers from short-circuiting and dead space exists. The influent jet in a conventional circular upflow clarifier enters the basin near the bottom. This flow has been found to travel directly along the basin bottom until it reaches the side wall or the end of the basin. It then flows up to the overflow weir. This is a common finding (McCorquodale et al., 1988; Guetler and Jain, 1991). McCorquodale communicated his findings on the study of flow in rectangular settling tanks. He stated that determining the actual flow patterns in settling tanks is an important factor in evaluating the performance of different tanks.

The problem with this flow behavior is that the flow is turbulent and confined to a narrow zone. This turbulence reduces the effective settling velocity of the particles. The available space is not fully utilized. This short-circuiting is due to thermally induced density currents, concentration gradients, and/or poor inlet and outlet structures. The influent jet and the increased flow velocity along the bottom causes resuspension or scour of the settled particles along the floor.

This problem has been recognized and studied for several decades (Takamatsu et al., 1974; Lumley and Balmer, 1991; Tahari and Bragg, 1992; Thorndahl, 1994). It is for this reason that basins have been designed with more depth. This increase in depth may resolve the resuspension problem but it does not reduce the short-circuiting problem and causes the cost of these basins to increase. Since it is widely shown that much of this depth is wasted, a solution for preventing resuspension and avoiding deeper more costly basins would be beneficial. This research looks into a possible solution on putting the available basin volume to better use.

Since these problems are found to be common, they should be considered in the design of sedimentation basins. Designs have been based on available surface area for a long time. It was found in 1904 that the basin's efficiency was independent of the basin's depth. Coe and Clevenger in 1916 delineated the four settling zones present in a sedimentation basin. These zones include: the discrete settling zone, the flocculant settling zone, the hindered settling zone and the compression zone. They discussed a method to predict thickener surface area from batch settling tests. They performed batch settling test on metallurgical pulp and suggested the following design equations (using their specific symbols and definitions):

$$C = \frac{62.35\ R}{(F - D_p)} \qquad (2.13)$$

$$A = \frac{2000}{24\,(\frac{62.35\,R}{(F-D_p)})} \qquad (2.14)$$

where

	C	capacity, lb/ft^2-h
	62.35	weight of 1 lb of water per cubic foot
	R	settling rate, ft/h
	F	initial pulp consistency, ft^3/lb
	D_p	consistency of discharge pulp, ft^3/lb
	2000	lb of solid to be thickened per day, lb/d
	24	h/d
	A	thickener area, ft^2

The variable C is the solids flux and the variables F and D which he calls consistencies are actually the inverse of the density. Coe and Clevenger suggested a method of calculating the required thickener area by first obtaining the solid particle settling velocity versus solids concentration curve and then calculating the different capacities corresponding to the different settling velocities present. The limiting capacity or solids flux was found to then calculate the area.

Kynch in 1951 supplemented Coe and Clevenger's work with further theoretical analysis. He performed theoretical studies on sedimentation of particles in a suspension having a large particle density. He defined particle flux as follows and developed the continuity equation:

$$S = \rho V_s \qquad (2.15)$$

$$\frac{\partial(\rho dx)}{\partial t}dt = S(x+dx)dt - S(x)dt \qquad (2.16)$$

where S particle flux, kg/m^2-h

Talmage and Fitch (1955) also developed a method to determine the area required for the thickening of the sludge. With the results of one batch settling test, the area can be calculated using a graphical method to determine the time required to reach the desired underflow concentration. The equation used to calculate the area requirement is:

$$A_t = \frac{Q\,t_u}{H_o} \qquad (2.17)$$

where A_t area required for thickening, m^2

Q	flowrate, m^3/h
t_u	time required to reach desired underflow concentration, h
H_o	initial liquid level in column, m

Dick (1970), developed a more thorough method of determining sedimentation basin area requirements for secondary clarifiers. In secondary clarifiers, two processes must take place for a basin to be effective: clarification and thickening. He pointed out that the solids were transported to the bottom of the sedimentation basin by gravity and by bulk flow downwards due to sludge removal from the bottom of the basin. The total flux is then defined as:

$$S = C_i V_i + C_i U \tag{2.18}$$

where

C_i	solids concentration at point in question, mg/L
V_i	settling velocity of solids of concentration C_i, m/s
U	average underflow velocity caused by removal of sludge, m/s

The first term in the equation represents the amount of solids carried down by gravity. The second term represents the amount of solids carried down by bulk flow associated to sludge removal. Dick developed three methods to find the required area of the secondary clarifier. The method he describes as the most convenient uses a batch flux curve. Settling velocities for suspensions of different solids concentration are obtained from a series of batch settling tests. The solids flux due to gravity can be drawn versus solids concentrations. With this curve, different underflow velocities will give different resulting underflow concentrations and total fluxes. The conditions best suiting the case at hand can be chosen to be able to calculate the required area. His equation to calculate the settler area assuming total solids capture was:

$$A = \frac{Q_o C_o}{C_u U} \tag{2.19}$$

where

Q_o	influent flowrate, m^3/s
C_u	underflow concentration, mg/L

All these above mentioned solids flux analysis methods to calculate the required sedimentation basin area are still in use today. These methods still assume that the entire surface area is being utilized. Problems arise when a certain suspension is studied and its required surface area for settling is determined. If the sedimentation basin is built with this calculated surface area, the entire surface area is required for settling.

Hydraulic problems that cause short-circuiting and dead volume in the basin reduce the surface area actually being utilized. The utilized surface area becomes a fraction of the necessary surface area for that particular suspension and the basin quickly becomes inadequate. The sedimentation basin will therefore not be performing as well as it was designed to because of this under utilized space. The calculated necessary surface area is therefore a fraction of the area actually required when all these problems are considered and a safety factor must be added. A basin design that permits the influent suspension to fully benefit from the available surface area would be a great step forward.

This leads to the modifications proposed in this study. The proposed modifications attempt to: eliminate scour, eliminate unnecessary dead volume, achieve an even distribution of flow over the entire surface area and reach the performance of conventional sedimentation basins.

The proposed model involves the flow passing over several inclined plates and not through them. The purpose of the inclined plates was not similar to that of lamella in lamella clarifiers. The difference between the inclined plates for this experiment and the lamella was in the spacing between these and also the flow configuration. Lamella clarifiers contain many lamella that are essentially inclined plates that are very close together, from 1.3 cm (0.5 in.) to 10.2 cm (4 in.) as averages (Hansen and Culp, 1967).

The flow in lamella clarifiers is directed through the lamella in an upflow or downflow mode. The influent enters the basin from the bottom and passes through the lamella to then exit at the top or vice versa. These lamella increase the available surface area for settling. The loading rate to the clarifier can be increased two or three or more times the conventional loading rate. Lamella clarifiers are still not as widely used as conventional type clarifiers because of problems mentioned previously such as clogging, cleaning and the uncertainty of whether this type would apply to each specific case (Stuart, 1996).

This research project turned to these inclined plates to see if equivalent removal can be obtained. The flow will be confined to a horizontal layer over the plates. No reduction in turbulence will be achieved in the flow through zone. The plates provide a quiescent zone for the settling solids and prevent or diminish the amount of settled solids resuspended in the settling zone (scour). If any currents should disturb the settled particles, the inclined plates will act as a barrier and prevent the solids from mixing with the effluent stream. Inlet and outlet structures will be designed to optimize even distribution and not to disturb settled particles.

The inclined plates will essentially put the wasted space of a conventionally designed clarifier (dead volume) to better use. The reduction in flow through volume from a conventionally designed basin reflects the short-circuiting problems described in Chapter 1. Part of the volume in the basin is not utilized. Both the turbulence present in the settling zone and the resuspended solids inhibit or reduce the efficiency of the sedimentation basin.

The experimental study utilizes a scaled down model of a clarifier. Some rules must be followed when an experiment is performed at a different scale than actual size. Some adjustments are necessary to compensate for the scaling down of the apparatus. Ideally densimetric Froude number similarity is required for scaling the sediment used in the experiment (Van Marle and Kranenburg, 1994; Zhou et al., 1992) and Reynolds number similarity is required for scaling of the hydrodynamic conditions in the experimental basin (Van Marle and Kranenburg, 1994).

The solids concentration must be higher in a smaller basin to compensate for its reduction in size to be able to achieve the appropriate scaling of sediment. For kinematic similarity, the densimetric Froude number (Fr_i) should be similar in the prototype and model. The densimetric Froude number is:

$$Fr_i = \frac{V_o}{\sqrt{\varphi g h_i}} \tag{2.20}$$

where $$\varphi = \left(\frac{\rho_i - \rho_t}{\rho_t}\right) \tag{2.21}$$

and $$\rho_i = \rho_r + C_i\left(1 - \frac{1}{s.g.}\right) \tag{2.22}$$

and:

Fr_i	densimetric Froude number, [0]
φ	fractional density difference, [0]
g	acceleration of gravity, 9.8 m/s^2
h_i	depth of water at inlet, m
ρ_i	density of influent suspension, kg/m^3
ρ_t	density of water in basin, kg/m^3
ρ_r	density of water, 1 kg/m^3

C_i TSS concentration of influent stream , mg/L
s.g. specific gravity of solid particles in suspension, [0]

Actual streams from a wastewater treatment plant would be an inappropriate choice for this experiment because artificially concentrating the suspension to achieve kinematic similarity would be problematic. Van Marle and Kranenburg suggest using clay.

As a secondary issue, Reynolds number similarity would be ideal but it is less important (Zhou et al., 1992). This similarity is difficult to obtain. Some researchers add aeration at the inlet of the basin to obtain this (Van Marle and Kranenburg, 1994). The flow in a scaled down model would tend to not be turbulent. Turbulence reduces the effective settling velocity of particles. The effect of turbulence would be similar in both the control and experimental model. For this reason, it is a less critical issue.

The variables being considered, the experimental set-up as well as the testing procedure will be explained in the following chapters.

CHAPTER 3

EXPERIMENTAL DESIGN

This research involves the experimental study of the impact of several modifications to a conventionally designed sedimentation basin by comparing its performance with a conventionally designed basin. The main experiments consist of running a suspension through three parallel scaled down sedimentation basins. Thus comparing the TSS removal efficiency of the control basin (simulating a conventionally designed basin) to that of two different experimental basins (designed for flow over inclined plates).

Samples taken at the entrance of the basin as well as at the exit were analyzed with a TSS test and the removal was calculated from these results. Along with the main runs through the basins, this study included several settling column tests to characterize the suspension and several tracer tests to compare the actual retention times in the different basins.

The following sections will describe these points:

- apparatus design
- variables and their values
- procedure for the sedimentation basin runs including filling, reaching steady state, sampling, emptying and cleaning
- the TSS test procedure
- the settling column test procedure
- the tracer test procedure

3.1 APPARATUS DESIGN

The experimental apparatus included: a cubic steel tank with sides measuring 2.286 m (7.5 ft). This tank was sub-divided into three parallel rectangular basins. Inlet and outlet structures were added to this tank as well as adjustable inclined plates. A supply tank, pumps and a mixer were also part of the apparatus.

A rectangular tank configuration was chosen rather than a circular because rectangular was easier to construct and rectangular units can usually be upgraded more cost effectively (Esler, 1994). If results are positive, the concept will be applicable to new as well as existing basins. Experiments involving the addition of lamella or tubes in the sedimentation basin are generally conducted in horizontal flow basin configurations (Hansen and Culp 1967; Culp et al. 1968; Slechta and Conley 1971, Létourneau and Sérodes 1988; Lessard et al. 1993). The addition of such apparatus inside sedimentation basins such as the case of this research with inclined plates is less complex in a rectangular geometry. They can also be added to circular basins but the set-up is not as simple.

3.1.1 THE TANK

A picture of the cubic steel tank is displayed in Fig. 3.1.

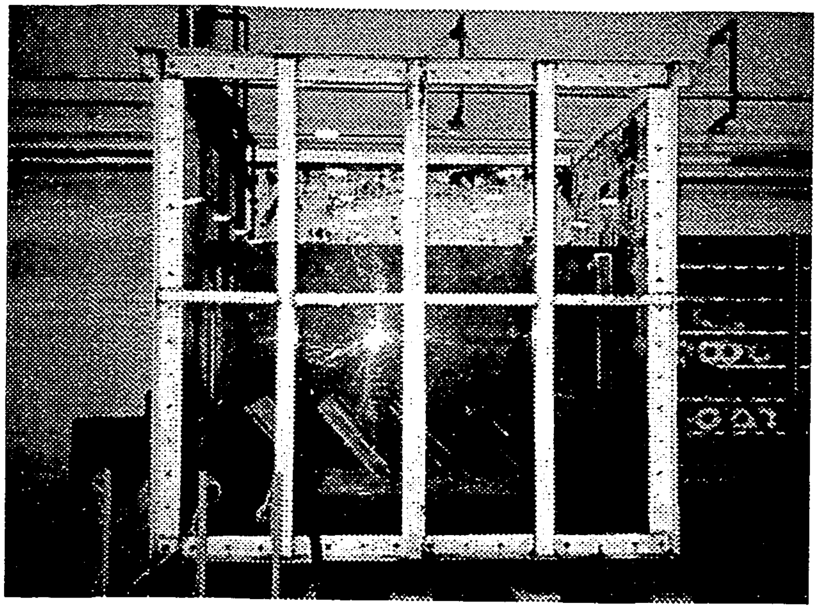

Figure 3.1 Experimental tank

It is desirable to use a large tank to minimize scale up effects. When experiments are conducted on smaller models, it is difficult to scale up the results. It was considered that this tank size is as large or larger than typical laboratory scale experiments. Table 3.1 displays different experimental basin sizes. It was not feasible to get a much larger tank because problems such as cost and size of auxiliary equipment (pumps, valves, pipes), size of supply tank, space availability and water supply become too great.

Table 3.1 - Previous sedimentation experiments basin sizes

Authors	Length of Rectangular Basin or Radius of Circular Basin Section (m)	Width of Rectangular Basin (m)	Volume of Basin (m^3)
Camp (1936)	length = 0.69	0.55	not available
Hansen and Culp (1967)	not available	not available	0.306
Létourneau and Sérodes (1988)	length = 1.24	0.15	0.138
Garde et al. (1990)	length = 0.8, 3 and 5	0.75	not available
Van Marle and Kranenburg (1994)	radius = 2.95	-	not available
present research	length = 2.286	0.762	1.60 and 1.95

A descriptive diagram of the top view of the basin can be found in Fig. 3.2.

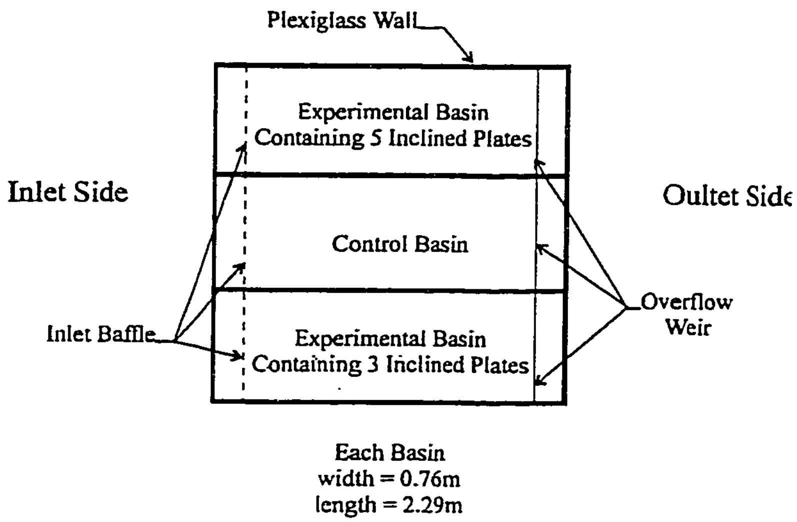

Figure 3.2 Basin configuration (top view)

This tank was made of steel, open at the top and had one vertical side fabricated of clear plexiglass. Three parallel basins were created by dividing the tank with two plywood walls (of 1.9 cm or 3/4 in. thickness) that spanned the total length of the basin of 2.286 m (7.5 ft) and had a height of 1.83 m (6 ft). The divisions were made parallel to the clear plastic side so that it showed the length of one basin The plywood was held in place by welding 2.5 cm (1 in.) steel angles to the steel tank and sliding the wood in place between two parallel brackets.

Table 3.2 displays design parameters for full scale basins found in four different sources. Design parameters for rectangular as well as circular basins are indicated.

Table 3.2 Secondary sedimentation basin design parameters summary

Source	range	upflow rate m^3/m^2d	depth m	diameter[a] (m)	width of rect.	length of rect.
Metcalf & Eddy 1991	low high	16.3 32.6	3.66 8	10 40	-	depth : length 1:10 (max.)
Droste 1997	low high	20 34	3 5.5	12 46	width : length 1:3, 1:5	-
EPA 1975	low high	16.3 32.6	3.6 4.6	16.8 42.7	-	-
WEF/ASCE 1991	low high	16.32 28.56	3.35 4.6	12.2 42.7	width : length 1:1.5, 1:15	-

a - The diameter refers to the diameter of a circular shaped clarifier.

The dividing walls gave a total of three basins of 2.286 m (7.5 ft) in length, 0.76 m (2.5 ft) in width and 1.83 m (6 ft) in maximum depth. This size tank produces an experimental set-up with a scale factor of 1:10 to 1:15 from actual size. The width to length ratios for the design of clarifiers range from 1:3 to 1:5 (Droste, 1997). The width to length ratio for this tank was 1:3. The three parallel basins are shown in Fig. 3.2.

Secondary clarifiers are most commonly circular basins. This experimental research was performed in rectangular basins due to the complexity and cost factors involved in building a circular prototype. Most research for secondary clarifiers are performed in rectangular basins (Létourneau and Sérodes, 1988; Garde et al., 1990; McCorquodale et al., 1988) or in small sectors of circular basins (Zhou et al., 1992; Van Marle and Kranenburg, 1994).

The entire apparatus is described in the following sub-sections.

3.1.1.1 Inlet Structure

Inlet structures are designed to dissipate the inlet flow velocity, to distribute the flow uniformly and to prevent short-circuiting. Submerged inlet ports coupled with a baffle wall make a good combination for a proper inlet structure (WPCF, 1985). The inlet structure for the control basin as well as for the experimental basin included both a submerged inlet port and a baffle wall.

The following two figures describe the baffle wall itself and the inlet structures for both the control basin and the experimental basin containing inclined plates.

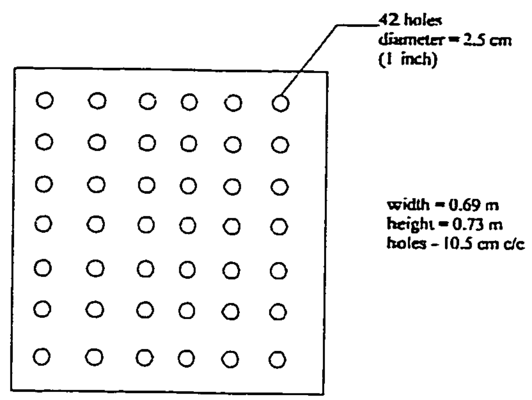

Figure 3.3 Baffle design (1.9 cm plywood)

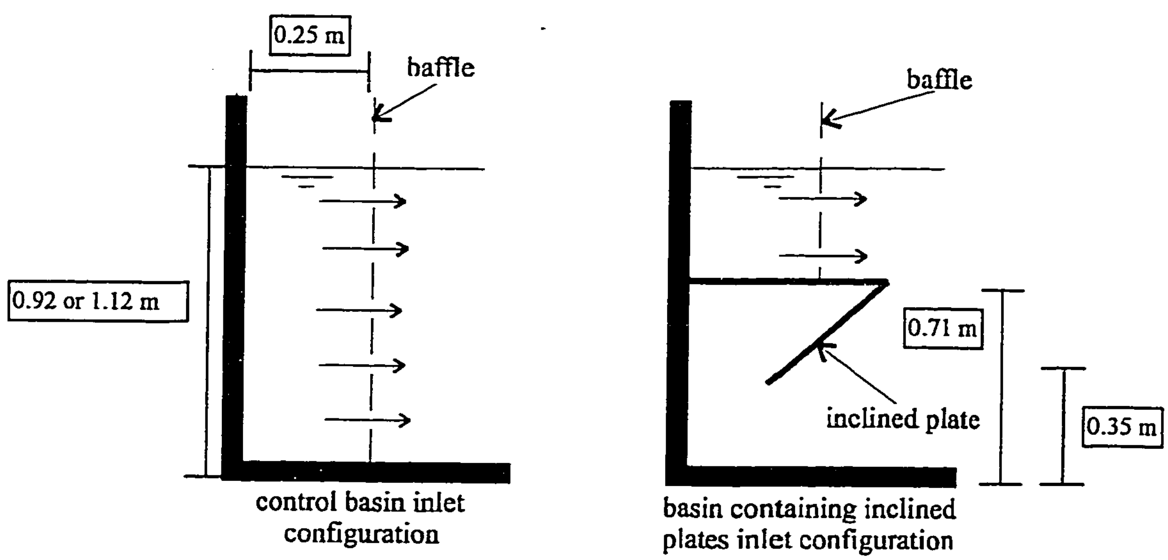

Figure 3.4 Inlet structure designs

The solids suspension was pumped from the supply tank to the basin through three separate 1.9 cm (¾ in.) rubber hoses and entered all three basins individually through a submerged inlet orifice. The inlets were a single 1.9 cm (3/4 in.) hole for each basin perforated through the steel tank wall and located on a common vertical wall at one end of the tank. The outside of this hole was covered with a 1.9 cm (3/4 in.) steel flange with a hole of the same size. The center of the inlet port was located at 89 cm (35 in.) from the bottom of the tank. In each of the three individual basins, the hole was centered horizontally on the width of each basin.

These submerged orifices need an additional device to dissipate the inlet flow energy and distribute the flow uniformly. At 25.4 cm (10 in.) from this inlet wall lengthwise in each of the three basins, a removable vertical perforated baffle wall was installed parallel to the inlet wall. The distance between the inlet and the baffle wall was based on these findings. Van Marle and Kranenburg (1994) placed the baffle wall at a distance of approximately 10% of the total diameter in their prototype. WEF and ASCE (1992) state that a baffle wall should be located at a distance of 0.6 to 0.9 m from the inlet in a full scale sedimentation basin. In this case, a 25.4 cm distance is equivalent to 11% of the total basin length. This distance is equal to approximately half of the minimum distance required in a full scale basin.

This baffle wall was made from a sheet of plywood 1.9 cm (3/4 in.) thick. It was perforated with holes which covered 4.2 percent of its surface area. Droste (1997) states that the area that the baffle orifices should be approximately 3 to 6 percent of the total wall area. Each orifice had a diameter of 2.54 cm (1 in.) and were located uniformly at approximately 10.5 cm (4.2 in.) apart center to center on each inlet wall.

The baffle wall spanned the width of each basin. In the control basin, it covered the entire depth. In the two experimental basins it stopped and was boxed in by another sheet of plywood horizontally at the height of the top of the inclined plates which will be described in the following section. This was to direct the flow in these basins over the inclined plates and prevent a current from forming under the inclined plates. The baffles were also slid into place between two parallel steel angle brackets that were welded in place or bolted through the wooden, steel walls and the clear plastic wall.

3.1.1.2 Inclined Plates

The inclined plates were added to the experimental basins. The bottom edge of the inclined plates reached a depth of 35.5 cm (14 in.) from the bottom of the steel tank. This was done to leave space for the sludge accumulation zone below the inclined plates. The top edge reached a depth of 71 cm (28 in.)

from the bottom. The total height of each plate was 45.7 cm (18 in.) when not inclined. The width of the plates was equal to the basin width at approximately 0.81 m (32 in.). The plates were fabricated of plywood sheets of 1.9 cm (3/4 in.) thickness.

A minimum horizontal spacing between each plate of 35 cm (14 in.) was tested. This spacing gave a total of five inclined plates in the basin. A spacing of 70 m (28 in.) was also chosen as a variable to be tested. This spacing gave a total of three inclined plates in the basin. It was considered that these spacing values were sufficiently large as not to promote clogging or cleaning problems due to biological growth. Lamella and tube clarifiers have these problems but have a spacing value usually approximately 1 and 4 inches (as mentioned in Chapter 2).

The lamella inclination angled varied between 45 and 55° from the horizontal in lamella clarifiers (Applegate et al. 1989). Smaller angles of inclination would promote clogging problems in lamella. The angle for the inclined plates for this experimental apparatus was chosen to be the median of the range suggested above (i.e. 50°) from the horizontal. The inclined plates were placed along the width of the basins inclined towards the outlet of the basins and the actual number of plates varied during the experiments. These were removable and slid into place between two parallel steel angles to secure them into place. Figure 3.6 shows a side view of the basin configurations involved.

3.1.1.3 Outlet Structure

Two types of effluent outlet designs are commonly used: overflow weirs and submerged effluent collectors. Since the outlet structure is not in question in the experiment, a common design was chosen for all three basins. An overflow weir design was selected for this research to enable the adjustment of the depth of flow in the basins. Depth was a variable in the experiments. The outlet structure consists of an overflow weir and an outlet orifice on the tank wall. The overflow weir was adjustable to 2 different heights to accommodate the two different depths. Figure 3.5 describes the weir sizes and placement.

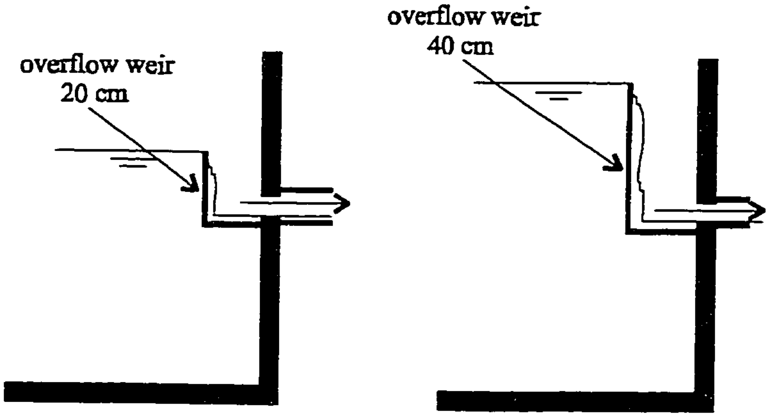

Figure 3.5 Outlet structure configuration

The weirs were located along the opposite end wall from the inlet wall over the entire width of each basin. In each of the three basins, at 71 cm (28 in.) from the bottom of the tank, a permanent horizontal plate with a width equal to that of the basin's and a length of 20 cm (7.9 in.) was installed. They served as stepping surfaces for a person to be able to reach the bottom of the basins and as the support for the overflow weirs. The removable overflow weirs consisted of pieces of plywood with a width equal to that of the basin width and a height of 20 cm (7.9 in.) and 40 cm (15.7 in.). Two interchangeable weirs were fabricated for each basin because the depth of the flow was to be changed between the experiments.

Once a weir height was selected and installed for the particular experiments, silicone sealant was applied to all edges to prevent leakage below the top edge of the weir.

In each basin, an orifice having a diameter of 3.8 cm (1.5 in.) was made on the tank wall to permit the discharge of the effluent. The diameter of the orifice did not slow the effluent flow velocity and create a backwater condition. The orifice was located at a height of 74 cm (29 in.) from the bottom of the tank. This height was equal to the height of the permanent horizontal plate. Flanges were attached to the outside of these orifices to permit the attachment of pipes to direct the discharge of the basins. The reasons for the selection of the weir depth are considered in the variables section.

For the case of rectangular primary clarifiers, no specific evidence particularly shows that the weir loading rate has an effect on the basins efficiency (WPCF, 1985). For this reason, the outlet structure was placed only across the full width of the basins.

3.1.1.4 Drains and Valves

At the bottom surface of the tank, holes had to be added to enable each tank to be emptied. A hole of 7.6 cm (3 in.) already existed in one corner of the tank. This hole became the drain hole for one basin. At each inlet end of the two other basins on the bottom floor, 3.8 cm (1.5 in.) holes were made. Steel flanges were attached to the outside of the holes to attach the necessary pipes to direct the flow.

These holes had to have the possibility of being opened or closed. At each hole, pipes were connected and flow control valves were added. At the 7.6 cm hole a butterfly valve was installed. At the two other holes, gate valves were added.

Figure 3.6 shows the side view of the three basins.

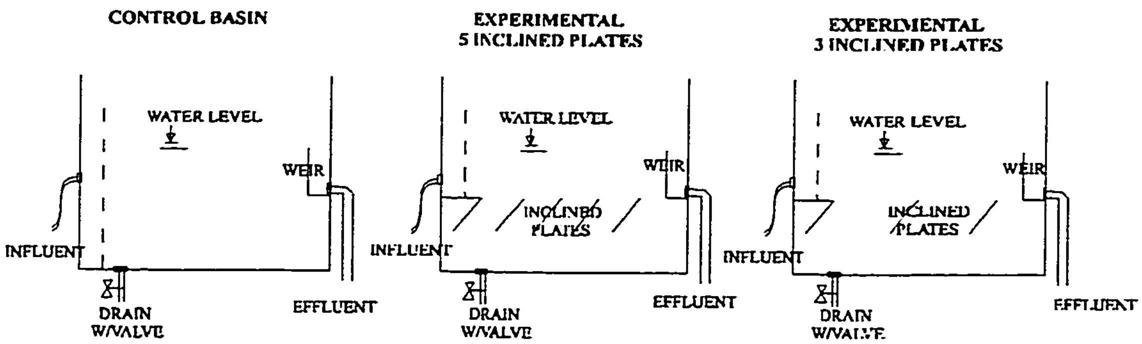

Figure 3.6 Side view of the 3 different basin configurations

3.1.2 SUPPLY BASIN AND EQUIPMENT

Since the experiment was conducted with an inorganic solids suspension, the feed to the three basins was provided by the supply tank. The effluent of the three basins was redirected to this supply tank to be recycled.

This tank was filled with water and solids were added to attain the required concentration. As the suspension was pumped from this tank and brought to the sedimentation basins, the incoming effluent kept the water level constant in the tank. The concentration of solids had to be kept constant by continuous solids addition because the settleable solids were being settled in the sedimentation basins and did not return to the supply tank. These procedures are explained in detail in the following sections.

The design of the sump tank, the sump pumps, as well as the mixer are also described in this section.

3.1.2.1 Supply Basin

The facility where the experiments were conducted had a sump available to contain the supply tank. A section had to be built by blocking off the available section with concrete blocks. The existing sump was a long channel of 1.2 m (4 ft) in width and 2.13 m (7 ft) in depth. The top level of this channel was located at the floor level and it was made of lined concrete. A section of 3.66 m (12 ft) in length was available for the experiment. Concrete blocks filled with concrete were used to fabricate the two walls to section this channel. The result gave a sump tank of 1.98 m (6.5 ft) depth, 1.2 m (4 ft) width and 3.66 m (12 ft) length made of filled concrete blocks. The maximum capacity of the basin was 8835 L. This tank was equipped with a drain valve at the lowest bottom corner to permit complete draining.

3.1.2.2 Mixer

The solids suspension was maintained in the supply tank to be fed to the three sedimentation basins. Water and a fixed quantity of solids had to be kept in a continuously uniform suspension. To attain good mixing conditions and a uniform suspension, a mixer was installed on the sump floor. The mixer was FLYGHT mixer model number 4400-414. The motor rating was 2.4 kW (3.2 hp). The mixer consisted of a propeller circulating the water. The propeller diameter was equal to 0.22 m (8.7 in.).

3.1.2.3 Pumps

The liquid solids suspension was moved from the supply sump tank to the three sedimentation basins. This allowed the flows to easily be adapted to the required rates.

The pump had to be submersible, inexpensive, able to lift a slurry of inorganic solids at the existing height difference and able to pump at the set flowrates for the experiments. The concentration of suspended solids in the water to be pumped varied from as low as 1000 mg/L to as high as 7000 mg/L. The head difference between the two water levels, the level in the sump tank and the level in the three basins (all at an equal level) varied from 2.13 m (7 ft) and 2.44 m (8 ft). The flowrates varied from 20 L/min to 40 L/min.

A utility submersible sump pump was first selected; but although it was able to pump at the required flowrate, it could not handle the solids loading. The motor was not strong enough to withstand long periods of time under the given conditions. The Barnes automatic 1/4 hp submersible sump pump model number BP3000 was later selected and was capable of performing under the required conditions. This pump cost a little more but was made to last longer and was stronger. This pump was capable of pumping at higher than required flowrates. The flowrates were then controlled with a control valve placed before the basin inlet.

The Barnes pump has a plastic fiber reinforced impeller, a mechanical type shaft seal and the volute was fabricated in cast iron. The motor housing and hardware were made of stainless steel. The motor was single phase with an air-filled permanent split capacitor with overload protection. The shaft was made of stainless steel and it had lower and top ball bearings. The motor had a speed of 3450 RPM. The pump also had a 3.175 cm (1.25 in.) vertical discharge.

3.1.2.4 Fittings

In the supply sump tank, the mixer was fixed to the floor at approximately 61 cm (2 ft) from one of the end walls with four 9 kg (20 lb) weights tied to each of its corners. The pumps were located at the opposite end of the sump tank at the same distance from the end wall.

These pumps however could not be placed on the floor of the tank. A more homogeneous suspension existed in the middle depth; therefore, pumps were placed at approximately 0.91 m (3 ft) from the floor. This was equal to half of the depth of the tank. At the floor of the tank, some heavier solids could settle and mixing is not always close to ideal near surfaces. The pumps were suspended from the top of the sump tank to this level with the help of a supporting rod. The pumps were fixed in place by a rope going from the pump to the top supporting rod and another rope going from the pump to a 9 kg (20 lb) weight located under the pump on the floor of the tank and back up to the supporting rod. This rope configuration was required to fix the pumps in place and prevent them from swinging about from the mixing currents. They could also be pulled out easily for regular maintenance. The pumps were placed about 30 cm (1 ft) apart from each other.

The liquid was pumped through a 1.9 cm (3/4 in.) flexible hose to the control valve of each basin. A reducer coupling had to be placed at the pumps 3.175 cm (1.25 in.) discharge to fit on the smaller hose. This hose was selected because it was flexible, strong and in the appropriate price range. The delivery hose diameter could not have been 3.175 cm because the flow velocity would be low in the hose and solids deposition could occur.

The three hoses delivering the fluid to each of the three sedimentation basins were attached to the flow control valves. These valves were then attached to the outside tank wall flanges. The flowrate for each basin was measured individually with a 10 L graduated plastic container and a stopwatch. Three consecutive measurements were taken at the outlet pipe discharges. An average of these measurements was calculated. Adjustments were made accordingly.

Between the control valve and the wall flange on each basin, a sampling port was added. This consisted of a tee type fitting on the main line with a gate valve. When the valve was open, the fluid flowed through this pipe and was discharged through the sampling port. This enabled the sampling of the influent before it entered the individual basins. The following picture shows this set-up.

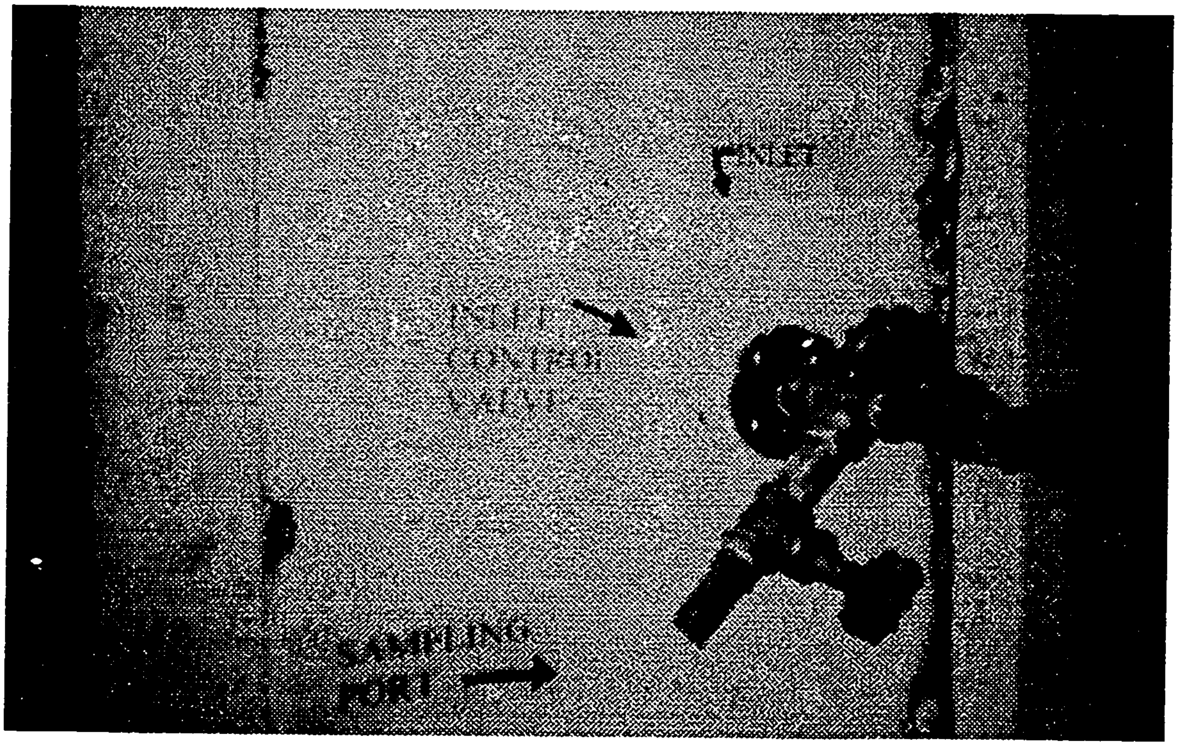

Figure 3.7 Sampling port, control valve and hose configuration

Once the water passed through the three individual basins and went over the weirs at the opposite end, it exited through the orifice placed after the weirs. This orifice had a flange attached on the outer side of the steel tank. The orifice had a diameter of 3.8 cm (1.5 in.). A 90° elbow was connected to each of the three individual flanges on the outside of the tank and pointed downwards. A plastic pipe with the same diameter as the orifice was attached to the elbows to convey the flow to the sump. Since the sedimentation tank was placed directly over the supply tank, the effluent went directly back to the opposite end from which it left the tank. Figure 3.8 shows this set-up.

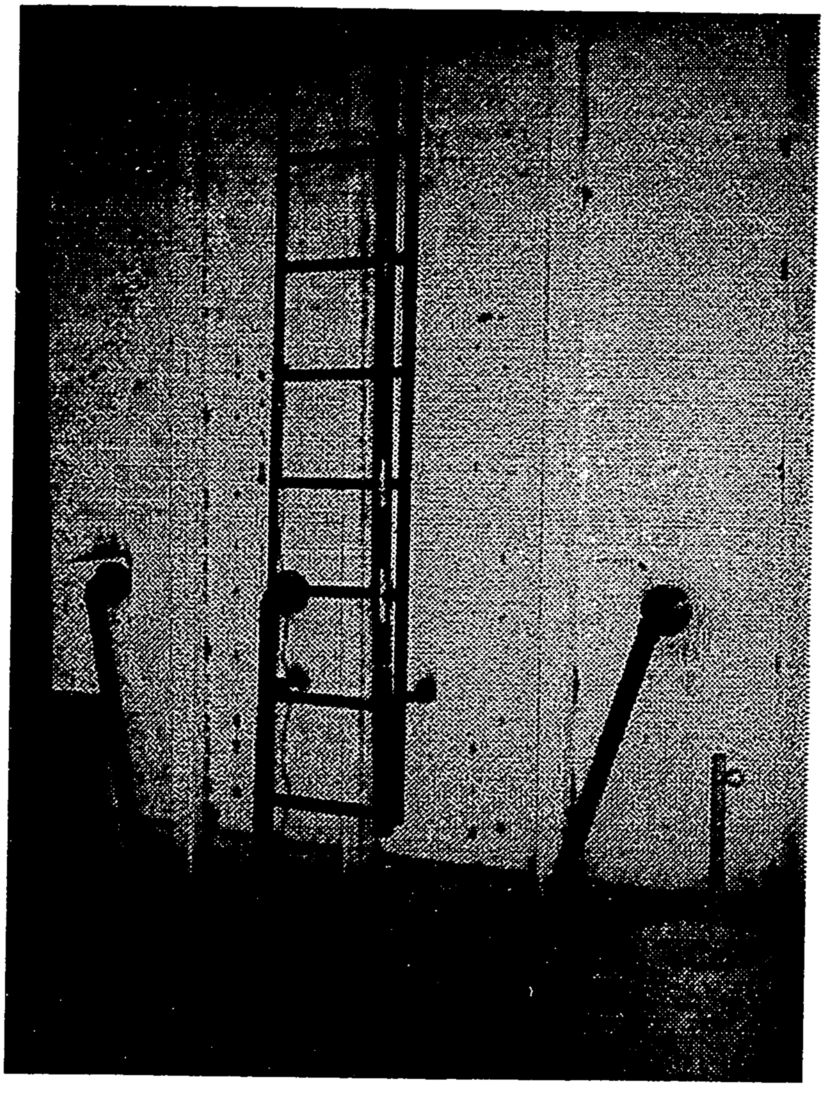

Figure 3.8 Effluent discharge configuration

The entire set-up includes the supply basin, the mixer, the pumps, the steel tank with all the fittings. Figure 3.9 describes how they are all related to each other.

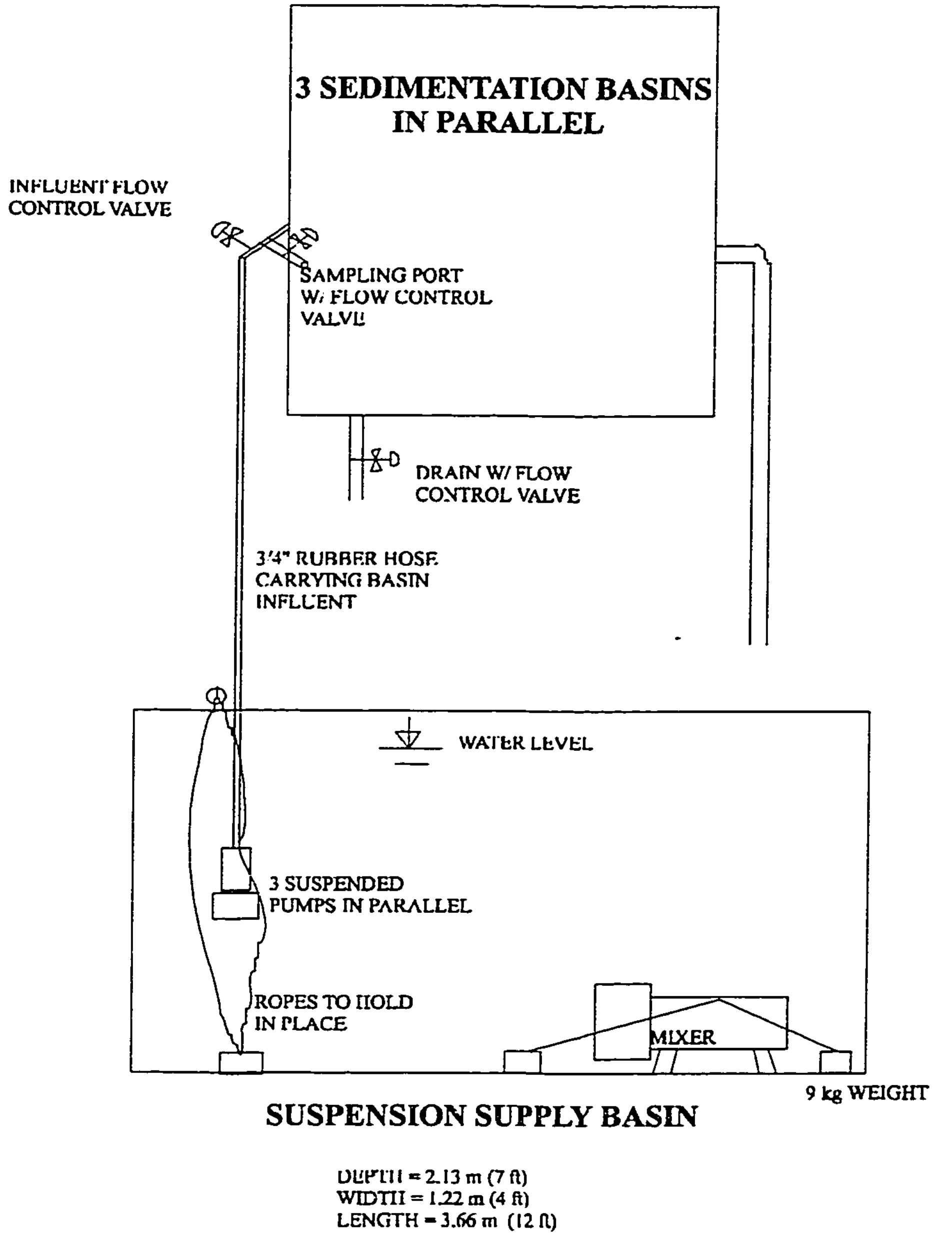

Figure 3.9 Descriptive diagram of entire set-up

3.1.3 SUSPENSION

The sedimentation experiments required solids to be settled from a suspension. Using an inorganic medium versus an actual wastewater treatment plant stream for the experiments provides more consistent suspension characteristics between each run. Clay offered a good range of particle sizes. The solids selection was based on the settling velocity criterion. Since three different flowrates were being tested and the flow through velocities of the control basin and the two experimental basins were not equal, the critical settling velocity was not constant. A suspension containing a wide range of particle sizes and settling velocities covering all the flow through velocities along with much slower particles as well as much faster particles was needed. The most important objective of the work was to determine the relative performance of the basins rather than their total removals.

Several samples of clay were obtained from a local pottery supply store and a chemical supplier. Supplier information can be found in Appendix A. A quick check to reduce the number of sample choices was done. The samples were placed in jars and water was added. The jars were agitated. The time required for the solid particles to settle out of the suspension was observed. It was estimated which solids sample settled at approximately the ideal range of settling velocities and two were selected (this range is explained later in Chapter 5). A settling column test was performed on the two selected samples to determine the range of particle settling velocities contained in it. The two samples were kaolin clay and Hawthorne bond fireclay.

Chapter 4 gives the results of the settling column tests with the p-v curves and Chapter 5 discusses the results and the reasons behind the choice of suspension. For the purpose of calculations in the following sections, the choice of suspension is stated in this section.

The suspension selection was the Hawthorne bond fireclay. The results suggest that this suspension contained a wide range of particle sizes. The specific gravity of Hawthorne bond fireclay is 2.65. No flocculant was used in the experiments.

3.2 VARIABLES

The variables under consideration were: the flowrate, the solids concentration, the depth of water over the inclined plates in the experimental basins and the inclined plate spacing or the number of plates. The effects of changes of these variables on the removal efficiencies of the control and the experimental basin were sought. Each variable and its selected experimental values are explained in the following sections.

3.2.1 FLOWRATE

The flowrates tested in the present research were based on values for upflow rates found in full scale sedimentation basins. Ranges of suggested upflow rates and typical basin dimensions for basins were obtained from four sources. They were: Metcalf & Eddy (1991), EPA (1975), WEF/ASCE (1991) and Droste (1997). Horizontal flow basins have dimensions and loading rates equivalent to circular basins. The data obtained from the above mentioned sources represent data for circular secondary clarifiers.

This research involves rectangular basins and the data had to be manipulated to determine the corresponding horizontal flowrate.

The corresponding flowrates to be used in this study were calculated. These calculations can be reviewed in Table 3.3. Detailed sample calculations are presented after the table. Corresponding values for the minimum and maximum upflow rates were found. Minimum design values were grouped together to obtain the minimum value for the given range of design criteria. The same was done for the maximum values. A combination of minimum and maximum design values can exist but its flowrate would lie within this calculated range. The table displays the full-scale upflow rates and their corresponding laboratory scale flowrates for this case.

In addition, as mentioned in Chapter 2, hydrodynamic similarity should be obtained; the Reynolds number of the prototype should be equal to that of the model. As shown in the following table, they are not equal. The Reynolds number for the experimental and control basins is lower than the Reynold's number in typical field units. Artificial means such as aeration or screens would be the only means to render them equal. Since this would have made the construction and the cleaning of the basins more complicated, it was decided to not augment the basins' Reynolds numbers with these means. This decision was made with the supporting fact that both the control and the experimental basins were to be tried in parallel and that only the relative differences in the removal behaviors of the two were sought. The effect of turbulence would be similar in both basin configurations, reducing the effective particle settling velocity.

Table 3.3 Flowrate calculations

depth over inclined plates equal = 20 cm; total depth = 0.92 m

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	Actual					Experimental - inclined plates									Experimental - conventional design								
Source	Q/A	d	D	Re	t_d	R_h	a	V	A	v	Re	Q	Q	t_d	R_h	a	V	A	v	Re	Q	Q	t_d
	m/d	m	m		min	m	m^2	m^3	m^2	m/d		m^3/d	L/min	min	m	m^2	m^3	m^2	m/d		m^3/d	L/min	min
Metcalf & Eddy	16.3	3.66	10	1887	323	0.131	1.74	0.348	0.152	186.3	1131	28.4	19.7	18	0.269	1.74	1.60	0.70	40.5	505	28.4	19.7	81
1991	32.6	8	40	15093	353	0.131	1.74	0.348	0.152	372.6	2263	56.8	39.4	9	0.269	1.74	1.60	0.70	81.0	1010	56.8	39.4	41
Droste	20	3	12	2778	216	0.131	1.74	0.348	0.152	228.6	1388	34.8	24.2	14	0.269	1.74	1.60	0.70	49.7	620	34.8	24.2	66
1997	34	5.5	46	18102	233	0.131	1.74	0.348	0.152	388.6	2360	59.2	41.1	8	0.269	1.74	1.60	0.70	84.5	1054	59.2	41.1	39
EPA	16.3	3.6	16.8	3169	318	0.131	1.74	0.348	0.152	186.3	1131	28.4	19.7	18	0.269	1.74	1.60	0.70	40.5	505	28.4	19.7	81
1975	32.6	4.6	42.7	16111	203	0.131	1.74	0.348	0.152	372.6	2263	56.8	39.4	9	0.269	1.74	1.60	0.70	81.0	1010	56.8	39.4	41
WEF/ASCE	16.32	3.35	12.2	2304	296	0.131	1.74	0.348	0.152	186.5	1133	28.4	19.7	18	0.269	1.74	1.60	0.70	40.6	506	28.4	19.7	81
1991	28.56	4.6	42.7	14115	232	0.131	1.74	0.348	0.152	326.4	1982	49.7	34.5	10	0.269	1.74	1.60	0.70	71.0	885	49.7	34.5	46

depth over inclined plates equal = 40 cm; total depth = 1.12 m

	Actual					Experimental - inclined plates									Experimental - conventional design								
Source	Q/A	d	D	Re	t_d	R_h	a	V	A	v	Re	Q	Q	t_d	R_h	a	V	A	v	Re	Q	Q	t_d
	m/d	m	m		min	m	m^2	m^3	m^2	m/d		m^3/d	L/min	min	m	m^2	m^3	m^2	m/d		m^3/d	L/min	min
Metcalf & Eddy	16.3	3.66	10	1887	323	0.195	1.74	0.697	0.305	93.2	842	28.4	19.7	35	0.284	1.74	1.95	0.85	33.3	438	28.4	19.7	99
1991	32.6	8	40	15093	353	0.195	1.74	0.697	0.305	186.3	1683	56.8	39.4	18	0.284	1.74	1.95	0.85	66.5	876	56.8	39.4	49
Droste	20	3	12	2778	216	0.195	1.74	0.697	0.305	114.3	1033	34.8	24.2	29	0.284	1.74	1.95	0.85	40.8	537	34.8	24.2	81
1997	34	5.5	46	18102	233	0.195	1.74	0.697	0.305	194.3	1755	59.2	41.1	17	0.284	1.74	1.95	0.85	69.4	913	59.2	41.1	47
EPA	16.3	3.6	16.8	3169	318	0.195	1.74	0.697	0.305	93.2	842	28.4	19.7	35	0.284	1.74	1.95	0.85	33.3	438	28.4	19.7	99
1975	32.6	4.6	42.7	16111	203	0.195	1.74	0.697	0.305	186.3	1683	56.8	39.4	18	0.284	1.74	1.95	0.85	66.5	876	56.8	39.4	49
WEF/ASCE	16.32	3.35	12.2	2304	296	0.195	1.74	0.697	0.305	93.3	843	28.4	19.7	35	0.284	1.74	1.95	0.85	33.3	438	28.4	19.7	99
1991	28.56	4.6	42.7	14115	232	0.195	1.74	0.697	0.305	163.2	1475	49.7	34.5	20	0.284	1.74	1.95	0.85	58.3	767	49.7	34.5	56

where
- v — flow velocity, m/d
- μ — viscosity, kg/m-s
- P — perimeter, m
- D — diameter, m
- Q/A — upflow rate, m^3/m^2-d
- a — plan area, m^2
- d — depth, m
- R_h — hydraulic radius, m
- A — cross-sectional area, m^2
- Q — flowrate, m^3/d
- t_d — detention time, min
- V — volume, m^3

Sample Calculations for the Actual Secondary Sedimentation Basin Case

1. Suggested upflow rate (column 2) and side wall depth (column 3) values for secondary clarifiers were obtained from several sources (column 1). The lower value of the upflow rate range was matched with the lower value of the range of the side wall depth. The same was done for the maximum range.

2. The value for the diameter (column 4) was obtained from Table 10-11 in WEF/ASCE (1991). The diameter obtained was found by interpolating with the corresponding side wall depth.

3. The Reynolds number (column 5) was calculated by using the following equation. The value for the first row is calculated as an example.

$$\mathrm{Re} = \frac{\rho v D}{\mu} \tag{3.1}$$

$$\text{ex: } \mathrm{Re} = \frac{1000\frac{\mathrm{kg}}{\mathrm{m}^3}\cdot 16.3\frac{\mathrm{m}}{\mathrm{d}}\cdot 10\ \mathrm{m}\cdot\frac{1\ \mathrm{d}}{24\ \mathrm{h}}\cdot\frac{1\ \mathrm{h}}{3600\ \mathrm{s}}}{0.001\frac{\mathrm{kg}}{\mathrm{m}\cdot\mathrm{s}}} = 1887$$

4. The detention time (column 6) was calculated using the following equation:

$$t_d = \frac{V}{Q} = \frac{A\cdot d}{Q} = \frac{d}{Q/A} \tag{3.2}$$

$$\text{ex: } t_d = \frac{3.66\ \mathrm{m}}{16.3\frac{\mathrm{m}^3}{\mathrm{m}^2\cdot\mathrm{d}}\cdot\frac{1\ \mathrm{d}}{24\ \mathrm{h}}\cdot\frac{1\ \mathrm{h}}{60\ \mathrm{min}}} = 323\ \mathrm{min}$$

Sample Calculations for the Experimental Clarifier Case

The tanks' width and length are fixed at 0.762 m and 2.286 m respectively. One variable for the proposed experiments consists of using different depths of water over the inclined plates. For the basins with the plates, the depth of the flow was confined to the layer above the plates. This depth will have values of 20 and 40 cm. The following explanation and sample calculations will consider the case where the depth is equal to 20 cm.

1. The hydraulic radius (column 7) required for the calculation of the Reynolds number was calculated using the following equation:

$$R_h = \frac{A}{P} \qquad (3.3) \qquad \text{ex: } R_h = \frac{0.20\ \text{m} \cdot 0.762\ \text{m}}{0.20\ \text{m} + 0.762\ \text{m} + 0.20\ \text{m}} = 0.131\ \text{m},$$

2. The plan area (column 8) of the basin was calculated using the width and the length of the basin.

$$\text{ex: } a = 0.762\ \text{m} \times 2.286\ \text{m} = 1.74\ \text{m}^2$$

3. The volume of the basin (column 9) was calculated using the plan area and the flow depth.

$$\text{ex: } V = ad = 1.74\ \text{m}^2 \times 0.2\ \text{m} = 0.348\ \text{m}^3$$

4. The cross-sectional area (column 10) of the flow through the basin was calculated by multiplying the depth of flow with the basin width.

$$\text{ex: } A = 0.2\ \text{m} \times 0.762\ \text{m} = 0.152\ \text{m}^2$$

5. The flow velocity (column 11) was calculated by using the upflow rates found in the sources mentioned and adjusting it to the case in question. The upflow rate was multiplied by the plan area of the basin and then divided by the cross-sectional area of the basin.

$$v = \frac{Q/A \cdot a}{A} \qquad (3.4) \qquad \text{ex: } v = \frac{16.3\ \frac{\text{m}}{\text{d}} \cdot 1.74\ \text{m}^2}{0.152\ \text{m}^2} = 186\ \frac{\text{m}}{\text{d}}$$

6. The Reynolds number (column 12) was calculated using the following equation:

$$Re = \frac{4\rho v R_h}{\mu} \qquad (3.1)$$

$$\text{ex: } Re = \frac{4 \cdot 1000\ \frac{\text{kg}}{\text{m}^3} \cdot 186\ \frac{\text{m}}{\text{d}} \cdot 0.131\ \text{m} \cdot \frac{1\ \text{d}}{24\ \text{h}} \cdot \frac{1\ \text{h}}{3600\ \text{s}}}{0.001\ \frac{\text{kg}}{\text{m} \cdot \text{s}}} = 1132$$

7. The flowrate (column 13) was calculated by using the following equation:

$$Q = v \cdot A \qquad (3.5) \qquad \text{ex: } Q = 186\ \frac{m}{d} \cdot 0.152\ m^2 = 28.4 \frac{m^3}{d}$$

8. The flowrate in units of m^3/d was converted to units of L/min (column 14).

9. The detention time (column 15) was calculated by using the following equation:

$$t_d = \frac{V}{Q} \qquad (3.2) \qquad \text{ex: } t_d = \frac{0.348\ m^3}{28.4\ \frac{m^3}{d}} \cdot \frac{24\ h}{d} \cdot 60\ \frac{min}{h} = 18\ min$$

<u>Sample Calculations for the Experimental Conventional Basin Case</u>

The tanks' width and length are fixed at 0.762 m and 2.286 m respectively. The plan area is fixed at 1.98 m^2. The proposed experiments consists of using a fixed depths of water. The following calculations will consider a depth of 0.92 m (equivalent to the depth of the experimental basin with a depth of 20 cm over the inclined plates).

1. The hydraulic radius (column 16) required for the calculation of the Reynolds number was calculated using the following equation:

$$R_h = \frac{A}{P} \qquad (3.3) \qquad \text{ex: } R_h = \frac{0.92\ m \cdot 0.762\ m}{0.92\ m + 0.762\ m + 0.92\ m} = 0.269\ m$$

2. The plan area (column 17) of the basin was calculated using the width and the length of the basin.

$$\text{ex: } a = 0.762\ m \times 2.286\ m = 1.74\ m^2$$

3. The volume of the basin (column 18) was calculated using the plan area and the flow depth.

$$\text{ex: } V = a \times d = 1.74\ m^2 \times 0.92\ m = 1.60\ m^3$$

4. The cross-sectional area of the flow through the basin was calculated by multiplying the depth of flow with the basin width.

$$\text{ex: } A = 0.92\ m \times 0.762\ m = 0.70\ m^2$$

5. The flow velocity (column 20) was calculated by using the upflow rates found in the sources mentioned and adjusting it to the case in question. The upflow rate was multiplied by the plan area of the basin and then divided by the cross-sectional area of the basin.

$$v = \frac{\frac{Q}{A} \cdot a}{A} \qquad (3.4) \qquad \text{ex: } v = \frac{16.3\ \frac{m}{d} \cdot 1.74\ m^2}{0.70\ m} = 40.5\ \frac{m}{d}$$

6. The Reynolds number (column 21) was calculated using the following equation:

$$Re = \frac{4\rho v R_h}{\mu} \qquad (3.1)$$

$$\text{ex: } Re = \frac{4 \cdot 1000\ \frac{kg}{m^3} \cdot 40.5\ \frac{m}{d} \cdot 0.269\ m \cdot \frac{1\ d}{24\ h} \cdot \frac{1\ h}{3600\ s}}{0.001\ \frac{kg}{m \cdot s}} = 504$$

7. The flowrate (column 22) was calculated by using the following equation:

$$Q = v \cdot A \qquad (3.5) \qquad \text{ex: } Q = 40.5\ \frac{m}{d} \cdot 0.70\ m^2 = 28.4\ \frac{m^3}{d}$$

8. The flowrate in units of m^3/d was converted to units of L/min (column 23).

9. The detention time (column 24) was calculated by using the following equation:

$$t_d = \frac{V}{Q} \qquad (3.2) \qquad \text{ex: } t_d = \frac{1.60\ m^3}{28.4\ \frac{m^3}{d}} \cdot \frac{24\ h}{d} \cdot 60\ \frac{min}{h} = 81\ min$$

The results of the manipulation of data in the table are shown in column 14 and 23, the corresponding flowrates for this experiment. The flowrates tested in the laboratory were: 20 L/min, 30 L/min and 40 L/min. They represent the full range of upflow rates suggested by the four sources.

The actual flowrates for each basin were measured with a 10 L graduated plastic container and a stopwatch. Three consecutive measurements of volume and time were taken from each basin's effluent stream at the end of the discharge pipe. The corresponding flowrates were calculated and averaged. From this value, the flowrates were adjusted accordingly by opening or closing the control valves.

3.2.2 CONCENTRATION

Once the medium to be used in the experiments was chosen, the concentration values had to be set. To obtain similar settling in the experimental model as in the actual full scale basins, kinematic similarity, through the densimetric Froude numbers, should be obtained as mentioned in Chapter 2 (Van Marle and Kranenburg, 1994; Zhou et al., 1992). Using actual streams from a wastewater treatment plant would not satisfy this condition. Using a supply tank and recycling inorganic solids through this tank is more appropriate for this level of research. Hawthorne bond fireclay was selected as the inorganic medium.

The Froude number for a typical secondary clarifier was calculated using the following values: an average upflow velocity of 25 m/d, an average water depth of 6 m, an influent concentration of 1000 mg/L of activated sludge, an activated sludge specific gravity (s.g.) of 1.3 for the solids, and a fluid density of 1000 kg/m^3 for the water in the tank (these averages were found in Metcalf & Eddy, 1991 and Table 3.2). The resulting densimetric Froude number for a typical secondary clarifier was 0.0025.

The maximum solids concentration selected for the high concentration setting in the experiment was 5000 mg/L. The average solids concentration value selected for the low concentration setting was 2000 mg/L. The densimetric Froude number calculated for the experimental model of the control basin was 0.0063 for the low concentration and was 0.0040 for the high concentration. These numbers were calculated using the conditions in the control basin and were: an average flow through velocity of 60 m/d an average water depth of 1 m, a solid particle s.g. of 2.65, a fluid density in the tank of 1000 kg/m^3.

The Froude number for the experimental basin containing inclined plates is different because the inlet water level is different as well as the flow through velocity which is much higher. The following numbers were used to calculate the Froude number. The average flow through velocity was set at 300 m/d, the average inlet water depth at 0.3 m, the solid particle s.g. at 2.65 and the fluid density at 1000 kg/m^3. The same value for maximum and minimum solids concentration were used as for the control basin. The resulting densimetric Froude numbers are 0.036 for the high solids concentration and 0.181 for the low concentration case.

The densimetric Froude numbers are sufficiently similar at 0.0025 for the actual clarifier versus 0.0040 for the highly concentrated suspension in the control basin and 0.0063 for the less concentrated suspension in the control basin. A study by Zhou et al. (1992) deemed a difference of 0.006 acceptable for Froude number similarity. A maximum difference of 0.0038 is found in this case. The Froude numbers for the experimental basin are not of the same magnitude and are not taken into consideration. Only the control basin Froude numbers are compared because they are on the same basis. The internal geometry of the experimental basins is completely different. With these results, the concentration values to be tested in the experiments were a group in a lower range of approximately 1500 to 2300 mg/L and a group in the higher range of 3000 to 5000 mg/L and higher. The higher concentration range was set at values of 3000 to 5000 mg/L due to limitations of the pumps. At the continuous highly concentrated suspensions, the pumps would overheat. Concentration values were not always constant. Since the results to be analyzed were the relative removal percentages and not the final total suspended solids value, this was acceptable.

3.2.3 DEPTH OVER INCLINED PLATES

The total liquid depth for these experiments was equal in all three basins. This was done to compare the behavior of same size basins that did and did not include inclined plates. Research on basins of different volumes would be the next logical step for future work. The selection of the depth for these experiments was based on two methods: the design of the laboratory scale clarifier in an important study by Cordoba-Molina et al. (1978) and the other by using length to width to depth ratios used in the design of full size sedimentation basins. This was done because the size of the experiment was four times larger than that of Cordoba-Molina et al. and was approximately 10 - 15 times smaller than a full scale basin.

The scaled down model utilized in the Cordoba-Molina et al. study simulated a circular clarifier. The diameter of this model was set at 1.22 m (4 ft) and the depth at an average of 0.46 m (1.5 ft). Since this was a center feed circular clarifier, it would correspond to a 0.61 m (2 ft) length and a 0.46 m depth for a rectangular basin. The Cordoba-Molina laboratory scale sizes give a depth to length ratio of 0.75:1.

Full scale basin designs vary widely but the most common size ratio was found to be (depth:length) 3.66 m (12 ft):30 m (100 ft) or 0.122:1 (Metcalf & Eddy, 1991). The average of this ratio and the Cordoba-Molina ratio is 0.44:1. This average ratio was used as a design guideline in this case due to the fact that the scale of this experiment lies between the range of a laboratory scale and a full scale. The ratio of 0.44:1 gives a resulting depth of 1.01 m for a basin length of 2.286 m.

Two different depths were tested during the experiment, a total depth of 0.92 m (3 ft) and 1.12 m (3 ft-8 in.). These values lie on either side of the average depth found from the length to depth ratios. The total basin depth was broken down in three sections in the experimental basins containing the inclined plates. The solids accumulation zone on the bottom remained constant at a depth set at 36 cm (14 in.) from the bottom floor. The inclined plates were located above this zone and these plates occupied a zone of 36 cm (14 in.) in depth. The remainder of the depth contained the flow through zone. Two different depths for this zone were tested, 20 cm (8 in.) and 40 cm (16 in.). The total basin depth for the control basin which did not contain any inclined plates was equal to the addition of all these depths. The total depth became 0.92 m (3 ft) for the first depth and 1.12 m (3 ft-8 in.) for the second depth tested. Refer to Fig. 3.4 for a description.

3.2.4 NUMBER OF INCLINED PLATES (OR SPACING BETWEEN THEM)

Only a few inclined plates were utilized. A minimum horizontal spacing between each plate of 35 cm (14 in.) was tested. This spacing gave a maximum total of five inclined plates in the basin. The choice of spacing was arbitrary. They had to prevent the combination of settled solids to the effluent stream, to provide a quiescent settling zone for particles to settle to the bottom (compared to conventional type designs) and to help confine the main flow of the basin to the top layer of the basin preventing short-circuiting or wasted space. A spacing of 70 cm (28 in.) was also chosen as a variable to be tested. This spacing gave a total of three inclined plates in the basin. Too small spacing creates problems found in lamella. However the spacing needs to be small enough to minimize the possibility of flow through the plates from the top.

3.2.5 SUMMARY OF VARIABLES

The variables involved in these experiments were mentioned previously. They are the flowrate, the solids concentration, the depth of water over the inclined plates, and the number of plates (or plate spacing). Table 3.4 summarizes the selected values for each variable.

Table 3.4 Variables and their values

Variables	1	2	3
Flowrate (L/min)	20	30	40
Solids Concentration (mg/L)	1500 - 2300	3000 - 5000	-
depth over inclined plates (m)	0.2	0.4	-
number of plates in the exp. Basin	3	5	-
spacing (cm)	70	35	

Each experiment took at least 8 hours to conduct including the preparation, sampling, and cleaning. Three runs could be performed simultaneously because, three parallel basins are available. Each experiment was run in duplicate.

3.3 SEDIMENTATION EXPERIMENT PROCEDURE

The main objective of the research work was to compare the removal efficiencies of a control sedimentation basin (designed following current conventional design standards) to that of two experimental basins (designed with inclined plates). The principal experiment consisted of runs through the three parallel basins previously described. This section describes the procedures followed for the main experiments. The procedures for the other tests performed during the course of this research including the TSS test, the settling column test and the tracer test using rhodamine WT will be described in the next sections.

3.3.1 ADJUSTING THE VARIABLES

The variables involved in the main runs were: the flowrate (Q), the solids concentration (C), the depth of water over the inclined plates (d) as well as the number of inclined plates (n) which had to be adjusted to their respective required values before each experiment.

3.3.1.1 Flowrate Adjustments

The three set flowrate values used during the course of the experiment were: 20, 30 and 40 L/min. The pumps were able to pump at slightly higher rates than these values. The flowrate was controlled with the flow control valve placed at the inlet of each three basins.

The three basins were first filled completely to the top level of the overflow weir with the pumps at maximum rate. Initial flowrate measurements were performed. Flow adjustments were made for each basin individually for each experiment. The flow was adjusted accordingly by closing the low control valve. After approximately ten minutes of continuous flow, the flowrates were measured again individually from all three basins at the effluent exit from the discharge pipes.

The flow was measured with a 10 L graduated container and a stopwatch. The flowrate from each discharge pipe was measured three times and then calculated and averaged. If the flowrate was too high, the valves were gradually closed and if the flowrate was too low the valves were opened as required.

Again, after ten minutes, the three flowrates were measured and calculated. This procedure was repeated until the desired flowrates were reached and stabilized.

3.3.1.2 Concentration Adjustment

Two TSS concentration levels were tested during the course of this experiment. A low concentration range varying from approximately 1500 mg/L to 2300 mg/L and a higher concentration range varying from approximately 3000 mg/L to 5000 mg/L were targeted. Due to the size of the supply basin and the entire apparatus, an exact concentration value for all the runs was difficult to attain. For this reason, ranges of concentration were targeted in each individual run.

All the low concentration experiments were grouped together in the lower ranges and those with higher concentrations were grouped together. Initially, with the volume of the supply tank and the desired concentration known, the initial quantity of solids required was calculated and was added. After this, the supply tank was mixed and preliminary samples were collected to compare the TSS concentration obtained in the tank relative to the amount added.

Since the TSS test is not instantaneous, results were unavailable at the same time as each experiment. After each experiment, the samples were analyzed for TSS immediately. These results were used as a guide as to the TSS concentration of the suspension in the supply tank. From this, it was possible to examine whether some solids should be added to replenish the supply basin or not. This method provided a control for the influent TSS concentration level.

This method was not very precise but since, the percent TSS removal efficiency was compared for each run and not the influent and effluent TSS concentrations in particular. All basins were receiving the same quality of influent.

To keep the solids concentration at approximately the same level during the course of a particular run, solids were added to the supply tank suspension intermittently. After a few trial runs, a system was developed. At the end of each run, the settled solids at the bottom of each sedimentation basin were vacuumed with a wet vacuum and collected in a graduated container. Since this amount of solids settled to the bottom during the run, it was added to the supply basin gradually during the course of the next run. The total volume of this slurry was divided in equal parts to be added every ten minutes to the supply tank. At the end of a run, the sedimentation basins were drained completely back into the supply tank.

To change from the lower concentration level (average of 2000 mg/L) to the higher concentration level (average of 5000 mg/L), more dry solids were added to the suspension in the supply tank. This amount was calculated from the existing concentration in the supply tank and the volume of suspension present. With initial TSS samples and tests this amount was adjusted.

To change from the higher concentration level to the lower one, some of the solids suspension solution had to be wasted through the bottom supply tank drain and clean dilution water had to be added until the desired concentration was obtained.

3.3.1.3 Depth over the Inclined Plates Adjustment

This variable had two set values, depths of 20 cm (8 in.) and 40 cm (16 in.) over the top level of the inclined plates. This depth was varied by selecting either the 20 cm or the 40 cm overflow weir. These weirs were removable, slide in place, pieces of plywood. They were easily interchangeable. Once one was selected and put in place, all the sides were sealed with silicone waterproof sealant to prevent any leaks below the top of the weir level. This was done in all three basins.

3.3.1.4 Number of Inclined Plates Adjustment

The three basins were designed to be able to receive a maximum of five slide in place inclined plates supported by steel angles. There were no inclined plates in the control basin. One of the two experimental basins had three inclined plates in place for all the runs [i.e., a plate in the first, third and fifth possible position or 70 cm (28 in.) apart]. The other experimental basin had five inclined plates [i.e., one in each possible position or 35 cm (14 in.) apart]. These plates had to be secured in place with clamps. This set-up was maintained throughout the experiments so that they could always be tested in parallel at equivalent operating conditions.

3.3.2 *FILLING AND STABILIZING*

To fill the three individual sedimentation basins, the following procedures were followed:

- the mixer in the supply tank was started,
- all three bottom drain valves of the sedimentation basins were closed tightly,
- the three influent flow control valves to all three basins were open completely to permit quick filling at the maximum possible flowrate,
- all three submersible pumps were started,
- the three basins were filled, the filling time was approximately 40 to 50 minutes,

- as the liquid level reached the top of the weirs, the flowrates to each basin were adjusted to the appropriate value,
- once the flowrates were all adjusted and stabilized, the clock was set at time zero,
- solids addition to the supply basin was started as explained in the previous section.

3.3.3 SAMPLING

Samples were collected at times of 60 and 120 min. To protect the pump motors from overheating, it was necessary to stop the experiment after 120 minutes. The theoretical residence times (t_d) were calculated for each basin's respective flow through volume for flowrates of 20, 30 and 40 L/min respectively, are displayed in Table 3.5.

Table 3.5 Theoretical residence times for each basin at each flowrate

		Theoretical retention time (min)		
Tank	Depth (m)	Q_1 (20 L/min)	Q_2 (30 L/min)	Q_3 (40 L/min)
control	0.92	80	53	40
control	1.12	96	64	48
experimental (with inclined plates)	0.92	17	12	9
experimental (with inclined plates)	1.12	35	23	17

The calculation of these retention times will be explained will be explained in greater detail in the discussion section for the tracer test.

Samples had to be collected at the three inlet sampling ports and at the end of the three discharge pipes of the three basins to characterize the influent and effluent. The samples were first collected at the discharge location and then at the inlet sampling port. Taking the samples of the influent first would disturb the flow in the basins and may have had an effect on the discharge samples. Individual samples of approximately 35 mL were collected directly in labeled sample bottles from the end of the three discharge pipes.

Samples from the influent were collected as follows. The sampling port valve was completely opened and the sampling port was cleaned out in a large container or bucket. After 2 or 3 L of influent had been collected and returned to the supply tank, a labeled sampling bottle was placed at the sampling port nozzle and a 35 mL sample was collected. The valve was then closed completely. This procedure was repeated for every sampling port. Every influent and effluent sample was taken in duplicate.

3.3.4 EMPTYING AND CLEANING

Once the run was terminated and all the samples were collected, the pumps and mixer were stopped and the three basins emptied. All three bottom drain valves into the supply tank were opened completely. The drains were located at the inlet end of the basins and the flows to the drains were slow enough to leave the settled solids on the basins' floors. Once the water had been transferred to the supply tank, the floors of the three basins were vacuumed and the basins were cleaned.

The vacuumed slurry was used during the following run by adding it gradually to the supply tank to replenish the supply of solids being depleted during the run.

To vacuum the three basins, the inclined plates had to be removed. The entire bottom surfaces of all three basins were cleaned. After this, the inclined plates could be replaced in their respective positions.

3.4 SUSPENDED SOLIDS TEST PROCEDURE

Solids present in a solution can be either suspended or dissolved in a solution. The total solids concentration of a stream includes both the TSS and the total dissolved solids. The TSS are those solids found on the filter after filtration. *Standard Methods for the Examination of Water and Wastewater* (1992) defines total dissolved solids as those solids that are retained by a filter of 2.0 μm or smaller pore size. Whatman GF/C filters were used for the TSS analysis in this research. They have a pore size of 1.2 μm.

The exact procedure followed for performing the total suspended solids test is found in *Standard Methods for the Examination of Water and Wastewater.* The procedure is listed in section 2540D, "Total Suspended Solids Dried at 103-105°C." This procedure was followed for all TSS tests.

3.5 SETTLING COLUMN TEST PROCEDURE

"Flocculant settling takes place when settling velocity of the particles increases due to coalescence with other particles."(Ramalho, 1983). The flocculant settling test is performed to obtain the range of settling velocities of the different solids present in solution or the suspension in question at different solution concentrations.

The test was performed in a Plexiglas column with an outer diameter of 15.24 cm (6 in.) and a height of 180 cm (6 ft). This column had sampling ports at heights of 28, 59, 84, and 120 cm measured from the bottom. The procedure followed for this test and the analysis of the results was taken from Ramalho (1983).

The major steps for the test itself and the data analysis are described in the next sub-sections.

3.5.1 SETTLING COLUMN TEST

1. The column was filled with the suspension to be tested at the desired concentration.
2. A uniform concentration throughout the column must be attained. In the case of this study, mixing was provided with 2 air stones bubbling compressed air through the suspension.
3. The mixing was stopped and the time recorded.
4. Samples of the suspension were extracted from each port at pre-determined times and the water level in the column was recorded. For each sample extraction, a 10 mL volume of suspension was first taken and discarded to rinse the sampling port of accumulated solids. Then a 20 mL volume sample was collected to be analyzed.
5. A TSS test was performed on each collected sample.
6. The data obtained were analyzed following the steps described in the data analysis section.

3.5.2 DATA ANALYSIS

Once the data had been collected and the test was complete, the following steps were followed to analyze this data.

1. The time of sampling, the sampling port number as well as the height of liquid in the column before the extraction were indicated for each sample.

2. The TSS concentrations versus time for each sampling port were recorded. Four curves were obtained.

3. The percentage removal of suspended solids versus time was calculated and plotted. The percentage removal of TSS could be calculated by using the following equation.

$$R = [(C_o - C_i) / C_o] \times 100 \tag{3.6}$$

4. The height of liquid above each port was obtained from the water level recorded at the time of sample extraction and the total depth of liquid in the column using the following equation. These procedures allow for the decreasing liquid levels as more samples are extracted.

$$d_x = H_i - H_p \tag{3.7}$$

where d_x depth of sampling port from interface, mm

H_i total height of liquid in column at time of sampling, mm

H_p height of the sampling port, mm

5. The corresponding time values for arbitrarily set removal rates were interpolated from the removal percent versus time curves for each sampling port. The corresponding depths of the interface were found using the data calculated in step 4 and plotted versus time for each set removal rate. These are called isoremoval curves.

6. From the isoremoval curves, the depth between each isoremoval (Δd_n) curve was obtained for set times.

7. These depths enable the calculation of the total removal at each time (t_i).

$$\text{total percent removal at } t_i = \Sigma[(\Delta d_n / d_t) * ((R_n + R_{n+1})/2)] \tag{3.8}$$

where d_n depth between isoremoval curves, mm

d_t total depth, mm

R_n, R_{n+1} removal percent of isoremoval curve n or n+1, %

8. The corresponding minimum settling velocities for the removed solid particles were found by dividing the column total depth of liquid by the elapsed time (t_i). The total percent of removed particles found in step 7 settle at this velocity or faster.

$$v_s = d_t / t_i \tag{3.9}$$

where v_s particle settling velocity, mm/min

9. The percentage of particles settling slower than the settling velocity (p_i) calculated in step 8 can be found by subtracting the total removal percent at time t_i found in step 7 from 100.

$$p_i = 100 - \text{total removal percent at } t_i \qquad (3.10)$$

10. A p-v plot can be made from the information found in steps 8 and 9.

The resulting p-v plot can then be analyzed to discover what settling velocity distribution exists in the sample at hand.

3.6 TRACER TEST PROCEDURE

The definition of a tracer can be stated as:

> "A tracer follows or outlines something else, the tracee. The tracer, a labeled species, must act the same as the non-labeled species in the system of interest, and its behavior must be representative of the whole population of the species. The tracer must not interfere with the process being studied." (Welch et al., 1972)

The dye, rhodamine WT (RWT), a pink dye, was used for the tracer tests in this research. The hydraulic behavior in the sedimentation basin during an experiment could be visualized by injecting this dye at the tank inlet. Flow behavior was analyzed theoretically by injecting a known amount of dye and monitoring the effluent dye concentration over time. Samples were collected at different time intervals until the dye concentration was no longer detectable. The concentration of the dye RWT was measured using a fluorometer. The procedure to follow for calibrating the fluorometer, sampling and measuring the RWT concentration can be found in Appendix B. The data analysis procedure to find the actual basin retention times will be described in Section 5.2.

For tracer test no. 3, approximately 75 mg of RWT tracer were injected and for tracer tests no. 1, 2 and 4, 50 mg of RWT tracer were injected. Samples of the tank effluent were collected frequently to capture the variation of the RWT concentration with time. For the case of this project, samples were collected at approximately every 60 s for the first 15 min, then at every 2.5 min for the next 15 min, every 5 min for the following 30 min and finally every 10 min for the next 30 min.

CHAPTER 4

RESULTS

The main sedimentation experiments were those performed in the tank which, as described, was divided into three individual parallel sedimentation basins. The three basins were always used simultaneously resulting in three sedimentation experiments run in parallel. The three basins included the control and two experimental sedimentation basins (one containing 3 inclined plates and the other containing 5 inclined plates). This configuration remained constant throughout the main sedimentation experiments while the flowrate, concentration and depth over the inclined plates were changed.

The results obtained from the experiments conducted throughout this research work were compiled and presented in this chapter. The tests performed include for the settling column tests, tracer tests as well as total suspended solids tests and are presented in separate sections. Chapter 5 will discuss these results.

4.1 SETTLING COLUMN TEST RESULTS

Settling column tests were performed to investigate the composition of solid suspension samples. More precisely, this test gives a particle settling velocity distribution for the different solid particles present in the suspension.

The first suspension sample tested was a potential candidate for the main sedimentation experiments of this study. The sample was kaolin clay called Hydrite flat D obtained from a clay supplier called Debro Chemicals (see Appendix A for additional supplier information). A 23 L suspension with a concentration of 10 000 mg/L was created and placed in the settling column. This was done to simulate the maximum possible concentration conditions in the sedimentation experiments. The results of this first settling column test labeled settling test no. 1 are shown in Fig. 4.1, a p-v chart displaying the percentage of particles settling slower than the corresponding settling velocities. The raw data can be found in Appendix C. The manipulation of the data was explained in Chapter 3.

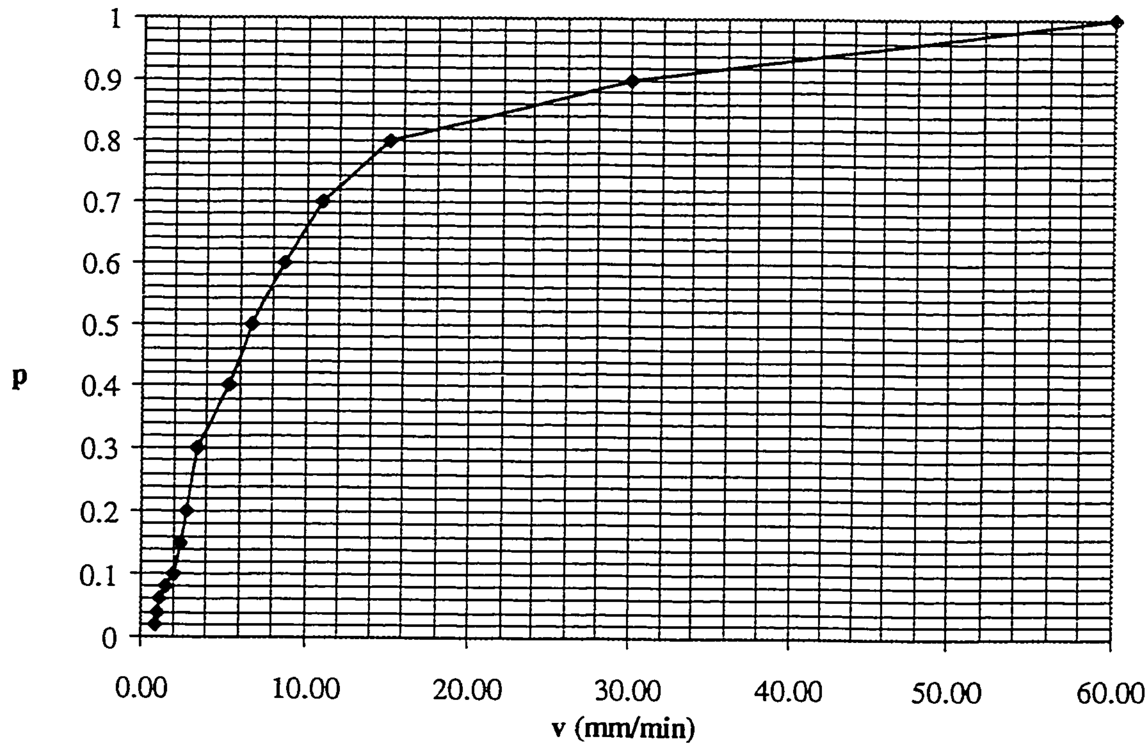

Figure 4.1 Kaolin clay settling velocity distribution curve (settling test no. 1)

The settling column test no. 2 was performed on a second candidate for the sediment in the sedimentation experiments. This solid sample was Hawthorne fire bond clay (see Appendix A for additional supplier information). A 23 L suspension was created with an initial solid concentration equal to that of the previous test of 10000 mg/L. Figure 4.2 displays the resulting percent of particle solids settling slower than the corresponding settling velocity (p-v chart) for the fire bond clay. The raw data are presented in Appendix C.

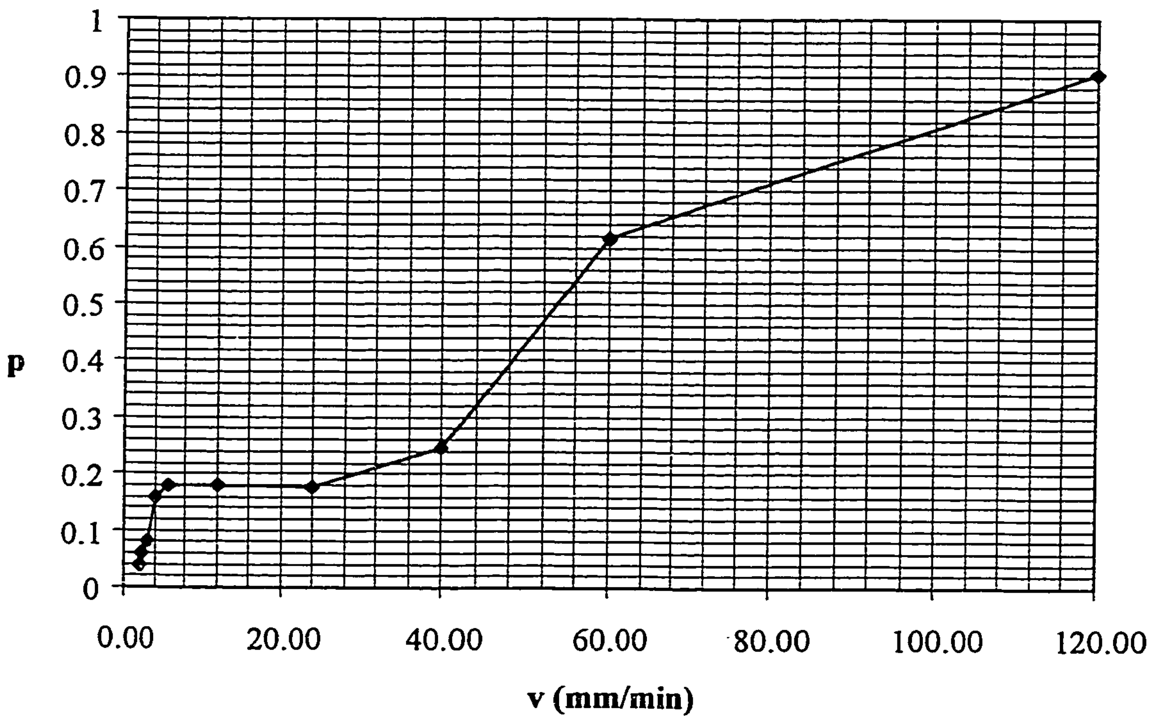

Figure 4.2 Fire bond clay settling velocity distribution curve (settling test no. 2)

After analyzing the results of the preliminary column settling tests on these two samples, the Hawthorne fire bond clay was selected as the medium for the suspension to be used in the main settling experiments). Once this medium was chosen, the sedimentation experiments were started.

During the sedimentation experiments, samples of the influent and effluent to the basins were taken to obtain the composition of actual streams entering and exiting the basins. The settling velocity distributions present in the streams were obtained for several runs. Samples for settling velocity analysis were extracted from the influent stream to the basin containing 5 inclined plates and from the effluent stream of both the control basin and the basin containing 5 inclined plates.

The experimental conditions were: a flowrate of 30 L/min (the average value), a depth over the inclined plates of 20 cm (total depth = 112 cm) and an influent TSS concentration in the high range (6570 mg/L). It was assumed that the influent to both basins was similar due to the fact that the supply source was the same for both basins.

Settling column test no. 3 was performed on a sample from the influent to the basin containing 5 inclined plates and produced the following p-v chart, Fig. 4.3. The raw data are presented in Appendix C. Samples taken from the effluent streams of the control basin and the basin containing 5 inclined plates were also subjected to the column settling test and labeled test no. 4 and 5 respectively. The concentration of TSS from the control basin effluent was 5150 mg/L while the concentration of TSS from the basin containing 5 inclined plates was 5070 mg/L. The resulting TSS removals were 21.6% removal for the control basin and 22.8% for the experimental basin. The p-v charts for both cases are presented in Fig. 4.3 and the raw data can be found in Appendix C.

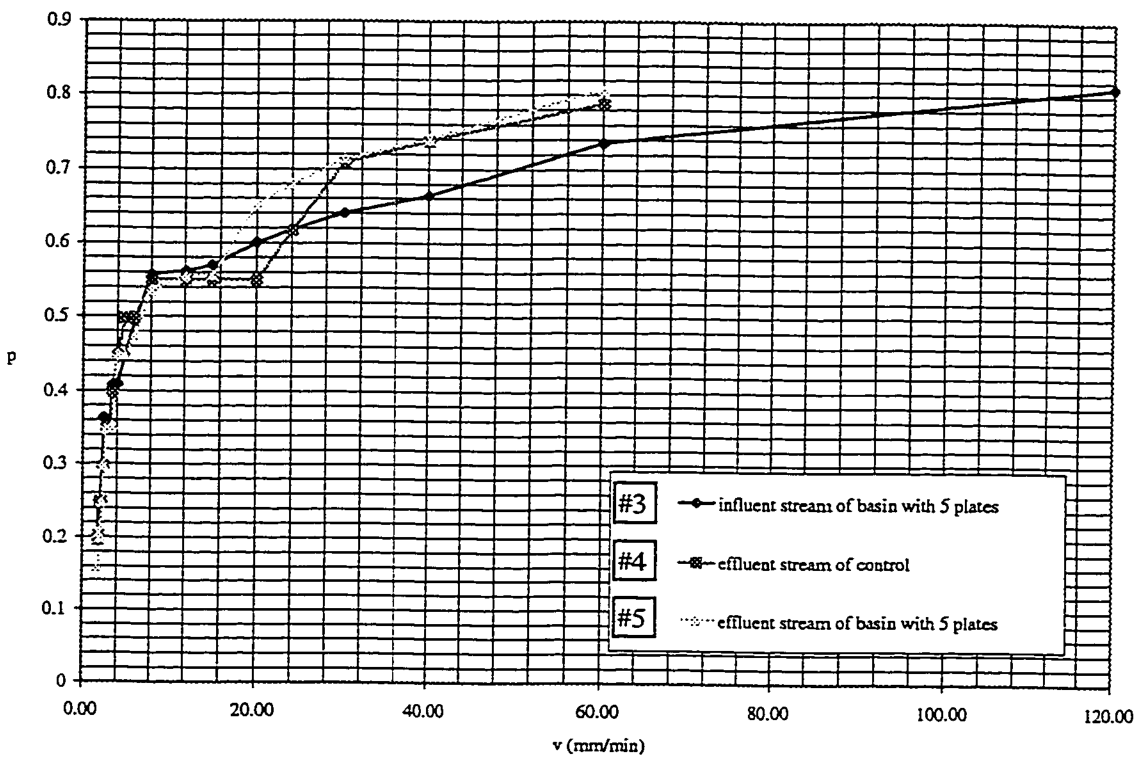

Figure 4.3 **Settling velocity distribution of influent to basin with 5 plates (settling test no. 3), effluent of control basin (test no. 4) and basin with 5 plates (test no. 5)**

4.2 TRACER TEST RESULTS

Four RWT tracer tests were performed. The tracer tests are described as follows:

no. 1 - control basin, total depth of 1.12 m,

no. 2 - control basin, total depth of 0.92 m,

no. 3 - experimental basin containing 5 inclined plates, total depth of 1.12 m (40 cm over plates)

no. 4 - experimental basin containing 5 inclined plates, total depth of 1.12 m (20 cm over plates)

The flowrate was set at 30 L/min for all four tests to provide an equal comparison. To perform these tests, the outlet pipes were rearranged to discharge to the sewer and not to the supply tank to avoid recirculation of the tracer. The four tests were done during four separate runs. The same calibration curve applies to all four runs because all the tests were done within two weeks. RWT decay is insignificant over this time period. The linear regression of the calibration curve gives a relationship between the fluorometer readings and the RWT concentration. The equation for the calibration curve in this case is:

$$y = 0.0009x \tag{4.1}$$

where y = RWT concentration, mg/L
x = fluorometer reading, [0]

The results of the RWT tracer test no. 1 are displayed in Fig. 4.4. All the tracer tests are plotted as E versus time, E is the age distribution and has units of s^{-1}. The appropriate calculations are shown in Appendix B. The table listing the sample times along with the fluorometer readings and corresponding RWT concentrations in mg/L can be found in Appendix B. The fluorometer readings were converted to RWT concentrations using the calibration curve equation.

The equivalent results are shown in Fig 4.5 for the tracer test done in the control basin, tracer test no. 2, with a total depth of 0.92 m. (equivalent to 20 cm over the inclined plates for the experimental basins). The data for this plot can be found in Appendix B.

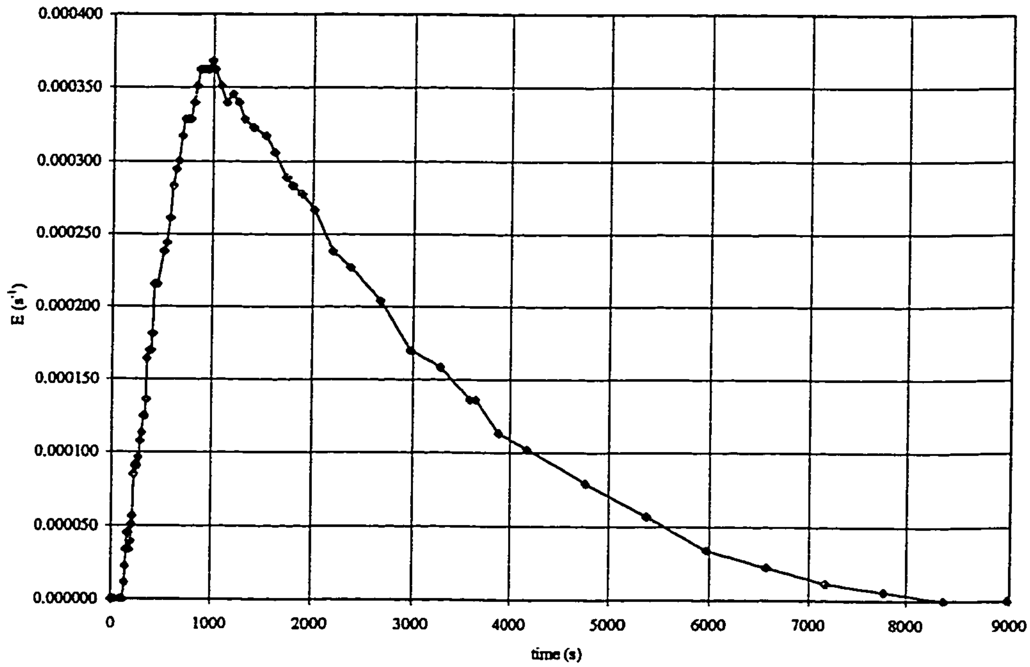

Figure 4.4 **Results of RWT tracer test no. 1**
(control basin, total depth of 1.12 m, Q = 30 L/min)

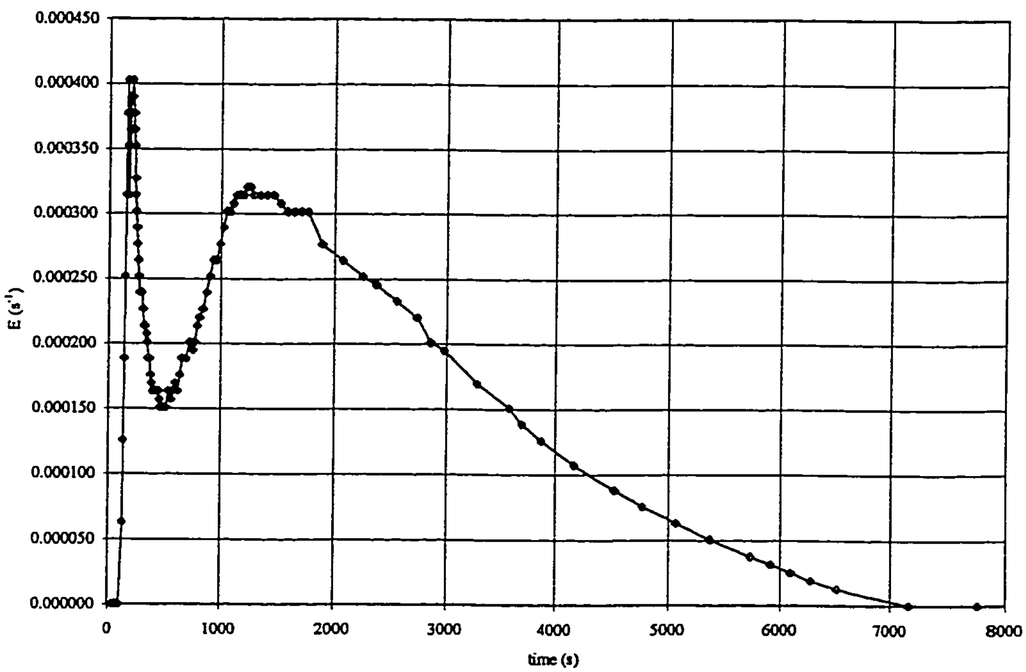

Figure 4.5 **Results of RWT tracer test no. 2**
(control basin, total depth of 0.92 m, Q = 30 L/min)

The RWT Tracer Test No. 3 was then performed in the experimental basin containing 5 inclined plates. A depth of 40 cm over the plates was used (equivalent to a total depth of 1.121 m). The flowrate was kept at 30 L/min. Figure 4.6, shows the results of this test and the data can be found in Appendix B. The same calibration curve mentioned above was used.

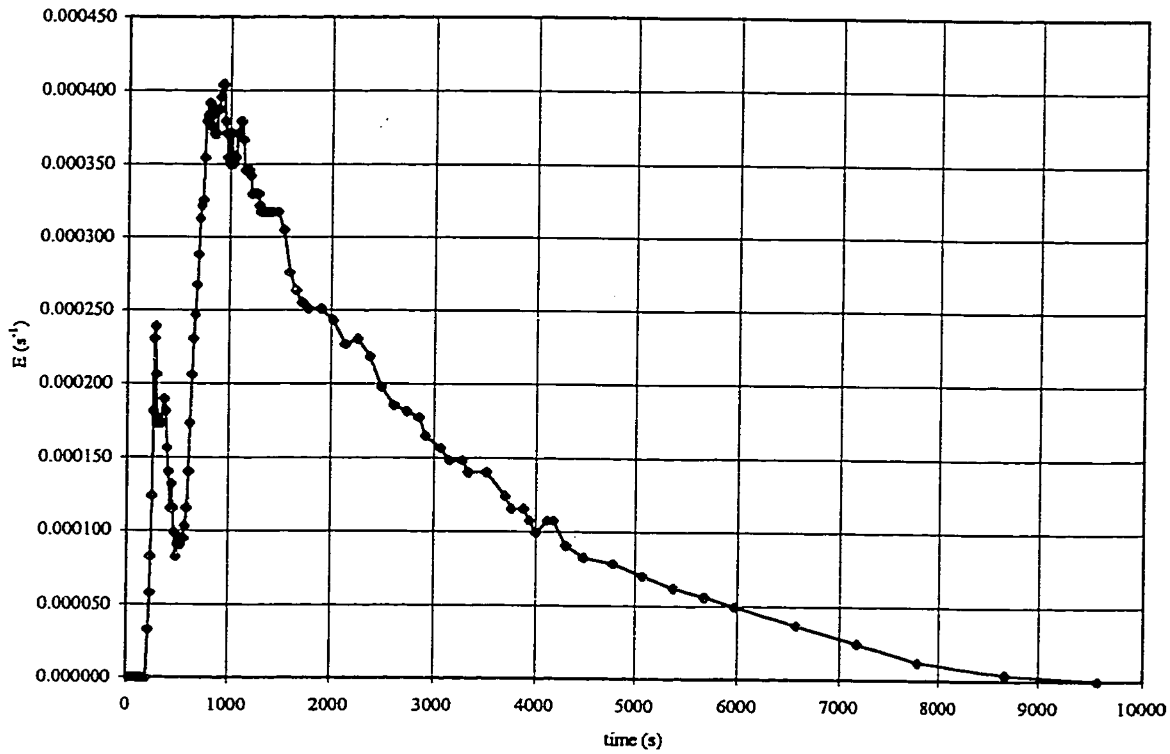

Figure 4.6 Results of RWT tracer test no. 3

(experimental basin with 5 inclined plates, total depth of 1.12 m, Q = 30 L/min)

Tracer test no. 4 was performed in the experimental basin containing 5 inclined plates. A depth of 20 cm over the inclined plates (equivalent to 0.92 m) was used with a flowrate of 30 L/min. The results are displayed in Fig. 4.7 and in Appendix B.

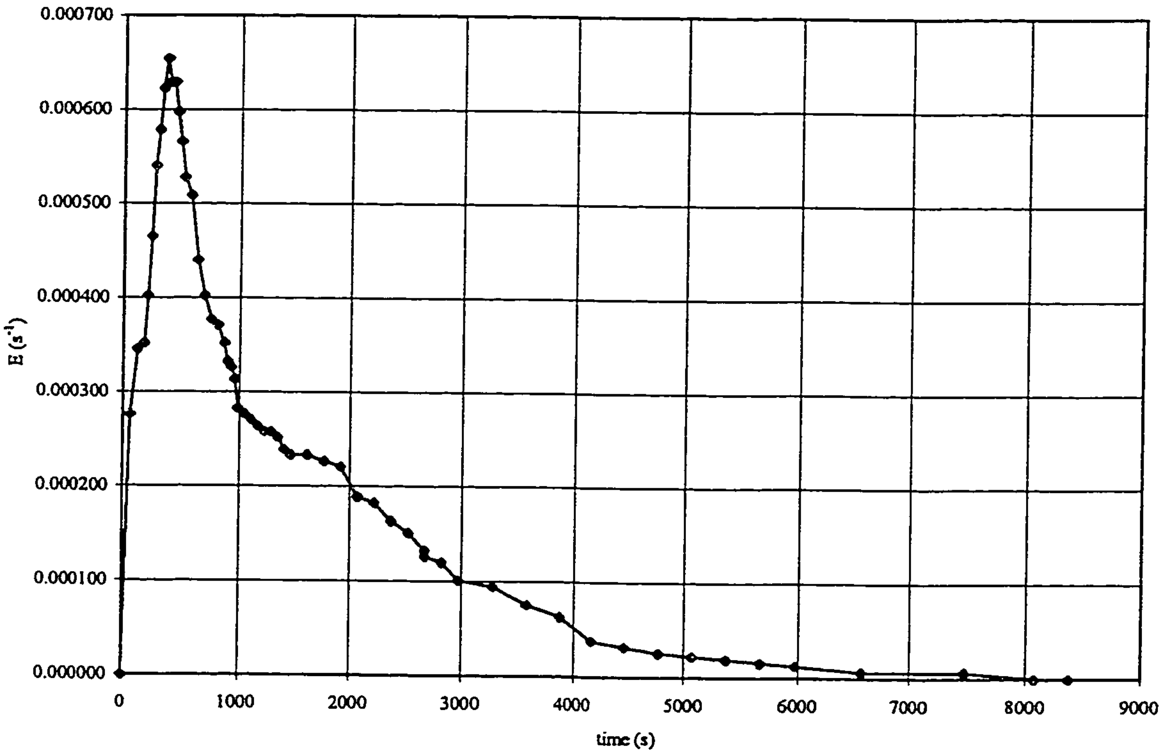

Figure 4.7 Results of RWT tracer test no. 4

(experimental basin with 5 inclined plates, total depth of 0.92 m, Q = 30 L/min)

4.3 TOTAL SUSPENDED SOLIDS TESTS

TSS measurements were made to determine the efficiency of the sedimentation basins.

A sample was collected at the influent end as well as at the effluent end of each basin at the pre-determined times of 60 and 120 minutes. In some experiments samples were collected at slightly differing times and sampling times are indicated where this applies.

The first test was the reproducibility test. The TSS concentration was conducted in triplicate for each sample. The test was performed to show the accuracy of the TSS test. This test was done on samples collected from the influent and effluent to the sedimentation basins during experimental runs. The results can be found in Table 4.1.

Table 4.1 TSS reproducibility test[a]

Sample. no.	location of sample	no. of inclined plates	C_1 mg/L	C_2 mg/L	C_3 mg/L	mean mg/L	std. dev. mg/L	std. dev. %
1	influent	0	5905	5800	5873	5859	53.8	0.92
2			5812	5846	5827	5828	17.0	0.29
3			5796	5809	5829	5811	16.6	0.29
4			5755	5733	5764	5751	15.9	0.28
5	influent	5	5669	5642	5655	5655	13.5	0.24
6			5725	5746	5733	5735	10.6	0.18
7			5798	5771	5762	5777	18.7	0.32
8			5803	5829	5831	5821	15.6	0.27
9	effluent	0	5176	5204	5158	5179	23.2	0.45
10			5080	5092	5055	5076	18.9	0.37
11			5134	5159	5153	5149	13.1	0.25
12			5221	5198	5185	5201	18.2	0.35
13	effluent	5	5284	5297	5303	5295	9.7	0.18
14			5190	5182	5211	5194	15.0	0.29
15			5025	5043	5057	5042	16.0	0.32
16			5133	5146	5162	5147	14.5	0.28
						average	18.2	0.3

a- The 16 samples were taken from experimental runs and were divided into three samples to test for reproducibility of the TSS test. The TSS of the three samples were measured and the symbols C_1, C_2 and C_3 represent those three samples.

The main experimental runs were then performed. The three basins were used in parallel, employing the same experimental variable settings for all three. The variables to be tested were the number of plates, the flowrate into the basins, the solids concentration of the suspension to be clarified and the depth of flow over the inclined plates as well as the number of inclined plates. Values for those variables are indicated in Chapter 3. All the results were compiled into three consecutive tables, Table 4.2 for the control basin, Table 4.3 for the experimental basin containing 5 inclined plates and Table 4.4 for the experimental basin containing 3 inclined plates. The tables display all the TSS concentrations in mg/L with all the operating conditions for each sample of the sedimentation tests as well as the resulting removal percent.

The consistency of the influent streams concentration was tested by comparing the resulting TSS concentrations of the duplicate or triplicate samples. The last three columns of the three tables show the mean and standard deviation in mg/L as well as in percent. This was done to determine the extent of the TSS concentration variation in a 1 to 2 minute time span.

The superscripts in the following three tables represent:

* - depth of flow over inclined plates, for the control basin, 20 cm is equivalent to a total basin depth of 0.92 m and 40 cm to 1.12 m with no inclined plates

[a] - TSS concentration of influent suspension

[b] - TSS concentration of effluent suspension

[c] - removal = (concentration of influent – concentration of effluent)/concentration of influent

Table 4.2 Compiled TSS results for the control basin with consistency statistical analysis

			Control Basin			Statistical Analysis					
						C_1			C_2		
flowrate (L/min)	depth* (cm)	time (min)	C_1[a] (mg/L)	C_2[b] (mg/L)	removal[c] (%)	mean	std.dev. (mg/L)	std.dev. %	mean	std.dev. (mg/L)	std.dev. %
30	40	60	1562	1228	21.4	-	-	-	-	-	-
30	40	120	1680	1208	28.1	-	-	-	-	-	-
30	40	180	2139	1238	42.1	-	-	-	-	-	-
30	40	60	1531	1176	23.2	-	-	-	-	-	-
30	40	90	1673	1226	26.7	-	-	-	-	-	-
30	40	120	1948	1079	44.6	-	-	-	-	-	-
42	40	40	1400	1231	12.1	-	-	-	-	-	-
42	40	60	1503	1227	18.4	-	-	-	-	-	-
42	40	80	1562	1233	21.1	-	-	-	-	-	-
42	40	100	1578	1408	10.8	-	-	-	-	-	-
42	40	120	2052	1374	33.0	-	-	-	-	-	-
30	40	65	1303	1053	19.2	1549	282.3	18.23	1089	56.7	5.20
30	40	65	1486	1059	28.7						
30	40	65	1857	1154	37.9						
20	40	100	2307	1102	52.2	2122	213.2	10.05	1198	84.5	7.05
20	40	100	1889	1231	34.8						
20	40	100	2171	1261	41.9						
20	40	60	2983	1538	48.4	2970	19.1	0.64	1575	51.6	3.28
20	40	60	2956	1611	45.5						
20	40	120	3561	1997	43.9	3588	38.2	1.06	2016	26.2	1.30
20	40	120	3615	2034	43.7						
20	40	60	2953	1842	37.6	2865	125.2	4.37	1818	34.6	1.91
20	40	60	2776	1793	35.4						
20	40	120	2950	2100	28.8	2931	26.9	0.92	2084	22.6	1.09
20	40	120	2912	2068	29.0						
30	40	60	2576	1850	28.2	2680	147.1	5.49	1868	24.7	1.33
30	40	60	2784	1885	32.3						
30	40	120	3273	2051	37.3	3335	87.7	2.63	2039	17.0	0.83
30	40	120	3397	2027	40.3						
30	40	60	2915	1587	45.6	2929	19.1	0.65	1586	2.1	0.13
30	40	60	2942	1584	46.2						
30	40	120	2993	1973	34.1	2946	66.5	2.26	1938	49.5	2.55
30	40	120	2899	1903	34.4						
40	40	60	3000	1824	39.2	3035	48.8	1.61	1891	94.8	5.01
40	40	60	3069	1958	36.2						
40	40	120	3021	2104	30.4	2925	135.8	4.64	2113	12.0	0.57
40	40	120	2829	2121	25.0						
40	40	60	3147	2023	35.7	3282	190.2	5.80	2050	38.2	1.86
40	40	60	3416	2077	39.2						
40	40	120	3257	2471	24.1	3370	159.8	4.74	2380	129.4	5.44
40	40	120	3483	2288	34.3						
40	40	60	2388	1422	40.5	2400	17.0	0.71	1691	379.7	22.46
40	40	60	2412	1959	18.8						
40	40	120	2791	2070	25.8	2779	17.0	0.61	2017	75.0	3.72
40	40	120	2767	1964	29.0						
30	40	60	2058	1588	22.8	2002	79.2	3.96	1645	80.6	4.90
30	40	60	1946	1702	12.5						
30	40	120	2161	1547	28.4	2183	30.4	1.39	1529	25.5	1.66
30	40	120	2204	1511	31.4						
40	40	60	1504	1326	11.8	1558	75.7	4.86	1320	9.2	0.70
40	40	60	1611	1313	18.5						
40	40	120	1684	1345	20.1	1699	21.2	1.25	1376	43.8	3.19
40	40	120	1714	1407	17.9						
20	40	60	1904	1174	38.3	1911	9.9	0.52	1184	13.4	1.14
20	40	60	1918	1193	37.8						

Table 4.2 (Continued)

20	40	120	1701	1226	27.9	1770	97.6	5.51	1238	17.0	1.37
20	40	120	1839	1250	32.0						
40	40	60	2030	1331	34.4	2175	204.4	9.40	1367	50.9	3.72
40	40	60	2319	1403	39.5						
40	40	120	1792	1362	24.0	1866	104.7	5.61	1385	32.5	2.35
40	40	120	1940	1408	27.4						
20	40	60	1576	1223	22.4	1691	162.1	9.59	1214	13.4	1.11
20	40	60	1805	1204	33.3						
20	40	120	1600	1192	25.5	1712	157.9	9.22	1163	41.0	3.53
20	40	120	1823	1134	37.8						
30	20	60	2000	1379	31.1	1966	48.8	2.48	1344	49.5	3.68
30	20	60	1931	1309	32.2						
30	20	120	1997	1405	29.6	1965	45.3	2.30	1405	0.7	0.05
30	20	120	1933	1404	27.4						
30	20	60	1992	1377	30.9	1932	84.9	4.39	1385	11.3	0.82
30	20	60	1872	1393	25.6						
30	20	120	2250	1464	34.9	2289	54.4	2.38	1460	6.4	0.44
30	20	120	2327	1455	37.5						
20	20	60	2448	1436	41.3	2467	26.9	1.09	1420	22.6	1.59
20	20	60	2486	1404	43.5						
20	20	120	2586	1502	41.9	2448	195.9	8.00	1510	10.6	0.70
20	20	120	2309	1517	41.3						
40	20	60	2109	1471	30.3	2063	65.1	3.15	1474	3.5	0.24
40	20	60	2017	1476	26.8						
40	20	120	1609	1409	12.4	1585	33.9	2.14	1436	37.5	2.61
40	20	120	1561	1462	6.3						
40	20	60	1390	1205	13.3	1384	8.5	0.61	1181	33.9	2.87
40	20	60	1378	1157	16.0						
40	20	120	1445	1264	12.5	1504	83.4	5.55	1278	19.8	1.55
40	20	120	1563	1292	17.3						
20	20	60	1614	1149	28.8	1567	66.5	4.24	1142	10.6	0.93
20	20	60	1520	1134	25.4						
20	20	120	1680	1192	29.0	1737	80.6	4.64	1187	7.1	0.60
20	20	120	1794	1182	34.1						
60	20	60	2576	1833	28.8	2625	69.3	2.64	1847	19.8	1.07
60	20	60	2674	1861	30.4						
60	20	120	3063	1975	35.5	2988	106.8	3.57	1983	11.3	0.57
60	20	120	2912	1991	31.6						
30	20	60	4494	2372	47.2	4372	173.2	3.96	2430	82.0	3.38
30	20	60	4249	2488	41.4						
30	20	120	4750	2888	39.2	4785	48.8	1.02	2813	106.8	3.80
30	20	120	4819	2737	43.2						
40	20	60	4724	3400	28.0	4675	70.0	1.50	3412	17.0	0.50
40	20	60	4625	3424	26.0						
40	20	120	5663	3739	34.0	5745	116.0	2.02	3773	48.1	1.27
40	20	120	5827	3807	34.7						
40	20	60	5738	4105	28.5	5748	14.1	0.25	4045	84.9	2.10
40	20	60	5758	3985	30.8						
40	20	120	6221	4456	28.4	6149	101.8	1.66	4480	33.2	0.74
40	20	120	6077	4503	25.9						
20	20	60	6605	4503	31.8	6547	82.7	1.26	4472	44.5	1.00
20	20	60	6488	4440	31.6						
20	20	120	7663	4772	37.7	7614	70.0	0.92	4763	12.7	0.27
20	20	120	7564	4754	37.1						
20	20	60	7043	5042	28.4	7474	608.8	8.15	5076	47.4	0.93
20	20	60	7904	5109	35.4						
20	20	120	7532	5362	28.8	7706	245.4	3.18	5373	14.8	0.28
20	20	120	7879	5383	31.7						
						Avg.	**100.8**	**3.7**	**Avg.**	**43.2**	**2.4**

Table 4.3 Compiled TSS results for the experimental basin with 5 inclined plates with consistency statistical analysis

			Experimental Basin 5 Inclined Plates			Statistical Analysis					
						C_1			C_2		
flowrate (L/min)	depth* (cm)	time (min)	C_1[a] (mg/L)	C_2[b] (mg/L)	removal[c] (%)	mean	std.dev. (mg/L)	std.dev. %	mean	std.dev. (mg/L)	std.dev. %
30	40	60	1657	1209	27.0	-	-	-	-	-	-
30	40	120	1630	1268	22.2	-	-	-	-	-	-
30	40	180	2005	1324	34.0	-	-	-	-	-	-
30	40	60	1529	1198	21.6	-	-	-	-	-	-
30	40	90	1754	1251	28.7	-	-	-	-	-	-
30	40	120	2560	942	63.2	-	-	-	-	-	-
42	40	40	1616	1182	26.9	-	-	-	-	-	-
42	40	60	1518	1227	19.2	-	-	-	-	-	-
42	40	80	1630	1271	22.0	-	-	-	-	-	-
42	40	100	1666	1275	23.5	-	-	-	-	-	-
42	40	120	2032	1410	30.6	-	-	-	-	-	-
30	40	65	1370	1061	22.6	1585	232.0	14.63	1145	123.1	10.75
30	40	65	1555	1087	30.1						
30	40	65	1831	1286	29.8						
20	40	100	1678	1038	38.1	1863	179.8	9.65	1096	54.5	4.97
20	40	100	2037	1105	45.8						
20	40	100	1874	1146	38.8						
20	40	60	3023	1518	49.8	3224	283.5	8.80	1532	19.8	1.29
20	40	60	3424	1546	54.8						
20	40	120	3673	1656	54.9	3672	1.4	0.04	1749	131.5	7.52
20	40	120	3671	1842	49.8						
20	40	60	2828	1742	38.4	3167	479.4	15.14	1757	20.5	1.17
20	40	60	3506	1771	49.5						
20	40	120	3205	1886	41.2	3222	23.3	0.72	1862	34.6	1.86
20	40	120	3238	1837	43.3						
30	40	60	2784	1891	32.1	2713	101.1	3.73	1885	8.5	0.45
30	40	60	2641	1879	28.9						
30	40	120	3249	2051	36.9	3425	248.2	7.25	2053	2.1	0.10
30	40	120	3600	2054	42.9						
30	40	60	3185	1728	45.7	3007	251.7	8.37	1705	32.5	1.91
30	40	60	2829	1682	40.5						
30	40	120	3292	1954	40.6	3100	272.2	8.78	1934	28.3	1.46
30	40	120	2907	1914	34.2						
40	40	60	3177	2005	36.9	3171	8.5	0.27	2006	0.7	0.04
40	40	60	3165	2006	36.6						
40	40	120	3095	2176	29.7	3607	724.1	20.07	2161	21.2	0.98
40	40	120	4119	2146	47.9						
40	40	60	3571	2074	41.9	3545	36.8	1.04	2105	43.1	2.05
40	40	60	3519	2135	39.3						
40	40	120	3256	2164	33.5	3301	63.6	1.93	2241	108.9	4.86
40	40	120	3346	2318	30.7						
40	40	60	2375	1854	21.9	2334	58.0	2.48	1855	1.4	0.08
40	40	60	2293	1856	19.1						
40	40	120	2814	1989	29.3	2927	159.8	5.46	1979	14.8	0.75
40	40	120	3040	1968	35.3						
30	40	60	2060	1571	23.7	2133	102.5	4.81	1586	20.5	1.29
30	40	60	2205	1600	27.4						
30	40	120	2284	1641	28.2	2316	44.5	1.92	1656	20.5	1.24
30	40	120	2347	1670	28.8						
40	40	60	1668	1267	24.0	1799	185.3	10.30	1302	48.8	3.75
40	40	60	1930	1336	30.8						
40	40	120	1636	1194	27.0	1705	96.9	5.68	1267	102.5	8.10
40	40	120	1773	1339	24.5						
20	40	60	1839	1297	29.5	1847	11.3	0.61	1289	11.3	0.88
20	40	60	1855	1281	30.9						
20	40	120	1951	1354	30.6	1891	85.6	4.53	1352	3.5	0.26

Table 4.3 (Continued)

20	40	120	1830	1349	26.3						
40	40	60	1751	1306	25.4	1778	37.5	2.11	1282	34.6	2.70
40	40	60	1804	1257	30.3						
40	40	120	1877	1333	29.0	1841	51.6	2.80	1338	7.1	0.53
40	40	120	1804	1343	25.6						
20	40	60	1844	1211	34.3	1799	63.1	3.51	1210	2.1	0.18
20	40	60	1754	1208	31.1						
20	40	120	1805	1231	31.8	1863	81.5	4.37	1252	29.0	2.32
20	40	120	1921	1272	33.8						
30	20	60	1919	1342	30.1	1890	41.7	2.21	1347	6.4	0.47
30	20	60	1860	1351	27.4						
30	20	120	1967	1379	29.9	1942	35.4	1.82	1385	7.8	0.56
30	20	120	1917	1390	27.5						
30	20	60	1862	1360	27.0	1840	31.1	1.69	1369	12.7	0.93
30	20	60	1818	1378	24.2						
30	20	120	2129	1652	22.4	2066	89.1	4.31	1625	38.9	2.39
30	20	120	2003	1597	20.3						
20	20	60	2075	1448	30.2	2118	60.1	2.84	1442	8.5	0.59
20	20	60	2160	1436	33.5						
20	20	120	2500	1509	34.6	2403	137.9	5.74	1530	29.0	1.90
20	20	120	2305	1550	38.0						
40	20	60	1931	1388	28.1	1966	48.8	2.48	1411	32.5	2.31
40	20	60	2000	1434	28.3						
40	20	120	1600	1394	12.9	1609	12.0	0.75	1377	24.7	1.80
40	20	120	1617	1359	16.0						
40	20	60	1424	1205	15.4	1422	3.5	0.25	1202	4.9	0.41
40	20	60	1419	1198	15.6						
40	20	120	1511	1242	17.8	1543	44.5	2.89	1226	22.6	1.85
40	20	120	1574	1210	23.1						
20	20	60	1415	1138	19.6	1477	87.7	5.94	1131	10.6	0.94
20	20	60	1539	1123	27.0						
20	20	120	1541	1160	24.7	1552	15.6	1.00	1155	7.8	0.67
20	20	120	1563	1149	26.5						
60	20	60	2609	1733	33.6	2614	7.1	0.27	1722	15.6	0.90
60	20	60	2619	1711	34.7						
60	20	120	3061	1853	39.5	3031	43.1	1.42	1864	14.8	0.80
60	20	120	3000	1874	37.5						
30	20	60	4043	2296	43.2	4004	55.2	1.38	2364	96.2	4.07
30	20	60	3965	2432	38.7						
30	20	120	4844	2675	44.8	4790	76.4	1.59	2630	64.3	2.45
30	20	120	4736	2584	45.4						
40	20	60	4728	3004	36.5	4663	92.6	1.99	3009	6.4	0.21
40	20	60	4597	3013	34.5						
40	20	120	5358	3478	35.1	5323	50.2	0.94	3505	38.2	1.09
40	20	120	5287	3532	33.2						
40	20	60	5664	3990	29.6	5636	40.3	0.72	3952	54.4	1.38
40	20	60	5607	3913	30.2						
40	20	120	6172	4277	30.7	6110	88.4	1.45	4212	92.6	2.20
40	20	120	6047	4146	31.4						
20	20	60	6087	4415	27.5	5936	213.5	3.60	4335	113.1	2.61
20	20	60	5785	4255	26.4						
20	20	120	7616	4522	40.6	7563	75.7	1.00	4447	106.1	2.39
20	20	120	7509	4372	41.8						
20	20	60	6750	4905	27.3	6710	57.3	0.85	4951	65.1	1.31
20	20	60	6669	4997	25.1						
20	20	120	7484	5202	30.5	7413	101.1	1.36	5194	12.0	0.23
20	20	120	7341	5185	29.4						
						Avg.	**107.8**	**3.9**	**Avg.**	**36.2**	**1.9**

Table 4.4 Compiled TSS results for the experimental basin with 3 inclined plates with consistency statistical analysis

			Experimental Basin 3 Inclined Plates			Statistical Analysis					
						C_1			C_2		
flowrate (L/min)	depth* (cm)	time (min)	C_1[a] (mg/L)	C_2[b] (mg/L)	removal[c] (%)	mean	std.dev. (mg/L)	std.dev. %	mean	std.dev. (mg/L)	std.dev. %
30	40	60	1571	1174	25.3	-	-	-	-	-	-
30	40	120	1619	1182	27.0	-	-	-	-	-	-
30	40	180	1872	1238	33.9	-	-	-	-	-	-
30	40	60	1556	1156	25.7	-	-	-	-	-	-
30	40	90	1734	1173	32.4	-	-	-	-	-	-
30	40	120	1924	1195	37.9	-	-	-	-	-	-
42	40	40	1477	1185	19.8	-	-	-	-	-	-
42	40	60	1501	1172	21.9	-	-	-	-	-	-
42	40	80	1478	1292	12.6	-	-	-	-	-	-
42	40	100	1608	1252	22.1	-	-	-	-	-	-
42	40	120	2027	1667	17.8	-	-	-	-	-	-
30	40	65	1330	1055	20.7	1510	218.3	14.45	1103	51.9	4.70
30	40	65	1448	1096	24.3						
30	40	65	1753	1158	33.9						
20	40	100	1217	959	21.2	1260	38.4	3.05	1002	38.8	3.87
20	40	100	1272	1034	18.7						
20	40	100	1291	1014	21.5						
20	40	60	2850	1510	47.0	2868	25.5	0.89	1402	152.7	10.89
20	40	60	2886	1294	55.2						
20	40	120	4158	1567	62.3	3779	536.0	14.18	1581	19.8	1.25
20	40	120	3400	1595	53.1						
20	40	60	1939	1510	22.1	1946	9.2	0.47	1526	22.6	1.48
20	40	60	1952	1542	21.0						
20	40	120	2885	1862	35.5	2849	51.6	1.81	1919	79.9	4.16
20	40	120	2812	1975	29.8						
30	40	60	2634	1834	30.4	2681	65.8	2.45	1782	73.5	4.13
30	40	60	2727	1730	36.6						
30	40	120	3117	1956	37.2	3130	18.4	0.59	1878	110.3	5.87
30	40	120	3143	1800	42.7						
30	40	60	2833	1694	40.2	2836	3.5	0.12	1698	5.7	0.33
30	40	60	2838	1702	40.0						
30	40	120	2815	1916	31.9	2760	77.8	2.82	1931	20.5	1.06
30	40	120	2705	1945	28.1						
40	40	60	2887	1988	31.1	2888	1.4	0.05	1984	6.4	0.32
40	40	60	2889	1979	31.5						
40	40	120	2740	2132	22.2	2762	31.1	1.13	2105	38.9	1.85
40	40	120	2784	2077	25.4						
40	40	60	2939	2071	29.5	3019	112.4	3.72	2073	2.8	0.14
40	40	60	3098	2075	33.0						
40	40	120	3156	2375	24.7	3128	40.3	1.29	2350	35.4	1.50
40	40	120	3099	2325	25.0						
40	40	60	2286	1878	17.8	2293	9.9	0.43	1873	7.1	0.38
40	40	60	2300	1868	18.8						
40	40	120	2759	1991	27.8	2724	50.2	1.84	1992	0.7	0.04
40	40	120	2688	1992	25.9						
30	40	60	1911	1552	18.8	1995	118.1	5.92	1546	8.5	0.55
30	40	60	2078	1540	25.9						
30	40	120	2012	1648	18.1	2079	94.8	4.56	1666	24.7	1.49
30	40	120	2146	1683	21.6						
40	40	60	1587	1346	15.2	1560	38.9	2.49	1355	12.7	0.94
40	40	60	1532	1364	11.0						
40	40	120	1655	1189	28.2	1692	52.3	3.09	1230	58.0	4.71
40	40	120	1729	1271	26.5						
20	40	60	1834	1277	30.4	1897	89.1	4.70	1271	8.5	0.67
20	40	60	1960	1265	35.5						
20	40	120	1818	1340	26.3	1845	37.5	2.03	1324	22.6	1.71

Table 4.4 (Continued)

20	40	120	1871	1308	30.1						
40	40	60	1833	1243	32.2	1834	0.7	0.04	1330	122.3	9.20
40	40	60	1834	1416	22.8						
40	40	120	1908	1408	26.2	1916	10.6	0.55	1454	65.1	4.47
40	40	120	1923	1500	22.0						
20	40	60	1686	1283	23.9	1708	31.9	1.87	1237	65.1	5.26
20	40	60	1731	1191	31.2						
20	40	120	1803	1168	35.2	1999	277.5	13.88	1203	48.8	4.06
20	40	120	2195	1237	43.7						
30	20	60	1823	1394	23.5	1840	24.0	1.31	1412	24.7	1.75
30	20	60	1857	1429	23.0						
30	20	120	1878	1481	21.1	1959	113.8	5.81	1478	4.2	0.29
30	20	120	2039	1475	27.7						
30	20	60	1848	1344	27.3	1861	18.4	0.99	1371	37.5	2.73
30	20	60	1874	1397	25.5						
30	20	120	2048	1396	31.8	2122	103.9	4.90	1498	144.2	9.63
30	20	120	2195	1600	27.1						
20	20	60	2141	1426	33.4	2111	43.1	2.04	1461	48.8	3.34
20	20	60	2080	1495	28.1						
20	20	120	2246	1497	35.1	2272	36.1	1.59	1519	30.4	2.00
20	20	120	2297	1540	33.0						
40	20	60	1739	1436	17.4	1788	69.3	3.88	1471	48.8	3.32
40	20	60	1837	1505	18.1						
40	20	120	1600	1364	14.8	1632	44.5	2.73	1382	25.5	1.84
40	20	120	1663	1400	15.8						
40	20	60	1443	1196	17.1	1442	1.4	0.10	1315	168.3	12.80
40	20	60	1441	1434	0.5						
40	20	120	1478	1206	18.4	1494	21.9	1.47	1233	37.5	3.04
40	20	120	1509	1259	16.6						
20	20	60	1550	1096	29.3	1571	29.0	1.85	1114	24.7	2.22
20	20	60	1591	1131	28.9						
20	20	120	1676	1161	30.7	1695	26.2	1.54	1154	10.6	0.92
20	20	120	1713	1146	33.1						
60	20	60	2596	1809	30.3	2624	39.6	1.51	1831	30.4	1.66
60	20	60	2652	1852	30.2						
60	20	120	2888	1959	32.2	2910	31.1	1.07	1983	33.9	1.71
60	20	120	2932	2007	31.5						
30	20	60	3884	2470	36.4	3941	80.6	2.05	2471	0.7	0.03
30	20	60	3998	2471	38.2						
30	20	120	4656	2759	40.7	4704	67.9	1.44	2864	147.8	5.16
30	20	120	4752	2968	37.5						
40	20	60	4584	3348	27.0	4657	103.2	2.22	3351	3.5	0.11
40	20	60	4730	3353	29.1						
40	20	120	5385	3735	30.6	5432	65.8	1.21	3807	101.1	2.66
40	20	120	5478	3878	29.2						
40	20	60	5446	4425	18.7	5537	128.7	2.32	4280	205.1	4.79
40	20	60	5628	4135	26.5						
40	20	120	5931	4566	23.0	5901	42.4	0.72	4510	79.9	1.77
40	20	120	5871	4453	24.2						
20	20	60	6184	4120	33.4	6159	36.1	0.59	4208	124.5	2.96
20	20	60	6133	4296	30.0						
20	20	120	5781	3865	33.1	5851	99.0	1.69	3946	114.6	2.90
20	20	120	5921	4027	32.0						
20	20	60	6514	4952	24.0	6598	118.8	1.80	4932	29.0	0.59
20	20	60	6682	4911	26.5						
20	20	120	7134	5048	29.2	7343	295.6	4.03	5171	173.2	3.35
20	20	120	7552	5293	29.9						
						Avg.	73.6	2.7	Avg.	55.0	2.9

CHAPTER 5

DISCUSSION

The results of this research study are interpreted in this chapter. The results are discussed in several sections, viz., the column settling test results, the tracer test results and TSS test results tests. The interpretation of these results is kept in these categories. A general summary of discussion follows these sections.

5.1 COLUMN SETTLING TESTS

The first two column settling tests were performed on two potential solid sample candidates to be used as the sediment in the main experiments. The first sample, kaolin clay, contained solid particles that settled much slower than the second sample, fire bond clay. Figure 4.1 of settling test no. 1, shows that 100% of the solid particles in the kaolin clay settled slower than 60 mm/min. Figure 4.2 of the settling test no. 2, shows that only 62% of the particles in the fire bond clay settle slower than 60 mm/min; 90% of the particles settle slower than 120 mm/min.

The settling velocity distribution range is twice as large for the fire bond clay compared to the kaolin clay. The suspension selection depended on the settling velocity range present in the solid sample. A range of settling velocities from 20 mm/min to over 260 mm/min would be ideal. This range of values for the settling velocities were obtained from Table 3.2. The flowrates to be used in the experiments vary from 20 to 40 L/min. These flowrates are equivalent to flow through velocities varying from 30 to 375 m/d or 20 to 260 mm/min for the different basin configurations. More than half of the solids on a mass basis in the fire bond clay are in this range. The fire bond clay was selected; its settling velocity distribution was satisfactory. The relative differences between removal percentages will be considered to arrive at any conclusions on TSS removal efficiencies.

The next settling column tests were performed on three samples taken from the sedimentation basins during an actual experimental run. At the end of the run, samples of 23 L each were collected from the control basin effluent, the influent as well as the effluent to the basin with 5 inclined plates to provide settling velocity distributions actually entering and exiting the sedimentation basins.

The settling velocity distribution of the stream entering the sedimentation basins (test no. 3) is displayed in Fig. 4.3. This figure shows that approximately 80% of the particles settle slower than 120 mm/min. 20% of the particles' settling velocities exceed this value. Also, approximately 50% of the particles settle slower than 6 mm/min. The stream contains particles settling as slow as 2 mm/min.

Figure 4.3 also displays the settling velocity distributions of the effluent streams from the control basin (test no. 4) and from the basin containing 5 inclined plates (test no. 5). They show that in the control basin and in the experimental basin containing 5 inclined plates approximately 80% of the solid particles settled slower than 60 mm/min and 50% of the particles settle slower than 6 mm/min. This same percentage was found in the influent stream sample. Therefore, these solid particles velocities are too slow to settle out of suspension in either basin.

These results show that the faster settling particles have settled out of the influent stream in both the control and the basin with 5 inclined plates. The settling velocity distributions for the effluent from both these tanks are very similar in shape. This indicates that particles having similar or equal settling velocities were able to settle in both the control basin and in the experimental basin containing 5 inclined plates. The reduction in the flow through zone in the case of the experimental basin with inclined plates did not affect the removal capability of the basin. This is an indication that the experimental basin was able to perform on a level equivalent to that of the control basin on this particular comparison from the point of view of the settling velocity of the particles removed.

5.2 TRACER TEST

Four tracer tests were performed. The results are displayed in the form of plots of the tracer age distribution versus time. From the resulting tracer test data, a value for the actual retention time of each test was found. The calculations to obtain this will be explained. Dividing this value with the theoretical retention time for each case gives the fraction of the volume of the basin actually utilized.

The theoretical retention time can be calculated by dividing the basin's flow through volume by the flowrate of the stream entering the basin and is displayed for each case in Table 5.2. The reliability of the tracer tests can be assessed by comparing the amount of tracer added with the amount of tracer recovered in the test. The amount of tracer recovered (Table 5.2) is calculated and shown in Tables B.2 to B.5. The amount of tracer added in tests no. 1, 2 and 4 was 50 mg and 75 mg in test no. 3.

The tracer test results enable the calculation of the actual retention time. The calculations are as follows (Levenspiel, 1972):

1. With a list of the sample times, calculate the time elapsed between each sample, t_i.

$$\Delta t = t_i - t_{i-1} \tag{5.1}$$

where Δt time elapsed between sample times, s
t_i time of sampling, s

2. Find the age distribution curve by first calculating the area under the time concentration curve. The area under the time concentration curve is equal to the sum of time multiplied by the concentration for each individual point.

$$Q_i = \Delta t \times C_i$$
$$Q = \sum Q_i \tag{5.2, 5.3}$$

where C tracer concentration, mg/L
Q area under time concentration curve, s-mg/L

3. The age distribution must then be found and plotted.

$$E_i = \frac{C_i}{Q}$$
$$E = \sum E_i \tag{5.4, 5.5}$$

where E age distribution, s^{-1}

4. The actual retention can be calculated using the age distribution.

$$t_d = \sum \frac{t_i E_i}{E_i} \tag{5.6}$$

where t_d actual retention time, s

5. The variance can also be calculated.

$$\sigma^2 = \frac{\sum t_i^2 E_i}{\sum E_i} - \bar{t}^2 \tag{5.7}$$

where σ^2 variance, s^2
σ standard deviation, s

These calculations were performed on the data found from the four individual tracer tests. Table 5.1 displays the actual retention time calculations for tracer test no. 1.

The same calculations were then performed for the next three tracer tests (tracer tests no. 2, no. 3 and no. 4). The results are displayed in Tables B.6, B.7 and B.8.

Table 5.1 Actual retention time and variance calculation for tracer test no. 1

t_i sample time (s)	fluoro-meter reading	C_i - RWT conc. (mg/L)[a]	$(t_i - t_{i-1})$ (s)	$Q_i=(t_i - t_{i-1})*C_i$ (s*mg/l)	$E_i=C_i/Q$ (s^{-1})	(t_i*E_i)	$(t_i^2*E_i)$ (s)
5	0	0.0000	35	0.0000	0.000000	0.00000	0.00
35	0	0.0000	30	0.0000	0.000000	0.00000	0.00
95	0	0.0000	60	0.0000	0.000000	0.00000	0.00
125	0	0.0000	30	0.0000	0.000000	0.00000	0.00
140	1	0.0009	15	0.0136	0.000011	0.00159	0.22
145	2	0.0018	4.98	0.0090	0.000023	0.00328	0.48
155	3	0.0027	10.02	0.0272	0.000034	0.00527	0.82
165	4	0.0036	10.02	0.0362	0.000045	0.00748	1.23
175	4	0.0036	9.96	0.0360	0.000045	0.00793	1.39
185	3	0.0027	10.02	0.0272	0.000034	0.00629	1.16
195	3.5	0.0032	10.02	0.0317	0.000040	0.00773	1.51
205	4.5	0.0041	9.96	0.0405	0.000051	0.01045	2.14
215	5	0.0045	10.02	0.0453	0.000057	0.01218	2.62
225	7.5	0.0068	10.02	0.0679	0.000085	0.01911	4.30
235	8	0.0072	9.96	0.0720	0.000091	0.02129	5.00
245	8	0.0072	10.02	0.0725	0.000091	0.02220	5.44
260	8	0.0072	15	0.1085	0.000091	0.02356	6.13
275	8.5	0.0077	15	0.1153	0.000096	0.02647	7.28
290	9.5	0.0086	15	0.1288	0.000108	0.03120	9.05
305	10	0.0090	15	0.1356	0.000113	0.03454	10.54
320	11	0.0099	15	0.1492	0.000125	0.03987	12.76
335	11	0.0099	15	0.1492	0.000125	0.04174	13.98
350	12	0.0108	15	0.1627	0.000136	0.04757	16.65
353	14.5	0.0131	3	0.0393	0.000164	0.05797	20.46
380	15	0.0136	27	0.3662	0.000170	0.06456	24.53
395	15	0.0136	15	0.2034	0.000170	0.06711	26.51
410	16	0.0145	15	0.2170	0.000181	0.07430	30.46
425	19	0.0172	15	0.2577	0.000215	0.09146	38.87
440	19	0.0172	15	0.2577	0.000215	0.09468	41.66
455	19	0.0172	15	0.2577	0.000215	0.09791	44.55
515	21	0.0190	60	1.1392	0.000238	0.12249	63.08
545	21.5	0.0194	30	0.5832	0.000244	0.13271	72.33
575	23	0.0208	30	0.6239	0.000260	0.14978	86.13
605	25	0.0226	30	0.6781	0.000283	0.17130	103.64
635	26	0.0235	30	0.7052	0.000294	0.18699	118.74
665	26.5	0.0240	30	0.7188	0.000300	0.19959	132.73
695	28	0.0253	30	0.7595	0.000317	0.22040	153.18
725	29	0.0262	30	0.7866	0.000328	0.23813	172.64

Table 5.1 (Continued)

755	29	0.0262	30	0.7866	0.000328	0.24798	187.22
785	29	0.0262	30	0.7866	0.000328	0.25783	202.40
815	30	0.0271	30	0.8137	0.000340	0.27692	225.69
845	31	0.0280	30	0.8409	0.000351	0.29668	250.70
875	32	0.0289	30	0.8680	0.000362	0.31712	277.48
905	32	0.0289	30	0.8680	0.000362	0.32800	296.84
935	32	0.0289	30	0.8680	0.000362	0.33887	316.84
965	32	0.0289	30	0.8680	0.000362	0.34974	337.50
995	32.5	0.0294	30	0.8816	0.000368	0.36625	364.42
1025	32	0.0289	30	0.8680	0.000362	0.37149	380.78
1085	31	0.0280	60	1.6817	0.000351	0.38095	413.33
1145	30	0.0271	60	1.6275	0.000340	0.38904	445.45
1205	30.5	0.0276	60	1.6546	0.000345	0.41625	501.59
1265	30	0.0271	60	1.6275	0.000340	0.42982	543.72
1325	29	0.0262	60	1.5732	0.000328	0.43520	576.64
1415	28.5	0.0258	90	2.3192	0.000323	0.45674	646.29
1535	28	0.0253	120	3.0380	0.000317	0.48679	747.22
1625	27	0.0244	90	2.1971	0.000306	0.49692	807.50
1745	25.5	0.0231	120	2.7667	0.000289	0.50397	879.43
1805	25	0.0226	60	1.3562	0.000283	0.51108	922.50
1895	24.5	0.0222	90	1.9937	0.000277	0.52583	996.45
2015	23.5	0.0212	120	2.5497	0.000266	0.53631	1080.66
2195	21	0.0190	180	3.4177	0.000238	0.52207	1145.93
2375	20	0.0181	180	3.2550	0.000227	0.53798	1277.70
2675	18	0.0163	300	4.8825	0.000204	0.54534	1458.79
2975	15	0.0136	300	4.0687	0.000170	0.50542	1503.61
3275	14	0.0127	300	3.7975	0.000159	0.51929	1700.68
3575	12	0.0108	300	3.2550	0.000136	0.48588	1737.02
3635	12	0.0108	60	0.6510	0.000136	0.49403	1795.81
3875	10	0.0090	240	2.1700	0.000113	0.43888	1700.65
4175	9	0.0081	300	2.4412	0.000102	0.42557	1776.75
4775	7	0.0063	600	3.7975	0.000079	0.37857	1807.66
5375	5	0.0045	600	2.7125	0.000057	0.30438	1636.06
5975	3	0.0027	600	1.6275	0.000034	0.20302	1213.02
6575	2	0.0018	600	1.0850	0.000023	0.14894	979.25
7175	1	0.0009	600	0.5425	0.000011	0.08126	583.06
7775	0.5	0.0005	600	0.2712	0.000006	0.04403	342.33
8375	0	0.0000	600	0.0000	0.000000	0.00000	0.00
8975	0	0.0000	600	0.0000	0.000000	0.00000	0.00
				Q = 79.8314	**E =** 0.013982	**sum(t_i*E_i)** 16.6935	**sum(t_i^2*E_i)** 33291.15

[a] - [RWT] = (fluorometer reading)/1106 from calibration curve

t_d = 1194 s, σ^2 = 955523 s^2, σ =978 s

Table 5.2 shows a summary of the actual retention times, the variances and the percent of tracer recovered from each tracer test.

Table 5.2 Summary of tracer test calculations

Tracer Test No.	# of inclined plates	total basin depth (m)	flowrate (L/min)	theoretical t_d (min)[a]	actual t_d sec (min)	σ^2 (s^2)	% RWT recovered
1	0	1.12	30	63.7	1194 (19.9)	955522	(39.9/50) * 100 80%
2	0	0.92	30	52.3	950 (15.8)	990421	(35.9/50) * 100 72%
3	5	1.12	30	23.2	1286 (21.4)	951780	(54.8/75) * 100 73%
4	5	0.92	30	11.6	900 (15)	728037	(33.7/50) * 100 67%

a - The theoretical retention time is equal to the basin flow through volume divided by the flowrate. The specific calculations are shown in Table 5.3.

Table 5.2 shows that the amounts of RWT tracer recovered varied between 67 and 80%. These percentages are too low to enable concrete conclusions as to the basins' hydrodynamic behavior. They are however high enough to permit relative observations between basins. Possible reasons behind the RWT tracer amounts lost or not recovered are seepage or diffusion of tracer to the basins parallel to the basin being tested, loss of tracer at the time of injection or in the injection device, adsorption of tracer on the plywood basin boundaries or inclined plates, and experimental error in laboratory measurements. Some color was observed in the water of the tank adjacent to the one being tested with the tracer and this is due to the fact that the basins could not be completely isolated from each other. It was also observed that the plywood used as a barrier between the basins and as inclined plates was slightly pink in color after the tests were performed.

The variance represents the square of the spread of the distribution. The actual magnitude of the variance for a certain basin indicates whether a basin's hydraulics are plug flow, complete mixed flow, or intermediate. A variance of zero would represent a perfect plug flow without longitudinal mixing. A large variance approaching infinity would represent a complete mixed flow. The basins involved in this research all have a hydraulic behavior that lies between plug flow and complete mixed flow. They all have variances that are quite large and of the same relative magnitude. When their variances are compared, it can be observed that they all have similar hydraulic behavior.

The experimental basin with 5 plates at a depth over the plates of 20 cm has the lowest variance making it the basin configuration that most closely approaches plug flow. This basin at a depth of 40 cm above the plates is slightly more "plug flow" than the control basin at a total depth of 1.12 m. The control basin with a total depth of 0.92 m is the closest, relatively speaking, to a complete mixed basin. These results indicate that as the depth over the inclined plates is decreased, the easier it is for the flow to go through the basin uniformly and undisturbed. It may be observed that confining the flow to a narrow zone over the plates slightly enhances the basin's plug flow behavior. However, as this layer becomes deeper, the hydraulic behavior quickly starts to resemble that of the control basins with no inclined plates.

Next, the actual retention times can be compared to the theoretical retention times. The percent of utilized volume was calculated and results are shown in Table 5.3. In the case of the experimental basins, the volume used for the retention time calculation is the flow through zone volume located above the inclined plates. It was assumed that no flow passes through the plates because it is a quiescent settling zone and the volume below these plates is the sludge accumulation zone which also has no flow. In the case of the control basin, the volume used for the theoretical retention time calculations was the entire basin volume.

Table 5.3 Actual and theoretical retention times

Tracer Test No.	Variable Settings			Depth of Flow Volume[b] (m)	Length of Basin (m)	Width of Basin (m)	Volume Flow Zone[c] (m^3)	**Theoretical Retention Time[d] (min)**	**Actual Ret. Time[e] (min)**	**Volume Utilized[f] (%)**
	No. of Incl. Plates[a]	Flowrate (L/min)	Depth over Plates (m)							
1	0	30	1.12 (total)	1.1	2.29	0.76	1.91	63.67	19.9	31.2
2	0	30	0.92 (total)	0.9	2.29	0.76	1.57	52.33	15.8	30.2
3	5	30	0.4	0.4	2.29	0.76	0.70	23.21	21.4	92.2
4	5	30	0.2	0.2	2.29	0.76	0.35	11.60	15	129

[a] - This indicates the number of inclined plates present in the basin during the tracer test. Zero inclined plates means that the basin was a control basin.

[b] - The depth of the flow through volume of the basin is equal to the total depth of the basin in the case of the control basin. The experimental basin flow through volume is situated above the inclined plates.

[c] - The volume of the flow through zone is equal to the depth of the flow through zone multiplied by the length and the width of the basin.

[d] - The theoretical retention time is equal to the basin flow through volume divided by the flowrate.

[e] - The actual retention time was calculated previously.

[f] - The volume utilized is equal to the actual retention time divided by the theoretical retention time.

The numbers seem to indicate that the volume of the conventionally designed sedimentation basin could be reduced or better utilized because there is evidence of short-circuiting and dead. Both configurations of the control basins, regardless of the 20 cm increase in total depth prove to have only 30.2% and 31.2% of their volume utilized. The increase in depth did not significantly improve its hydraulic behavior.

The addition of the inclined plates in a basin of the same size as the conventionally designed basin seems to significantly reduce the dead volume and/or short-circuiting. In the experimental basin with a depth of 40 cm over the inclined plates, the flow through volume is almost completely utilized. In fact, 92.2% of the basin's flow through volume is utilized. The reduction in flow through zone does benefit in it being able to better use its available space. Therefore the remainder of the basin volume can be put to use by preventing scour and providing a quiescent settling zone as opposed to just being wasted or not utilized costly flow through volume.

For the case of the experimental basin with a depth of 20 cm over the plates, the results are not as positive. The tracer test shows that the volume utilized is greater than its available flow through volume. Tracer was visually observed to be infiltrating between the inclined plates and flowing below the plates. These results indicate that a 20 cm depth was not sufficient and that flow was penetrating in the inclined plates zone. The effective volume of the control basin is almost equivalent to the experimental. Experimental error may also be a reason for the percentage of volume utilized to be much larger than 100%.

Overall these results indicate that the inclined plates can provide a better utilization of flow through volume. Short-circuiting or dead volume appear to be less a problem than they were in the control basin. The depth available over the inclined plates becomes a compromise between better plug flow behavior for a more shallow depth and insufficient volume producing penetration of flow between the plates. The actual detention time that was closest to its theoretical value was that of the basin with inclined plates and a depth of 40 cm over these plates. It showed significant evidence of better use of flow through volume.

Section 5.3 will indicate the changes in the TSS removal efficiency when inclined plates are added and certain conditions are varied.

5.3 TOTAL SUSPENDED SOLIDS TESTS

5.3.1 REPRODUCIBILITY TEST

The reproducibility of the TSS test was studied to determine its accuracy. Sixteen samples were each divided into three samples and their respective TSS content was measured. Table 4.6 displays the results and they show very good reproducibility. Standard deviations varying from 0.18 to 0.92% were found. These numbers prove that the actual TSS measured from a given sample can be very well reproduced with the same sample within 1%. The TSS test's accuracy is therefore reliable and reproducible.

5.3.2 CONSISTENCY TEST

Since the common supply basin for all three sedimentation basins was quite large, the dependability of the mixing was tested. All three submersible pumps feeding all three sedimentation basins were situated at the same depth in the supply basin at approximately 30 cm (1 ft) apart. It was necessary to determine whether the suspension taken from each pump was constant from one minute to the other. Duplicate and several triplicate samples were extracted from each inlet sampling port of the basins for each experimental run. The resulting TSS concentrations for these samples are shown in Tables 4.2, 4.3 and 4.4 along with the other TSS results for each experimental run. The results are compiled individually for each basin namely: the control basin, the basin containing five inclined plates [or having a plate spacing of 35 cm (14 in.)] and the basin containing three inclined plates [or having a spacing of 70 cm (28 in.)].

A mean and standard deviation were calculated for each duplicate or triplicate TSS test performed on the influent samples. From the above mentioned tables it can be realized that average values of 3.7% standard deviations were obtained from the influent samples and 2.4% from effluent samples for the control basin. The average standard deviations for the experimental basin containing 5 inclined plates were 3.9 and 1.9% for the influent and effluent samples respectively. Standard deviations of 2.7 and 2.9% for the influent and effluent respectively of the experimental basin with 3 inclined plates were found. Overall standard deviations ranged from 2.7 to 3.9% for the influent and from 1.9 to 2.9% for the effluent samples.

Such values for the standard deviations of duplicate or triplicate samples for the experimental runs are quite acceptable. The influent standard deviations indicate that the mixing was adequate and all three supply pumps are capable of providing a stream of consistent TSS loading to the basins and the TSS test results appear to be representative of the influent streams. A maximum standard deviation difference of 0.4 to 4.3% exists between samples of the same port taken one or two minutes apart. An average standard deviation of 3.3% exists between all influent duplicate sets of samples. Feed concentration varies with time but it varied equally for each basin and all the three basins are kept at the same level. These types of influent conditions are typical of feed to sedimentation basins in actual treatment plants.

The effluent TSS concentration standard deviations point out that the effluent streams also have a consistent concentration and that the resulting TSS concentrations of the samples are representative of the effluent streams.

5.3.3 BASIN EFFICIENCY

Table 4.2, 4.3 and 4.4 display the results obtained for the TSS removal efficiencies for each experimental run. Operating conditions are all indicated. For each run, the flowrate and the depth over the plates settings are stated along with the different times of sampling and the influent and effluent TSS concentrations for each individual basin. The TSS removal is calculated and expressed as a percentage for each basin.

In the following sections these results are compiled to determine the different effects of the basin modifications of adding inclined plates to the different basin removal efficiencies. Also, the effects of time, flowrate, inlet TSS concentration and depth on the basins performance are considered as well as the effect of inlet TSS concentration on the outlet TSS concentration.

The t-test is used in this research to determine whether or not two calculated means of removal efficiency are significantly or statistically different. The calculations for this test are displayed in

Appendix D. Only a summary of the final results will be discussed in each section. Table D.1 shows the t-test calculations for comparisons of mean removal efficiencies between the control basin and the two experimental basins at similar conditions. For example, the first comparison in row 1 of Table D.1 verifies whether the control basin's overall mean removal efficiency is statistically equal, greater than or smaller than the overall mean removal efficiency of the basin containing 5 inclined plates. Table D.2 has three sections displaying the individual basin comparisons with the t-test. For each basin comparisons were made to determine at which variable setting the basin in question best performed. For example, the first comparison in row 1 of Table D.2 determines for the control basin whether the mean removal efficiency at 60 min is statistically equal, greater than or smaller than removal at 120 min.

5.3.3.1 Effect of Time

Figures 5.1, 5.2 and 5.3 plots display the percent TSS removal for each basin configuration versus time in minutes. Most of the sampling was done at times of 60 and 120 min. A linear regression for the results of each basin configuration is shown on each graph. Linear regressions were performed to determine the average performance of each basin configuration and to find the general trend of each basin's performance with time. Several individual lines showing the removals at the earlier and later sampling times in a given run are displayed along with the overall trendline in the next three figures to show the general pattern occurring between points. Displaying all individual lines between the points would be too cumbersome and confusing. The thicker dashed line represents the overall trendline for all the points on the graph. The equation for this line is displayed in the corner of each graph.

Figure 5.1 displays the removal percent versus the time in minutes for the control basin.

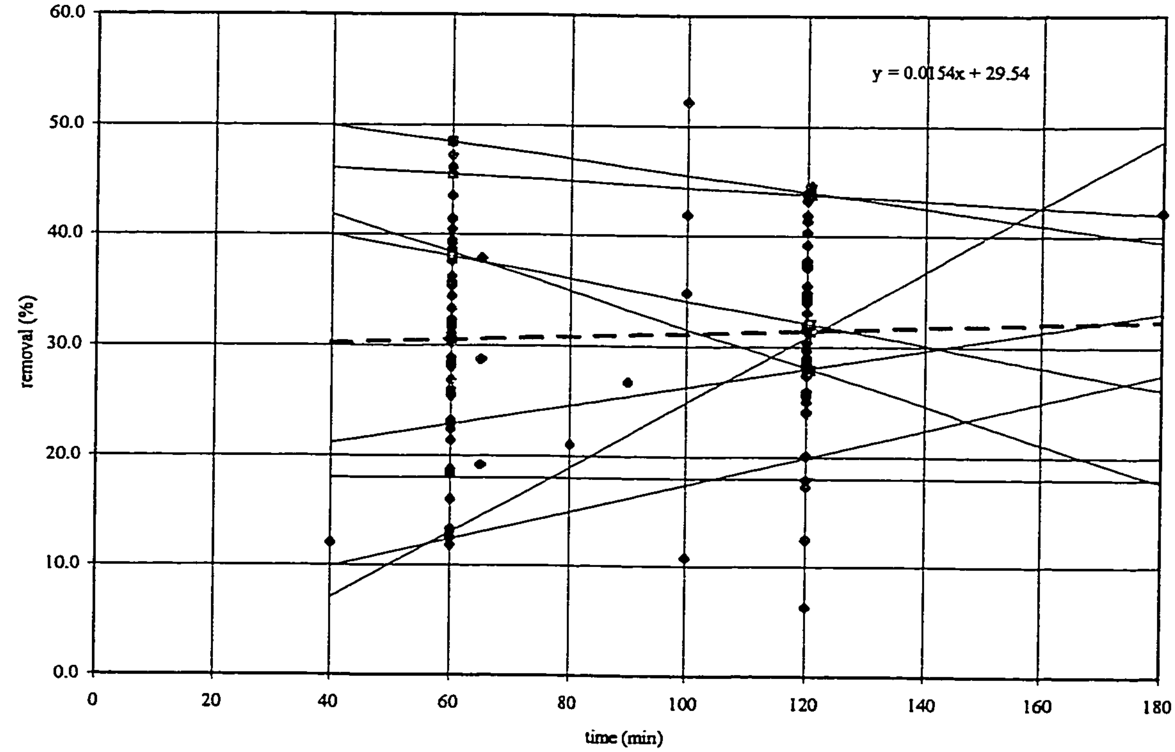

Figure 5.1 Removal % of TSS versus time for the control basin

Figure 5.2 displays the TSS removal percent versus the time in minutes for the experimental basin containing 5 inclined plates.

Figure 5.3 displays the TSS removal percent versus time in minutes for the experimental basin containing 3 inclined plates.

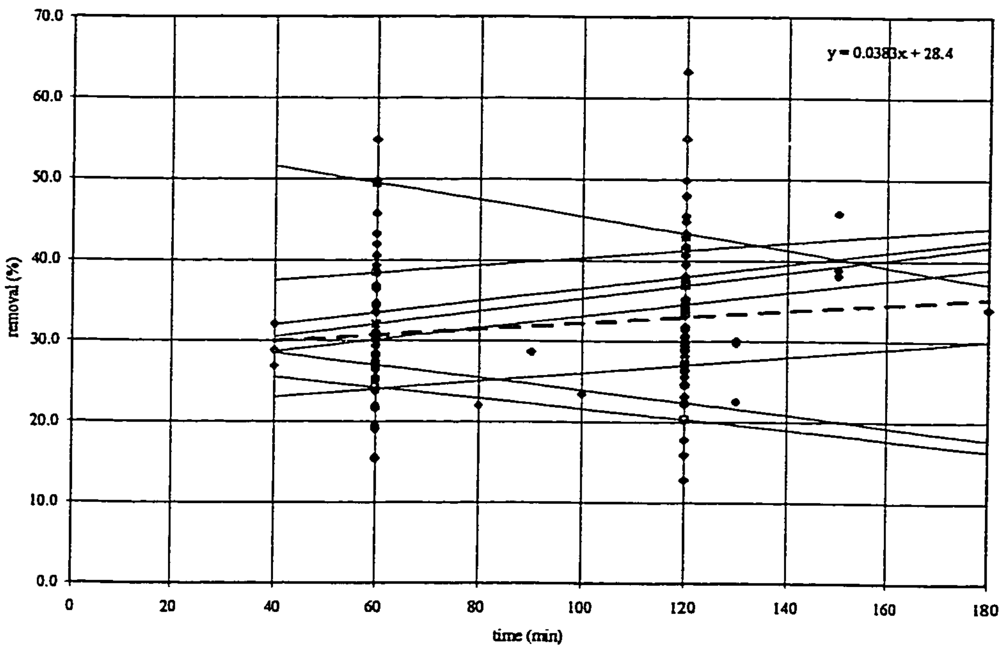

Figure 5.2 Removal % of TSS versus time for the experimental basin with 5 inclined plates

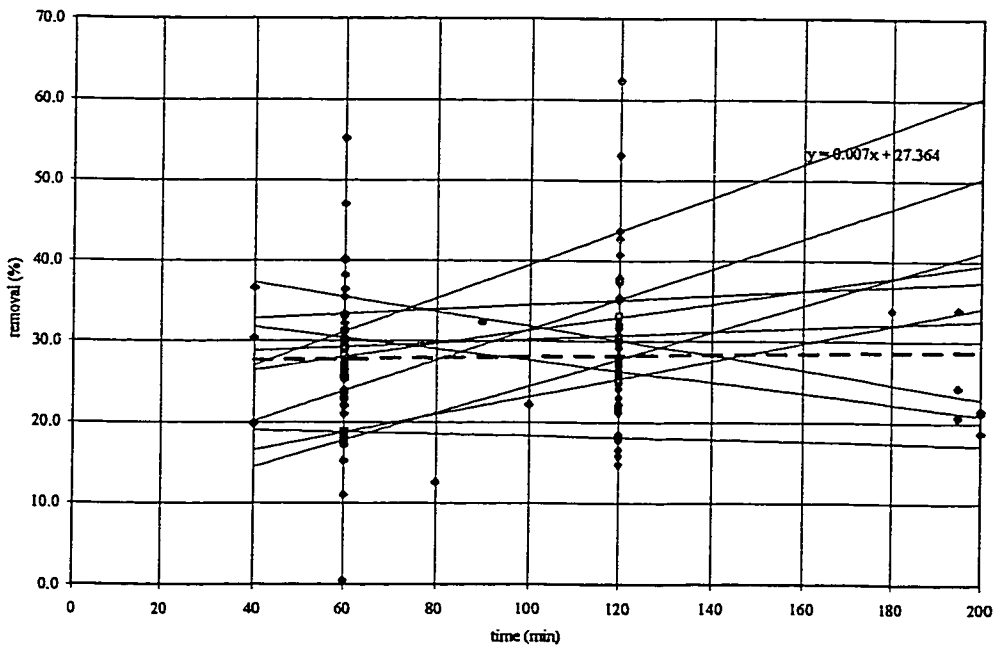

Figure 5.3 Removal % of TSS versus time for the experimental basin with 3 inclined plates

Figures 5.1, 5.2 and 5.3 show that in a given run TSS removal efficiency either increased, decreased or remained the same with time. The overall trendline of each graph shows that there was little difference in the removal whether the sampling was performed at 60 or 120 minutes. Table 5.4 lists the mean removal efficiency for each basin at each main sampling time. The standard deviation for each average is listed along with the results of the t-test.

Table 5.4 Summary of mean TSS removal efficiencies with respect to time

basin	t_1 = 60 min mean, X (%)	t_1 std. dev.	t_2 = 120 min mean, X (%)	t_2 std. dev.	Individual comparison with t-test*
control	31.65	9.2472	30.64	8.4111	$X(t_1) = X(t_2)$
5 plates	31.19	8.4582	32.87	9.7941	$X(t_1) = X(t_2)$
3 plates	27.37	9.0697	29.77	8.8374	$X(t_1) = X(t_2)$
overall comparison with t-test*	$X_{control} > X_{3\ plates}$ $X_{5\ plates} > X_{3\ plates}$		$X_{control} = X_{5\ pl.} = X_{3\ pl.}$		

* with a 99% confidence interval and t-test calculations are shown in Appendix D

The table shows that the means for each basin vary little with the difference in sampling time. The t-test confirms that the mean removals are statistically equal at 60 and 120 minutes for each case at a confidence interval of 99%. The comparison of the means between basins shows that the basin with 3 inclined plates has a mean removal statistically lower than both the control basin and the basin with 5 inclined plates. Time therefore did not have a significant impact on the either of the basin's performance and sampling times of 60 and 120 minutes are sufficient for this experiment. The basin with 3 inclined plates displayed a poorer performance overall when compared to the control basin and the basin with 5 inclined plates.

5.3.3.2 Effect of Flowrate

Figures 5.4, 5.5 and 5.6 represent the TSS percent removal versus the flowrate for the control basin, the experimental basin containing 5 inclined plates and the experimental basin containing 3 inclined plates respectively. The following three graphs show the removal efficiencies plotted versus the incoming flowrate. The overall trendline for each case is shown. No individual trendlines are shown for this case.

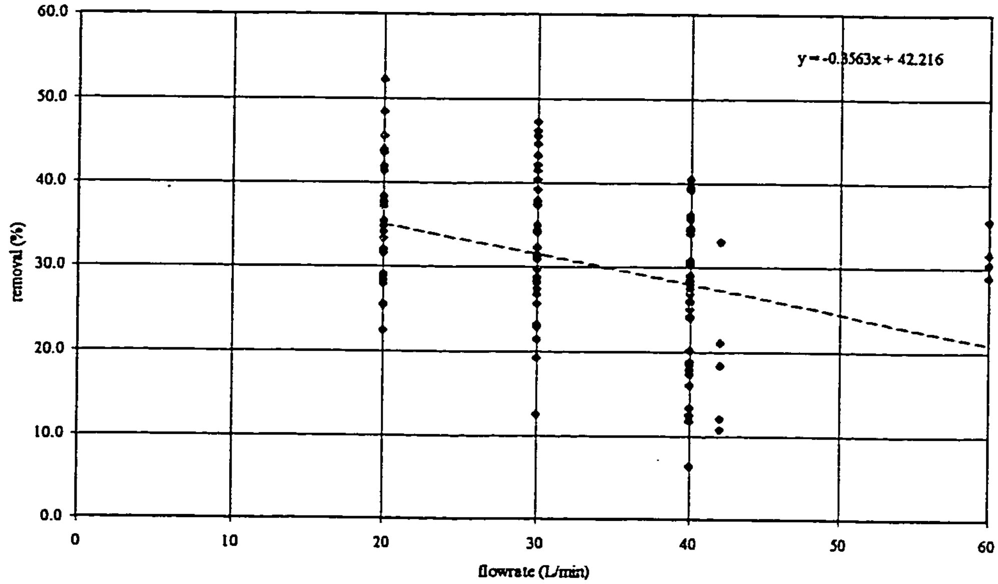

Figure 5.4 **Removal % of TSS versus flowrate for the control basin**

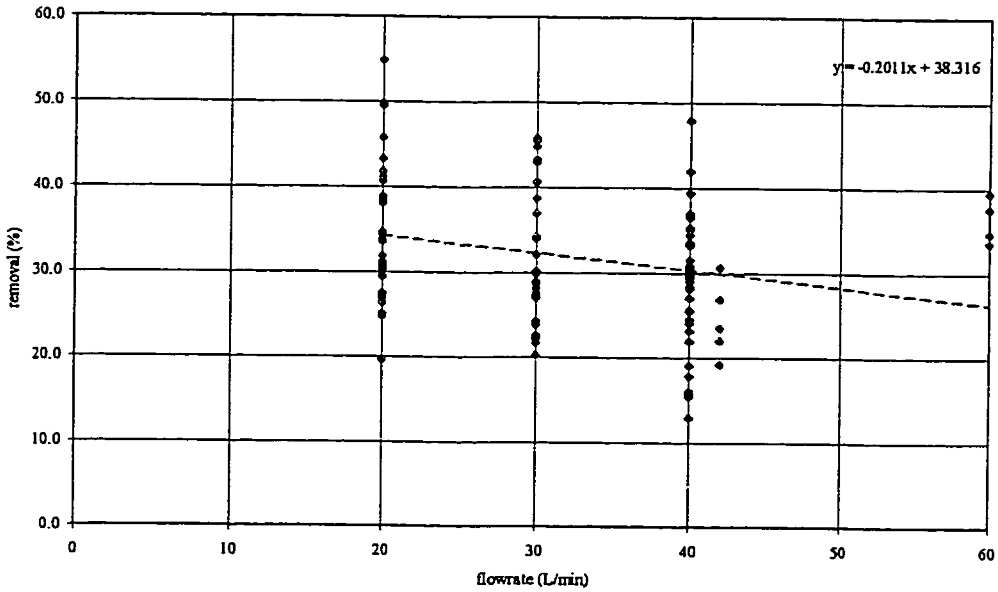

Figure 5.5 **Removal % of TSS versus flowrate for the experimental basin containing 5 inclined plates**

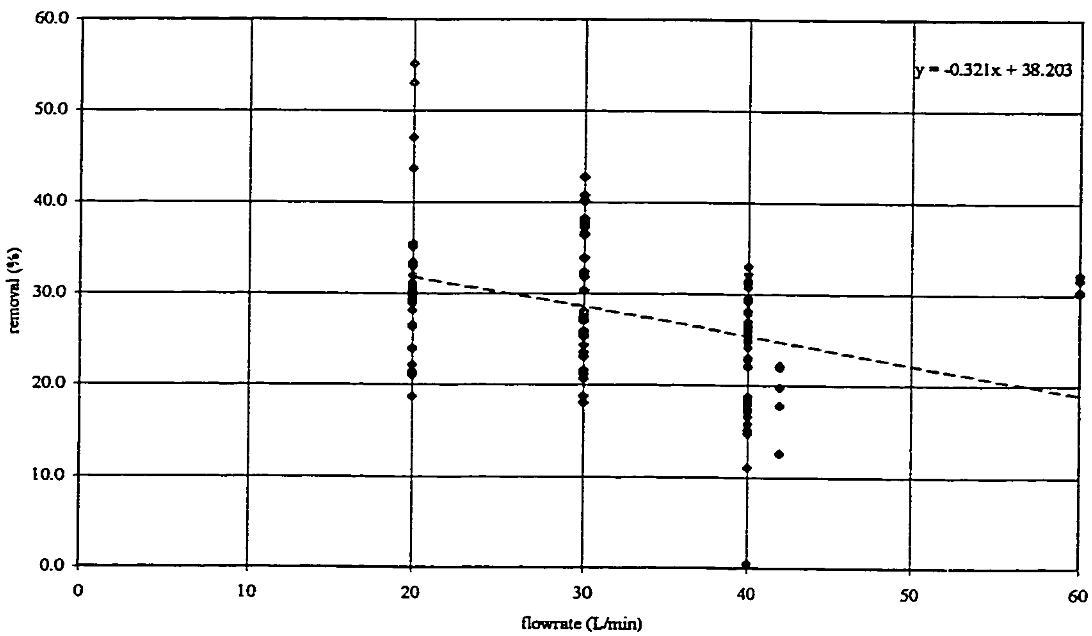

Figure 5.6 **Removal % of TSS versus flowrate for the experimental basin containing 3 inclined plates**

The flowrate of the incoming stream has an adverse effect on each basin's efficiency. As the flowrate increased the basin's TSS removal efficiency decreased for all three basin configurations. The three trendline equations show that the largest rate of decrease in TSS removal efficiency with increasing flowrate was found in the control basin. The basin containing five inclined plates has the lowest rate of decrease in efficiency. Table 5.5 displays the mean removal and the standard deviations as well as the t-test results for the basins.

Table 5.5 Summary of mean TSS removal efficiency with respect to flowrate change

basin	Q_1 20L/min mean, X (%)	Q_1 20L/min std. dev.	Q_2 30L/min mean, X (%)	Q_2 30L/min std. dev.	Q_3 40L/min mean, X (%)	Q_3 40L/min std. dev.	Individual comparison with t-test*
control	35.6	6.958	32.9	8.829	26.2	8.832	$X(Q_1) = X(Q_2)$ $X(Q_1) > X(Q_3)$ $X(Q_2) > X(Q_3)$
5 plates	35.3	8.934	32.4	9.2057	28.8	7.7251	$X(Q_1) = X(Q_2)$ $X(Q_2) > X(Q_3)$ (at 90% only) $X(Q_1) > X(Q_3)$
3 plates	32.38	9.5394	30.07	6.832	22.9	6.8147	$X(Q_1) = X(Q_2)$ $X(Q_1) > X(Q_3)$ $X(Q_2) > X(Q_3)$
overall comparison with t-test*	all means equal at 99% conf. int.		all means equal at 99% conf. int.		$X_5 > X_3$, $X_c > X_3$ at 90%, $X_c = X_5$		

* with a 99% confidence interval unless indicated otherwise and t-test calculations are shown in Appendix D

It is shown that the control basin has equivalent mean removal efficiencies at the flowrates of 20 and 30 L/min at a 99% confidence interval. The basin's performance however diminishes enough at the flowrate of 40 L/min to be proven statistically smaller than the two other mean removal efficiencies at a 99% confidence interval.

The basin containing 5 inclined plates exhibited similar mean removal efficiencies to those of the control basin. The t-test results indicate that this basin also has a mean removal efficiency at a flowrate of 20 L/min equal to that at 30 L/min at a 99% confidence interval. It is proven that the mean removal efficiency at 20 L/min is statistically greater than at 40 L/min also at a 99% confidence level. The difference between this basin and the control basin is that its mean removal efficiency at 30 L/min is proven greater than the mean removal at 40 L/min at a 90% confidence level. At 95 and 99% confidence levels, they are statistically equal. This means that the basin with 5 inclined plates performed as well at a flowrate of 40 L/min as at 30 L/min. The control basin did not exhibit this behavior.

From the t-test analysis Table 5.5, the basin with 3 inclined plates had mean removal efficiencies at flowrates of 20 and 30 L/min that were statistically equal at a 99% confidence level. The performance at 40 L/min is much lower than at the two other flowrate settings at a 99% confidence interval.

At flowrates of 20 and 30 L/min, all the mean removal efficiencies for each basin configuration were proven statistically equal to each other at a 99% confidence interval. At a flowrate of 40 L/min, the basin with 5 plates had a performance equal to that of the control and higher than the basin with 3 plates at a 99% confidence interval. The control basin's mean removal efficiency was higher than the basin with 3 plates at a 90% confidence interval only. At 95 and 99% levels, they were equal.

At a larger flowrate through a sedimentation basin, the basin can handle more wastewater than it could with a lower flowrate. The basin containing 5 inclined plates appears to be the best choice in this situation because of its equivalent performance at the lowest flowrate setting and its slowest rate of decrease with increasing flowrate (almost half of that of the control). A compromise must be made between the basin capacity and performance. This basin configuration apparently allows larger increases in capacity with the lowest effect on its removal efficiency.

The 5 inclined plates prove to be beneficial to the basin's tolerance to an increase in flowrate as opposed to the other basin configurations. The number of inclined plates appears to be important because the basin with 3 inclined plates performed at a much lower level. The optimal number of inclined plates must be studied further. In this case 5 inclined plates is better than none and none is better than 3.

5.3.3.3 Effect of Inlet Concentration

The TSS loading of the incoming streams to the sedimentation basins have an influence on the basins' removal efficiencies. Figures 5.7, 5.8 and 5.9 display the TSS removal efficiencies of the basins versus the inlet TSS concentration to the basin for the control basin, the experimental basin containing five inclined plates and the experimental basin containing three inclined plates respectively.

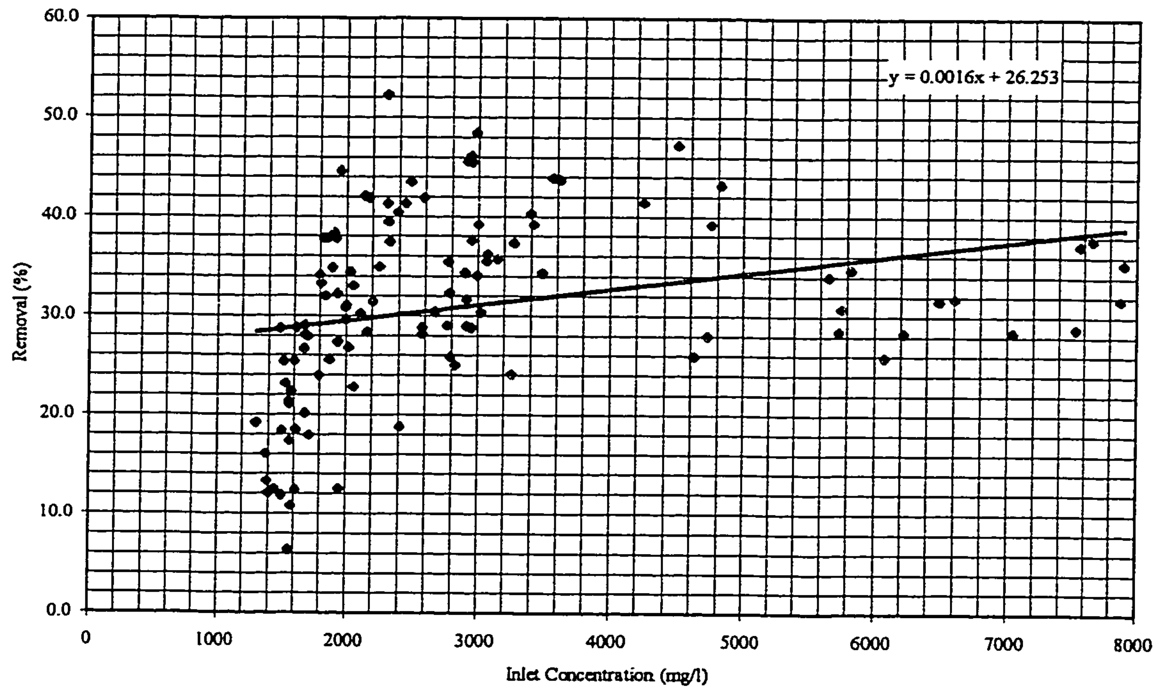

Figure 5.7 Removal & of TSS versus inlet concentration for the control basin

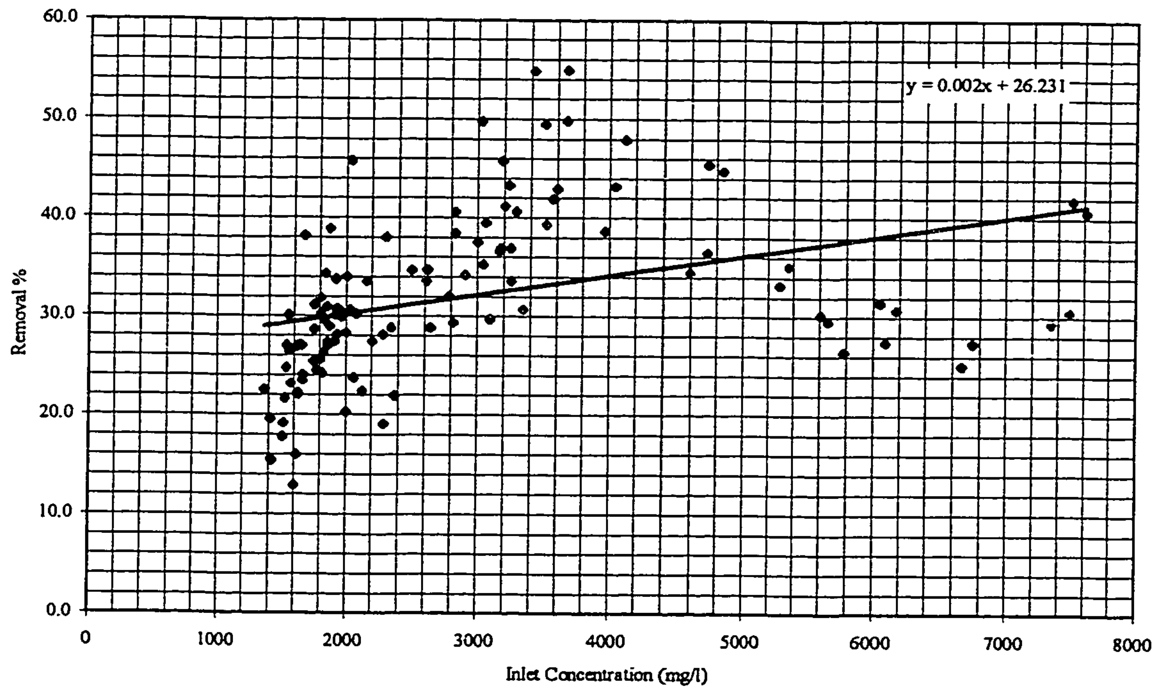

Figure 5.8 Removal % of TSS versus inlet concentration for the experimental basin with 5 inclined plates

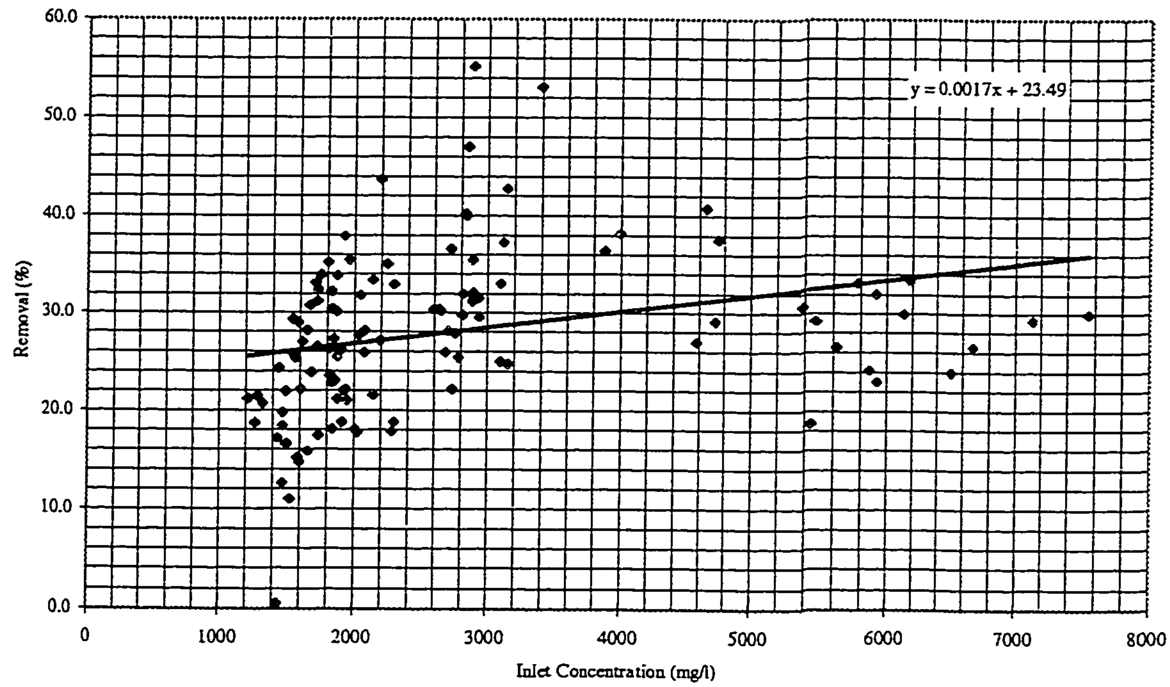

Figure 5.9 **Removal % of TSS versus inlet concentration for the basin containing three inclined plates**

The relationship between the basin's inlet TSS concentration and removal efficiencies is not very clear. A linear trendline was added to the graphs to show general behavior. The general behavior pattern is for the removal efficiency to increase with inlet TSS concentration.

The largest rate of increase (or trendline slope) occurs in the experimental basin with 5 inclined plates at a value of 0.002. The rate of increase for the control basin and for the experimental basin with 3 inclined plates are 0.0016 and 0.0017 respectively.

After inlet TSS concentrations of 5000 mg/L, each basin's results becomes less reliable due to fewer data points and larger scatter. Table 5.6 shows the calculated mean TSS removal efficiencies and standard deviations for each range of inlet TSS concentration for each basin configuration. The t-test results are also indicated.

Table 5.6 Summary of mean TSS removal efficiencies with respect to inlet TSS concentration change

basin	C_1 low range mean, X (%)	C_1 low range std. dev.	C_2 high range mean, X (%)	C_2 high range std. dev.	Individual comparison with t-test*
control	28.6	9.7181	34.9	6.5536	$X(C_1) < X(C_2)$
5 plates	27.2	6.1485	38.1	8.392	$X(C_1) < X(C_2)$
3 plates	25.2	7.3653	32.2	8.996	$X(C_1) < X(C_2)$
overall comparison with t-test*	$X_c = X_{5\ plates}$ $X_c > X_{3\ plates}$ $X_{5plate} = X_{3plate}$	at 99% at 95% at 99%	$X_{5\ plates} >$ $X_{control} >$ $X_{3\ plates}$	at 95% at 95%	

* with a 99% confidence interval unless indicated otherwise and t-test calculations are shown in Appendix D

All the basin configurations showed a significantly better individual performance at the higher inlet TSS concentration level when compared to the lower TSS concentration level at a 99% confidence level. Their mean removal efficiencies increased 6.3% in the control, 10.8% in the basin with 5 plates, 7.1% in the basin with 3 plates as inlet TSS concentration changed from the low range to the high range.

At the lower concentration range, the control basin had a mean removal efficiency statistically similar to the basin with 5 plates at 99% and a greater removal than the basin with 3 plates at 95%. The basins with 5 inclined plates and 3 inclined plates proved to have an equivalent performance at 99% confidence interval.

At the higher concentration range, the performance of the basin with 5 plates was statistically better than in the control at 95% confidence level and the control basin's performance is statistically greater than the basin with 3 plates at 95% confidence level.

The basin with 5 inclined plates appears to have the best reaction to increasing inlet TSS concentration because it reaches a higher removal at higher inlet TSS concentrations suspensions. The removal efficiency for lower concentrations is quite similar to that of the control even though it has a rate of increase which is a little lower. At an inlet TSS concentration range of 1500 to 2500 mg/L, the control basin appears to be an equal choice to the basin with 5 plates because their performances are quite similar. The basin with 5 plates is a slightly better choice at the higher concentration range.

5.3.3.4 Effect of Depth

Figures 5.10, 5.11 and 5.12 show the removal performances of all three basin configurations versus the depth. Figure 5.10 displays the results for the control basin.

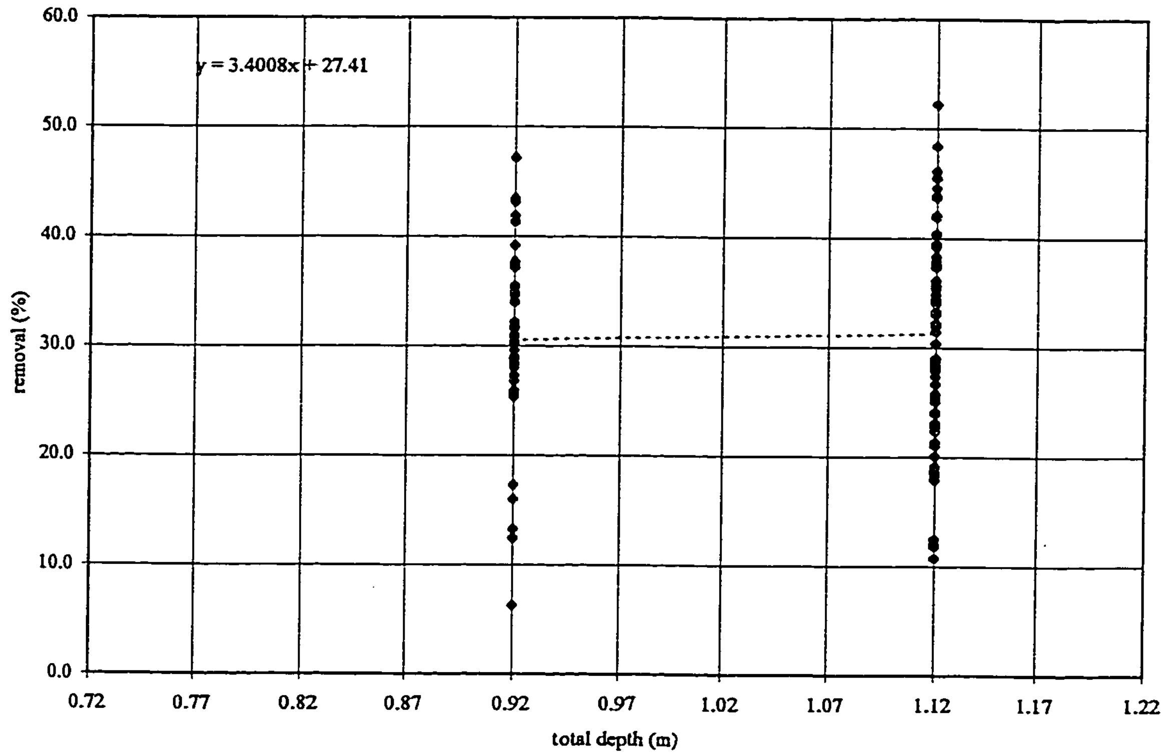

Figure 5.10 Removal % of TSS versus the total depth for the control basin

Figure 5.11 and 5.12 display the TSS removal percent for the experimental basins. The first one corresponds to the basin with 5 inclined plates and the second to the basin with 3 inclined plates.

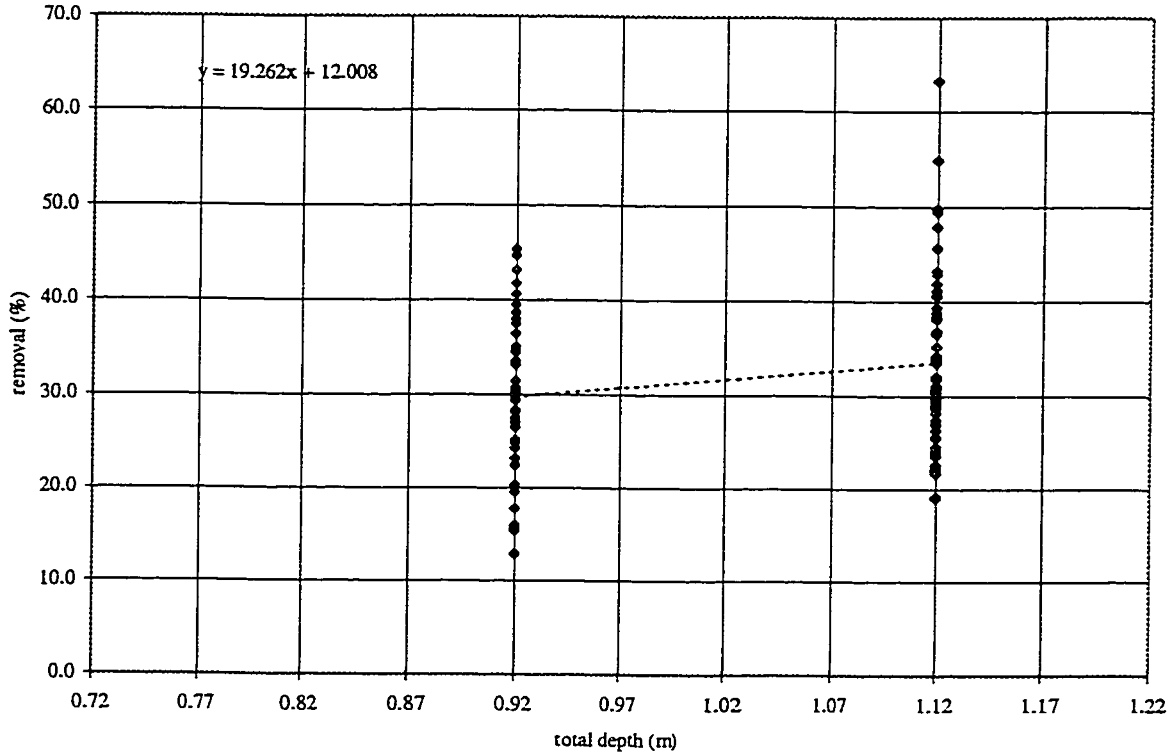

Figure 5.11 **Removal % of TSS versus the total depth for the experimental basin with 5 inclined plates**

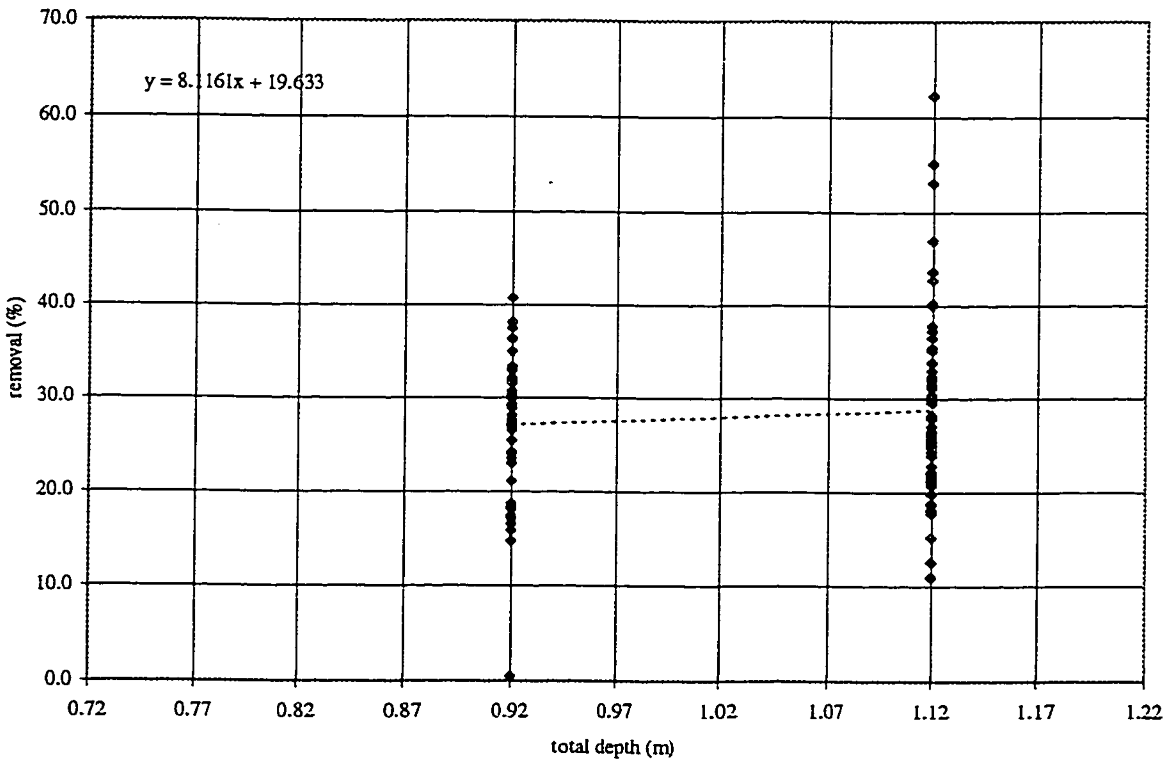

Figure 5.12 **Removal % of TSS versus the total depth for the experimental basin with 3 inclined plates**

Linear regressions for all three set of points are shown on the graphs. This gives an equation for the lines that represent the overall average behavior for all the runs in each basin. The control basin's efficiency has the lowest rate of change from 30.4 to 32.2%. The total depth has the strongest effect on the basin containing five inclined plates with efficiency increasing from 29.1 to 34.3% for a total depth increasing from 0.92 to 1.12 m. The basin containing three inclined plates has the lowest removal efficiency of the three configurations. The removal varies from approximately 26.7 to 29.6% with the total depth changing from 0.92 to 1.12 m. Since no depth higher than 1.12 m (or 40 cm above the inclined plates) was tested, it is not possible to indicate whether the basins' performances would continue to increase or reach a peak and then start decreasing with increasing depth.

Table 5.7 displays the mean removal efficiency, standard deviation and t-test results for each basin.

Table 5.7 Summary of mean TSS removal efficiency with respect to a change in depth

basin	d_1 0.92 m mean, X (%)	d_1 0.92 m std. dev.	d_2 1.12 m mean, X (%)	d_2 1.12 m std. dev.	Individual comparison with t-test*
control	30.4	8.8727	32.2	9.0154	$X(d_1) = X(d_2)$
5 plates	29.1	7.7675	34.34	9.2607	$X(d_1) < X(d_2)$
3 plates	26.7	7.3653	29.55	8.996	$X(d_1) = X(d_2)$
overall comparison with t-test*	$X_c = X_{5\ plates}$ $X_{5\ pl} = X_{3\ pl}$ $X_c > X_{3\ plates}$	at 95%	$X_c = X_{5\ plates}$ $X_{5\ pl} > X_{3\ pl}$ $X_{3\ pl} = X_c$		

* with a 99% confidence interval unless indicated otherwise and t-test calculations are shown in Appendix D

At the depth of 0.92 m, the control basin had a TSS removal efficiency slightly better than both other basins at the same total depth. Statistically it performed better than the basin with 3 inclined plates and equivalent to the one with 5 inclined plates, both at a 99% confidence level.

At a depth of 1.12 m, the control basin's performance was statistically equivalent to that of the basins with 5 and 3 inclined plates. The basin with 5 inclined plates however proved to have an increase of 5.2% in its performance level with an increase in its depth from 0.92 to 1.12 m (from 20 to 40 cm over the inclined plates). It therefore proved to have a better performance than the basin with 3 inclined plates. The basin with 3 inclined plates also had an increase in its performance of 2.8% with the increase in depth.

The control basin and the basin with 3 inclined plates had mean TSS removal efficiencies statistically equivalent at both of their depth settings. The increase in depth did not change or improve their performance. The basin with 5 inclined plates proved to have a statistically better mean removal efficiency at a total depth of 1.12.

The 5 inclined plates configuration has a slight advantage over the conventional and 3 inclined plates designs when the depth of the basin is considered. This result is positive in that this basin performed as good and eventually slightly better than its conventional counterpart. Its highest rate of change gives it more potential to be more efficient with a smaller increase in flow through depth. The basin with 3 inclined plates had a generally poorer performance level than the two other basin configurations regardless of its rate of change. Its performance was lower at both depths.

The basin with 5 inclined plates had the highest rate of improvement in removal efficiency with change in depth, also its performance level slightly higher than the control basin.

5.3.3.5 Effect of Inlet Concentration to Outlet Concentration

The TSS concentration of the streams exiting the individual sedimentation basins varied depending on the value of the TSS concentration of the stream entering the basins. Figures 5.13, 5.14 and 5.15 display the outlet TSS concentration in mg/L plotted versus the inlet TSS concentration in mg/L.

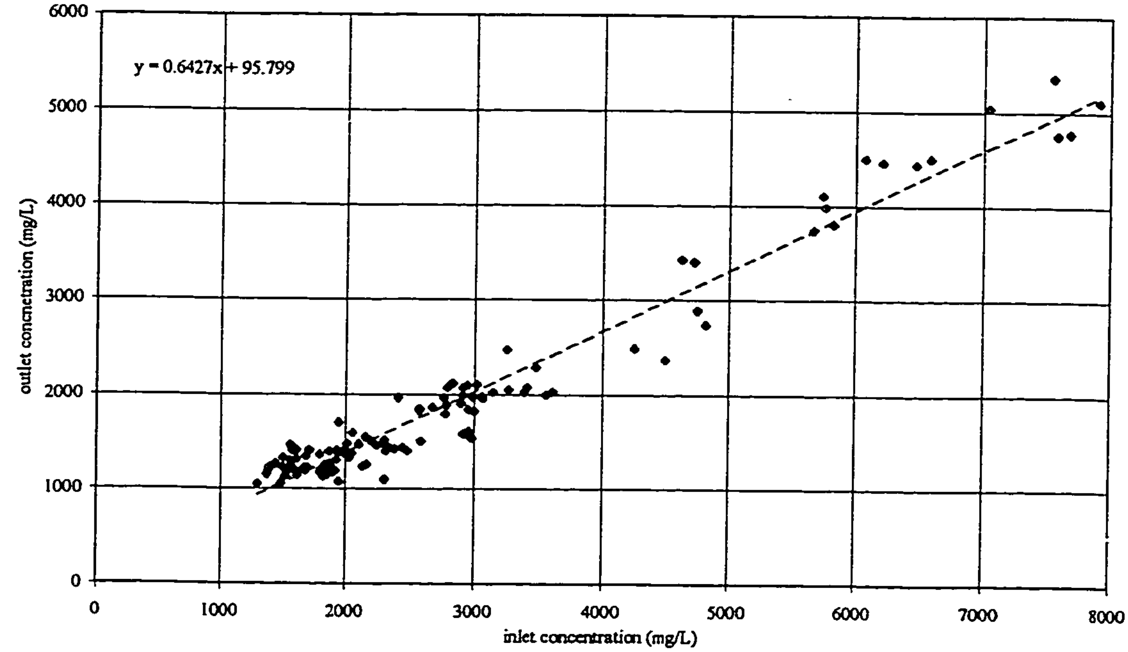

Figure 5.13 Outlet TSS concentration versus inlet TSS concentration for the control

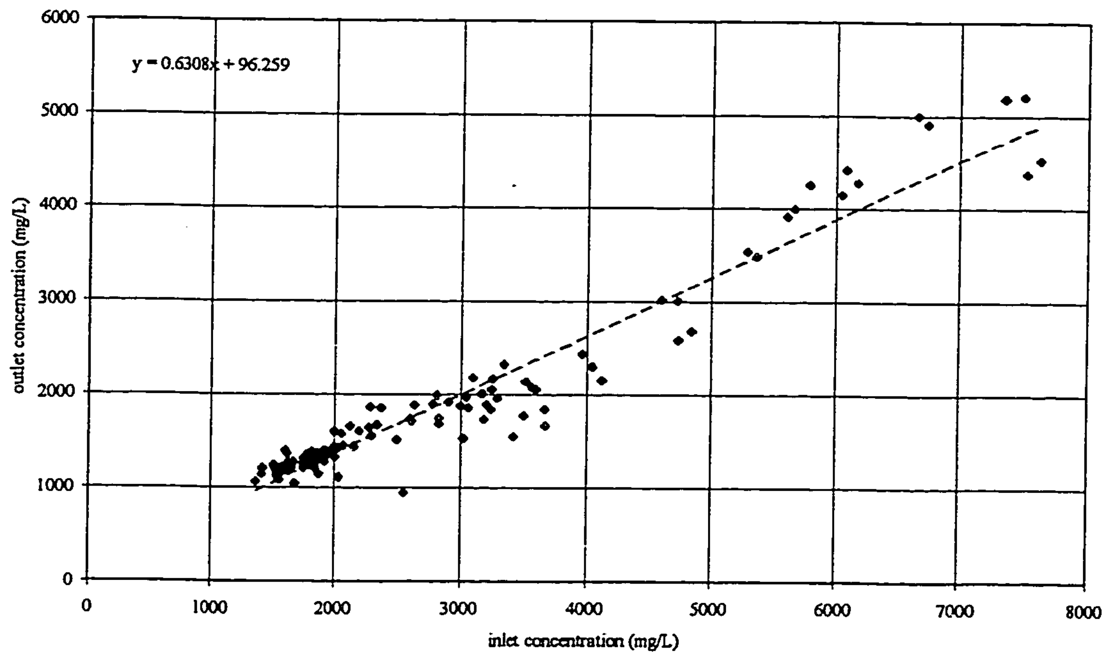

Figure 5.14 Outlet TSS concentration versus inlet TSS concentration for the experimental basin with 5 inclined plates

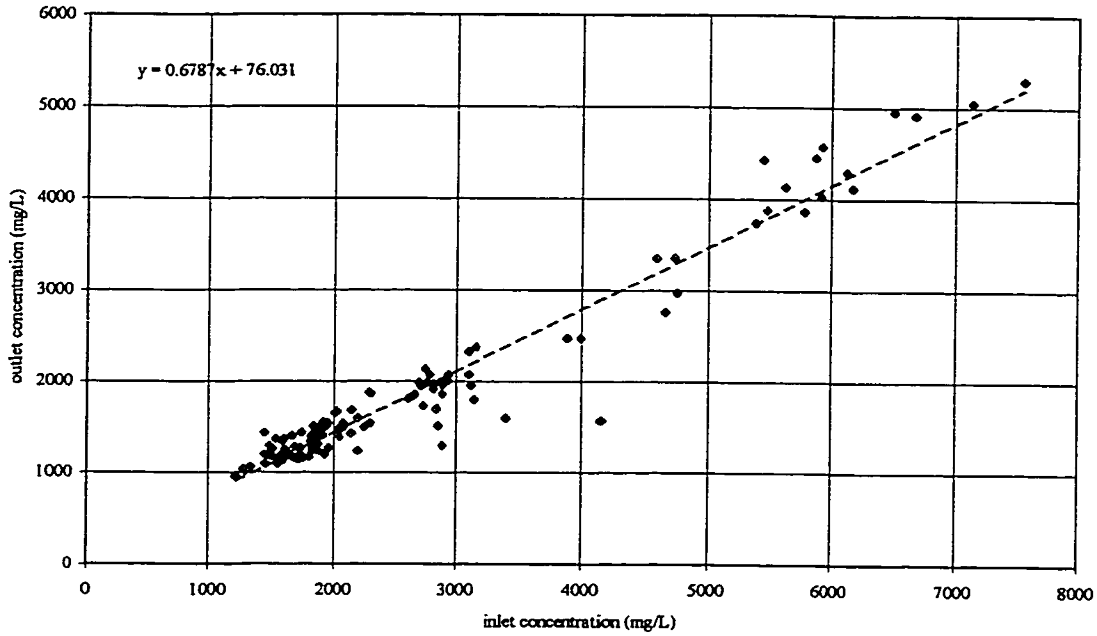

Figure 5.15 Outlet TSS concentration versus inlet TSS concentration for the experimental basin with 3 inclined plates

A linear regression curve for each set of points is added to the graph along with its corresponding equation. This points out the overall behavior pattern of the series of data points.

The general relationship in each basin between the outlet and the inlet TSS concentrations is for the outlet TSS concentration to increase as the inlet stream becomes more concentrated in suspended solids. The trendlines are all very similar in magnitude. The rate of change appears to be similar for each basin.

The removal efficiency also increased with inlet concentration. This was shown in the previous section. As the inlet TSS concentration becomes higher the basin's outlet TSS concentration also becomes higher. An important point is that all three basins followed a similar trend for both removal efficiency versus inlet concentration and outlet concentration versus inlet concentration.

Since the results of this analysis are very similar, the modifications did not deteriorate performance. The addition of inclined plates did not significantly disturb or aid each basin's performance. They are therefore considered equivalent in this respect.

Chapter 6 will compile and discuss the general conclusions.

CHAPTER 6

CONCLUSIONS

Tests performed during the course of this research work enabled the comparison of the TSS removal performance of a conventionally designed sedimentation basin with a basin including parallel inclined plates. Two different experimental basin configurations were tested, one with five inclined plates (a spacing of 35 cm or 14 in.) and one with three inclined plates (a spacing of 70 cm or 28 in.).

From settling column tests it was found that solid particles with similar settling velocities were removed in both the control basin and the experimental basin containing five inclined plates. The suspension exiting the two different basins had a very similar settling velocity distribution. There was a shift in the velocity distribution from the influent to the effluent confirming that particles with higher settling velocities were preferentially removed.

Tracer tests were performed on both the control basin and the basin with five inclined plates at 20 cm (total depth of 0.92 m) and 40 cm (total depth of 1.12 m) depth above the inclined plates. Their variances were all similar and of the same magnitude. The test results basically show that both basin configurations at both depths have approximately the same hydrodynamic behavior.

The major conclusions reached with the tracer test results were:

- the hydrodynamic behavior of each basin was between a plug flow and completely mixed flow,
- the control basin at both depths shows evidence of a large portion of volume being unused,
- the basin with five inclined plates with a depth of 40 cm over the plates proved to have the least wasted volume,
- the basin with five inclined plates with a depth of 20 cm over the plates proved to have a flow through zone which was too shallow for the flow.

The TSS of the samples collected were proven to be very reproducible (within a confidence interval of 1%).

The time or duration of an experimental run had a small and statistically insignificant increasing effect on the performance or removal efficiency of both the control as well as the two experimental basins. They had all reached steady state and the two sample times (60 and 120 min) were proven sufficient.

A flowrate increase had an adverse effect on all three basins' performances.

As the TSS concentration entering the basins increases, the outlet TSS concentration also increases.

In all three basin configurations, the mean removal efficiency at the higher inlet TSS concentration setting was statistically greater than at the lower inlet TSS concentration setting, at a 99% confidence interval.

The total basin depths tested were equal to 92 and 112 cm. In the experimental basin configuration the two tested depths were equivalent to a 20 and 40 cm depth over the inclined plate zone. An increase in the total basin depth, or depth over the inclined plates, had an increasing effect on the TSS removal. Larger values for depth were not tested; therefore, it is impossible to determine the optimal depth.

An overall assessment of all the factors such as time, flowrate, inlet TSS concentration and depth over the inclined plates, permits the observation that all three basin configurations (control, five inclined plates and three inclined plates) have a relatively similar behavior. Or rather, none of the basin configurations have a performance that greatly surpasses the others.

In summary, the basin with three inclined plates had the poorest performance and the control basin's performance was:

- at both flowrates of 20 and 30 L/min, statistically equivalent to the performance of the basin with five inclined plates,
- at a flowrate of 40 L/min, slightly lower but statistically equivalent to the performance of the basin with five inclined plates,
- at a lower inlet TSS loading, statistically equivalent to the performance of the basin with five inclined plates,

- at a higher inlet TSS loading, statistically lower than the performance of the basin with five inclined plates,
- at a depth of 20 cm over the inclined plates, statistically equivalent to the performance of the basin with five inclined plates,
- at a depth of 40 cm over the inclined plates, slightly lower but statistically equivalent to the performance of the basin with five inclined plates.

The control basin's performance was found to be statistically equivalent to the basin with 5 inclined plates performance on all conditions except at the higher inlet TSS concentration. The basin containing five inclined plates therefore proved to perform on an equivalent basis to that of the control. Making the design changes not detrimental to the basin's overall removal performance in the basin with 5 plates only. The number of inclined plates is a very important criteria and needs to be investigated further.

This research also confirms the presence of short-circuiting and shows that with the appropriate number of plates, the sedimentation basin performed as well as the control. With these inclined plates the flow through volume is more completely utilized and the remainder is put to better use by providing a quiescent zone for settling particles and creating a barrier to reduce scour of already settled solid particles.

The next step would be to reduce the volume of the control and the experimental basins with 5 inclined plates by reducing their depth and then again verifying both basins' performance. It is anticipated that the inclined plates will enable a reduction in depth with perhaps less compromise on the basin's performance. With no inclined plates present, a reduction in depth may bring on scour of the settled solids from the bottom.

The only restriction foreseen to the decrease of the depth in the experimental basin is the need to provide sufficient depth below the inclined plates to allow the functioning of the sludge removal mechanism. Assuming the inclined plates could be built as a stand-alone module and suspended from the top of the clarifier, this should not become a significant problem.

If the volume of sedimentation basins can be reduced, this will in turn reduce significantly the cost of such basins. The parallel inclined plates concept could perhaps be applied to existing basins to improve their performance or increase their capacity while retaining current efficiency levels.

CHAPTER 7

RECOMMENDATIONS FOR FUTURE RESEARCH

Recommendations for future research on the subject of adding inclined plates to sedimentation basins include:

- repeating research on basins of different volumes by reducing the depth of the inclined plates section and the sludge accumulation section of the experimental basins,

- fabricate plates and baffles of thinner plywood, plastic or metal sheets to make handling easier and to avoid warping when exposed to water for extended periods of time,

- perform tests with flocculating solids from streams at actual treatment plants, observe thickening and add coagulant,

- test basins with a smaller plate spacing (smaller than 35 cm) to determine the optimal plate spacing or number of plates,

- test greater depths over the inclined plates to determine the optimal flow through depth,
- add dividers parallel to flow above the inclined plates to help direct the flow,

- perform experiments on pilot and full scale basins.

APPENDIX A

CLAY SUPPLIERS' INFORMATION

Debro Chemicals

2055 Hymus Boulevard
Dorval, Quebec
H9P 1J8
(514)684-9775

Upper Canada Pottery Supplies

1139 Mill Street, Box 899
Manotick, Ontario
K4M 1A7
(613)692-2762

APPENDIX B

FLUOROMETER CALIBRATION

1. Solutions of concentrations of 0.01 mg/L, 0.025 mg/L, 0.05 mg/L and 0.1 mg/L of RWT in water were prepared.

2. Two 5 mL samples of each of the solutions were placed in individual cells for the fluorometer.

3. The cells were wiped clean with tissue.

4. Each cell was then placed in the fluorometer one at a time. The fluorometer reading was recorded.

5. A plot of the fluorometer measurement versus the solution concentration was drawn.

6. A straight line with the closest fit was drawn through the points. This results in the calibration curve to be used to relate the future fluorometer readings to the sample concentration.

The following table and graph display the calibration data for the fluorometer.

Table B.1 RWT calibration data

fluorometer reading	tracer RWT* concentration (mg/L)
0	0
11.5	0.01
26.5	0.025
57	0.05
110	0.1

* - RWT = rhodamine WT

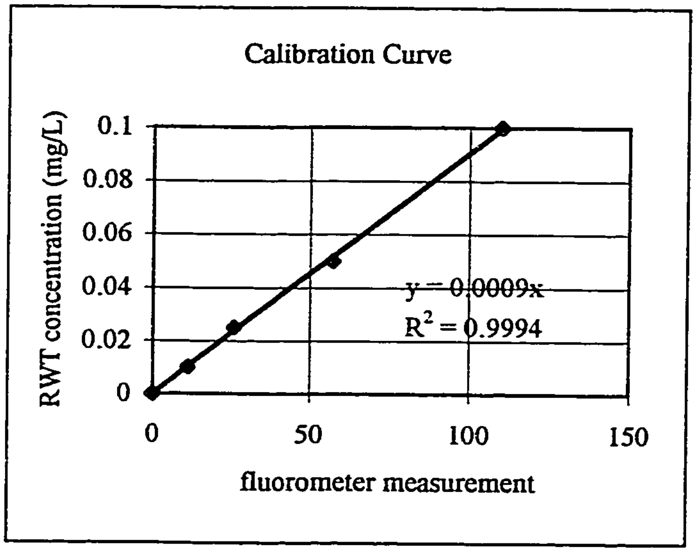

Figure B.1 RWT calibration curve

The same calibration curve could be used for the fluorometer measurements performed within several weeks of the calibration with the same instrument.

SAMPLING AND RWT CONCENTRATION MEASUREMENT

1. The collected samples were diluted to measurable concentrations for the fluorometer.

2. A 5 mL sample of each sample collected was placed into individual cells. The cells were wiped clean. A fluorometer measurement was taken.

3. Once a measurement was obtained from the fluorometer, it was converted to a RWT concentration value using the calibration curve.

4. The results were then plotted on an RWT concentration versus time graph.

5. All tracer test results are plotted in corresponding dimensionless variables as opposed to RWT concentration versus time. The resulting plot is of E versus time. E is the age distribution in s^{-1}. The appropriate calculations are displayed in the following tables and the procedure to calculate E is indicated in section 5.2. The corresponding actual retention times are also calculated.

The results of the tracer tests are displayed in the following tables.

Table B.2 Results of RWT tracer test no. 1

(control basin, total depth of 1.12 m, Q = 30 L/min)

ti sample time (s)	fluoro-meter reading	Ci - RWT concentration (mg/L)[a]	RWT amount (mg)
5	0	0.0000	0.0000
35	0	0.0000	0.0000
95	0	0.0000	0.0000
125	0	0.0000	0.0000
140	1	0.0009	0.0068
145	2	0.0018	0.0045
155	3	0.0027	0.0136
165	4	0.0036	0.0181
175	4	0.0036	0.0180
185	3	0.0027	0.0136
195	3.5	0.0032	0.0159
205	4.5	0.0041	0.0203
215	5	0.0045	0.0226
225	7.5	0.0068	0.0340
235	8	0.0072	0.0360
245	8	0.0072	0.0362
260	8	0.0072	0.0542
275	8.5	0.0077	0.0576
290	9.5	0.0086	0.0644
305	10	0.0090	0.0678
320	11	0.0099	0.0746
335	11	0.0099	0.0746
350	12	0.0108	0.0814
353	14.5	0.0131	0.0197
380	15	0.0136	0.1831
395	15	0.0136	0.1017
410	16	0.0145	0.1085
425	19	0.0172	0.1288
440	19	0.0172	0.1288
455	19	0.0172	0.1288
515	21	0.0190	0.5696
545	21.5	0.0194	0.2916
575	23	0.0208	0.3119
605	25	0.0226	0.3391
635	26	0.0235	0.3526
665	26.5	0.0240	0.3594
695	28	0.0253	0.3797
725	29	0.0262	0.3933

[a] - [RWT] = (fluorometer reading)/1106 from calibration curve

ti	fluo.	Ci	RWT
755	29	0.0262	0.3933
785	29	0.0262	0.3933
815	30	0.0271	0.4069
845	31	0.0280	0.4204
875	32	0.0289	0.4340
905	32	0.0289	0.4340
935	32	0.0289	0.4340
965	32	0.0289	0.4340
995	32.5	0.0294	0.4408
1025	32	0.0289	0.4340
1085	31	0.0280	0.8409
1145	30	0.0271	0.8137
1205	30.5	0.0276	0.8273
1265	30	0.0271	0.8137
1325	29	0.0262	0.7866
1415	28.5	0.0258	1.1596
1535	28	0.0253	1.5190
1625	27	0.0244	1.0986
1745	25.5	0.0231	1.3834
1805	25	0.0226	0.6781
1895	24.5	0.0222	0.9968
2015	23.5	0.0212	1.2749
2195	21	0.0190	1.7089
2375	20	0.0181	1.6275
2675	18	0.0163	2.4412
2975	15	0.0136	2.0344
3275	14	0.0127	1.8987
3575	12	0.0108	1.6275
3635	12	0.0108	0.3255
3875	10	0.0090	1.0850
4175	9	0.0081	1.2206
4775	7	0.0063	1.8987
5375	5	0.0045	1.3562
5975	3	0.0027	0.8137
6575	2	0.0018	0.5425
7175	1	0.0009	0.2712
7775	0.5	0.0005	0.1356
8375	0	0.0000	0.0000
8975	0	0.0000	0.0000
total RWT recovered			**39.9157**

Table B.3 Results of RWT tracer test no. 2

(control basin, total depth of 0.92 m, Q = 30 L/min)

ti sample time (s)	fluoro-meter reading	Cl - RWT conc. (mg/L)[a]	RWT amount (mg)
35	0	0.0000	0.0000
65	0	0.0000	0.0000
95	0	0.0000	0.0000
125	5	0.0045	0.0678
134.6	10	0.0090	0.0434
140	15	0.0136	0.0366
144.8	20	0.0181	0.0434
150.2	25	0.0226	0.0610
155	30	0.0271	0.0651
165.02	32	0.0289	0.1450
170	28	0.0253	0.0630
174.8	25	0.0226	0.0542
185	29	0.0262	0.1337
189.8	31	0.0280	0.0673
200	31	0.0280	0.1429
204.8	32	0.0289	0.0694
215	30	0.0271	0.1383
219.98	29	0.0262	0.0653
225.002	28	0.0253	0.0636
230	26	0.0235	0.0587
234.8	25	0.0226	0.0542
240.02	24	0.0217	0.0566
245	23	0.0208	0.0518
249.98	22	0.0199	0.0495
260	21	0.0190	0.0951
264.98	20	0.0181	0.0450
275	19	0.0172	0.0861
285.02	19	0.0172	0.0861
294.8	19	0.0172	0.0840
305	18	0.0163	0.0830
314.6	17	0.0154	0.0738
324.98	17	0.0154	0.0798
335	16.5	0.0149	0.0747
345.02	16	0.0145	0.0725
354.8	15	0.0136	0.0663
365	15	0.0136	0.0692
375.02	14	0.0127	0.0634
384.98	13.5	0.0122	0.0608
395	13	0.0118	0.0589
405.02	13	0.0118	0.0589
414.8	13	0.0118	0.0575
425	13	0.0118	0.0599
435.02	13	0.0118	0.0589
444.98	13	0.0118	0.0585
455	12.5	0.0113	0.0566
465.02	12	0.0108	0.0544
474.8	12	0.0108	0.0531
485	12	0.0108	0.0553
495.02	12	0.0108	0.0544
504.98	12	0.0108	0.0540
515	12	0.0108	0.0544
534.98	13	0.0118	0.1174
555.02	12.5	0.0113	0.1132
575	13	0.0118	0.1174
594.98	13.5	0.0122	0.1219
615.02	13	0.0118	0 1178

ti	fluo.	Cl	RWT
635	14	0.0127	0.1265
654.98	15	0.0136	0.1355
695	15	0.0136	0.2714
725	16	0.0145	0.2170
755	15.5	0.0140	0.2102
774.98	16	0.0145	0.1445
795.02	17	0.0154	0.1540
815	17.5	0.0158	0.1581
845	18	0.0163	0.2441
875	19	0.0172	0.2577
905	20	0.0181	0.2712
935	21	0.0190	0.2848
965	21	0.0190	0.2848
995	22	0.0199	0.2984
1025	23	0.0208	0.3119
1055	24	0.0217	0.3255
1085	24	0.0217	0.3255
1115	24.5	0.0222	0.3323
1145	25	0.0226	0.3391
1175	25	0.0226	0.3391
1205	25	0.0226	0.3391
1235	25.5	0.0231	0.3458
1265	25.5	0.0231	0.3458
1295	25	0.0226	0.3391
1355	25	0.0226	0.6781
1415	25	0.0226	0.6781
1475	25	0.0226	0.6781
1535	24.5	0.0222	0.6646
1595	24	0.0217	0.6510
1655	24	0.0217	0.6510
1715	24	0.0217	0.6510
1775	24	0.0217	0.6510
1895	22	0.0199	1.1935
2075	21	0.0190	1.7089
2255	20	0.0181	1.6275
2375	19.5	0.0176	1.0579
2555	18.5	0.0167	1.5054
2735	17.5	0.0158	1.4241
2855	16	0.0145	0.8680
2975	15.5	0.0140	0.8409
3275	13.5	0.0122	1.8309
3575	12	0.0108	1.6275
3695	11	0.0099	0.5967
3875	10	0.0090	0.8137
4175	8.5	0.0077	1.1528
4535	7	0.0063	1.1392
4775	6	0.0054	0.6510
5075	5	0.0045	0.6781
5375	4	0.0036	0.5425
5735	3	0.0027	0.4882
5915	2.5	0.0023	0.2034
6095	2	0.0018	0.1627
6275	1.5	0.0014	0.1221
6515	1	0.0009	0.1085
7175	0	0.0000	0.0000
7775	0	0.0000	0.0000
total RWT recovered			35.9412

a - [RWT] = (fluorometer reading)/1106 from calibration curve

Table B.4 Results of RWT tracer test no. 3

(experimental basin with 5 inclined plates, total depth of 1.12 m, Q = 30 L/min)

ti sample time (s)	fluoro-meter reading	Ci - RWT conc. (mg/L)[a]	RWT amount (mg)
35	0	0.0000	0.0000
65	0	0.0000	0.0000
95	0	0.0000	0.0000
125	0	0.0000	0.0000
155	0	0.0000	0.0000
195	0	0.0000	0.0000
215	4	0.0036	0.0361
230	7	0.0063	0.0475
235	10	0.0090	0.0225
245	15	0.0136	0.0679
255	22	0.0199	0.0995
265	28	0.0253	0.1263
275	29	0.0262	0.1314
285	25	0.0226	0.1132
289	21.5	0.0194	0.0385
293	21	0.0190	0.0382
315	21	0.0190	0.2091
325	21	0.0190	0.0946
335	21	0.0190	0.0951
365	23	0.0208	0.3119
380	22	0.0199	0.1492
395	19	0.0172	0.1288
410	17	0.0154	0.1153
425	14	0.0127	0.0949
440	16	0.0145	0.1085
455	14	0.0127	0.0949
470	12	0.0108	0.0814
485	10	0.0090	0.0678
500	11	0.0099	0.0746
515	11	0.0099	0.0746
530	11	0.0099	0.0746
545	11.5	0.0104	0.0780
560	11.5	0.0104	0.0780
575	12.5	0.0113	0.0848
590	14	0.0127	0.0949
605	17	0.0154	0.1153
620	21	0.0190	0.1424
635	25	0.0226	0.1695
650	28	0.0253	0.1899
665	30	0.0271	0.2034
680	32.5	0.0294	0.2204

ti	fluo.	Ci	RWT
695	35	0.0316	0.2373
710	38	0.0344	0.2577
725	39	0.0353	0.2645
740	39.5	0.0357	0.2679
755	43	0.0389	0.2916
770	46	0.0416	0.3119
785	46.5	0.0420	0.3153
800	47.5	0.0429	0.3221
815	46.5	0.0420	0.3153
830	45.5	0.0411	0.3085
845	45	0.0407	0.3052
860	45	0.0407	0.3052
875	47	0.0425	0.3187
890	47	0.0425	0.3187
905	48	0.0434	0.3255
920	49	0.0443	0.3323
935	49	0.0443	0.3323
950	46	0.0416	0.3119
965	45	0.0407	0.3052
980	43	0.0389	0.2916
995	42.5	0.0384	0.2882
1010	45	0.0407	0.3052
1025	42.5	0.0384	0.2882
1040	43	0.0389	0.2916
1055	43	0.0389	0.2916
1070	45	0.0407	0.3052
1085	45	0.0407	0.3052
1100	46	0.0416	0.3119
1115	46	0.0416	0.3119
1130	44.5	0.0402	0.3018
1145	42	0.0380	0.2848
1160	42	0.0380	0.2848
1175	42	0.0380	0.2848
1190	42	0.0380	0.2848
1205	41.5	0.0375	0.2814
1220	40	0.0362	0.2712
1235	40	0.0362	0.2712
1250	40	0.0362	0.2712
1265	40	0.0362	0.2712
1280	40	0.0362	0.2712
1295	39	0.0353	0.2645
1310	38.5	0.0348	0.2611
1325	38.5	0.0348	0.2611
1340	38.5	0.0348	0.2611

ti	fluo.	Ci	RWT
1355	38.5	0.0348	0.2611
1385	38.5	0.0348	0.5222
1415	38.5	0.0348	0.5222
1475	38.5	0.0348	1.0443
1535	37	0.0335	1.0036
1595	33.5	0.0303	0.9087
1655	32	0.0289	0.8680
1715	31	0.0280	0.8409
1775	30.5	0.0276	0.8273
1895	30.5	0.0276	1.6546
2015	29.5	0.0267	1.6004
2135	27.5	0.0249	1.4919
2255	28	0.0253	1.5190
2375	26.5	0.0240	1.4376
2495	24	0.0217	1.3020
2615	22.5	0.0203	1.2206
2735	22	0.0199	1.1935
2855	21.5	0.0194	1.1664
2915	20	0.0181	0.5425
3065	19	0.0172	1.2884
3155	18	0.0163	0.7324
3275	18	0.0163	0.9765
3335	17	0.0154	0.4611
3515	17	0.0154	1.3834
3695	15	0.0136	1.2206
3755	14	0.0127	0.3797
3875	14	0.0127	0.7595
3935	13	0.0118	0.3526
3995	12	0.0108	0.3255
4115	13	0.0118	0.7052
4175	13	0.0118	0.3526
4295	11	0.0099	0.5967
4475	10	0.0090	0.8137
4775	9.5	0.0086	1.2884
5075	8.5	0.0077	1.1528
5375	7.5	0.0068	1.0172
5675	6.75	0.0061	0.9155
5975	6	0.0054	0.8137
6575	4.5	0.0041	1.2206
7175	3	0.0027	0.8137
7775	1.5	0.0014	0.4069
8675	0.5	0.0005	0.2034
9575	0	0.0000	0.0000
total RWT recovered			**54.844**

[a] - [RWT] = (fluorometer reading)/1106 from calibration curve

Table B.5 Results of RWT tracer test no. 4

(experimental basin with 5 inclined plates, total depth of 0.92 m, Q = 30 L/min)

ti sample time (s)	fluoro-meter reading	Ci - RWT conc. (mg/L)[a]	RWT amount (mg)
0	0	0.0000	0.0000
210	20	0.0181	0.5967
240	25	0.0226	0.7459
255	28	0.0253	0.7595
270	27	0.0244	0.4340
330	26	0.0235	0.5018
357	29.5	0.0267	0.5832
409.8	34	0.0307	0.6239
420	36	0.0325	0.6713
450	41.5	0.0375	0.7052
510	45	0.0407	0.6781
600	46	0.0416	0.6781
630	46	0.0416	0.6442
660	43.5	0.0393	0.6103
690	42	0.0380	0.5696
720	40	0.0362	1.0986
750	35	0.0316	0.9494
780	34	0.0307	0.8680
810	33.5	0.0303	0.8137
840	32	0.0289	0.8002
870	31	0.0280	0.7595
900	30	0.0271	0.3594
930	29.5	0.0267	0.3526
960	26	0.0235	0.3391
990	25	0.0226	0.3052
1050	23	0.0208	0.5967
1110	22	0.0199	0.5832
1170	21	0.0190	0.5696
1230	21	0.0190	0.5561
1290	20.5	0.0185	0.5561

ti	fluo.	Ci - RWT	RWT
1350	20	0.0181	0.5425
1410	20	0.0181	0.5154
1470	19	0.0172	0.5018
1620	18.5	0.0167	1.2545
1770	18	0.0163	1.2206
1920	17.5	0.0158	1.1867
2070	16.5	0.0149	1.0172
2220	15	0.0136	0.9833
2370	14.5	0.0131	0.8816
2520	13	0.0118	0.8137
2670	11	0.0099	0.7120
2670	10	0.0090	0.0000
2820	9.5	0.0086	0.6442
2970	8	0.0072	0.5425
3270	8	0.0072	1.0172
3570	7	0.0063	0.8137
3870	6	0.0054	0.6781
4170	4	0.0036	0.4069
4470	3	0.0027	0.3391
4770	2	0.0018	0.2712
5070	1.75	0.0016	0.2373
5370	1.5	0.0014	0.2034
5670	1.25	0.0011	0.1695
5970	1	0.0009	0.1356
6570	0.5	0.0005	0.1356
7470	0.5	0.0005	0.2034
8070	0	0.0000	0.0000
8370	0	0.0000	0.0000
total RWT recovered			33.7364

[a] [RWT]=(fluo. reading)*(0.0009) from calibration curve

RETENTION TIME AND VARIANCE CALCULATIONS FOR TRACER TESTS

Table B.6 Actual retention time and variance calculation for tracer test no. 2

t_i sample time (s)	fluoro-meter reading	C_i - RWT conc. (mg/L)[a]	$(t_i - t_{i-1})$ (s)	$Q_i = (t_i - t_{i-1}) * C_i$ (s*mg/L)	$E_i = C_i/Q$ (s^{-1})	$(t_i * E_i)$	$(t_i^2 * E_i)$ (s)
35	0	0.00000	35	0	0.000000	0.00000	0.00
65	0	0.00000	30	0	0.000000	0.00000	0.00
95	0	0.00000	30	0	0.000000	0.00000	0.00
125	5	0.00452	30	0.13562	0.000063	0.00786	0.98
135	10	0.00904	9.6	0.08680	0.000126	0.01693	2.28
140	15	0.01356	5.4	0.07324	0.000189	0.02641	3.70
145	20	0.01808	4.8	0.08680	0.000252	0.03643	5.27
150	25	0.02260	5.4	0.12206	0.000314	0.04723	7.09
155	30	0.02712	4.8	0.13020	0.000377	0.05849	9.07
165	32	0.02893	10.02	0.28991	0.000403	0.06642	10.96
170	28	0.02532	4.98	0.12608	0.000352	0.05987	10.18
175	25	0.02260	4.8	0.10850	0.000314	0.05497	9.61
185	29	0.02622	10.2	0.26745	0.000365	0.06748	12.48
190	31	0.02803	4.8	0.13454	0.000390	0.07401	14.05
200	31	0.02803	10.2	0.28590	0.000390	0.07799	15.60
205	32	0.02893	4.8	0.13888	0.000403	0.08243	16.88
215	30	0.02712	10.2	0.27667	0.000377	0.08113	17.44
220	29	0.02622	4.98	0.13058	0.000365	0.08024	17.65
225	28	0.02532	5.022	0.12714	0.000352	0.07924	17.83
230	26	0.02351	4.998	0.11749	0.000327	0.07522	17.30
235	25	0.02260	4.8	0.10850	0.000314	0.07383	17.34
240	24	0.02170	5.22	0.11327	0.000302	0.07246	17.39
245	23	0.02080	4.98	0.10356	0.000289	0.07088	17.37
250	22	0.01989	4.98	0.09906	0.000277	0.06918	17.29
260	21	0.01899	10.02	0.19025	0.000264	0.06868	17.86
265	20	0.01808	4.98	0.09005	0.000252	0.06666	17.66
275	19	0.01718	10.02	0.17213	0.000239	0.06572	18.07
285	19	0.01718	10.02	0.17213	0.000239	0.06812	19.41
295	19	0.01718	9.78	0.16801	0.000239	0.07045	20.77
305	18	0.01627	10.2	0.16600	0.000226	0.06905	21.06
315	17	0.01537	9.6	0.14756	0.000214	0.06727	21.16
325	17	0.01537	10.38	0.15955	0.000214	0.06949	22.58
335	16.5	0.01492	10.02	0.14948	0.000208	0.06953	23.29
345	16	0.01447	10.02	0.14495	0.000201	0.06944	23.96
355	15	0.01356	9.78	0.13264	0.000189	0.06694	23.75
365	15	0.01356	10.2	0.13834	0.000189	0.06887	25.14
375	14	0.01266	10.02	0.12684	0.000176	0.06604	24.77
385	13.5	0.01221	9.96	0.12157	0.000170	0.06537	25.17
395	13	0.01175	10.02	0.11778	0.000164	0.06459	25.51
405	13	0.01175	10.02	0.11778	0.000164	0.06623	26.82
415	13	0.01175	9.78	0.11495	0.000164	0.06783	28.13
425	13	0.01175	10.2	0.11989	0.000164	0.06950	29.54
435	13	0.01175	10.02	0.11778	0.000164	0.07113	30.94
445	13	0.01175	9.96	0.11707	0.000164	0.07276	32.38
455	12.5	0.01130	10.02	0.11325	0.000157	0.07154	32.55
465	12	0.01085	10.02	0.10872	0.000151	0.07019	32.64
475	12	0.01085	9.78	0.10611	0.000151	0.07167	34.03
485	12	0.01085	10.2	0.11067	0.000151	0.07321	35.50
495	12	0.01085	10.02	0.10872	0.000151	0.07472	36.99
505	12	0.01085	9.96	0.10807	0.000151	0.07622	38.49
515	12	0.01085	10.02	0.10872	0.000151	0.07773	40.03
535	13	0.01175	19.98	0.23485	0.000164	0.08748	46.80
555	12.5	0.01130	20.04	0.22649	0.000157	0.08727	48.43
575	13	0.01175	19.98	0.23485	0.000164	0.09402	54.06
595	13.5	0.01221	19.98	0.24388	0.000170	0.10103	60.11
615	13	0.01175	20.04	0.23555	0.000164	0.10057	61.85

Table B.6 (Continued)

635	14	0.01266	19.98	0.25291	0.000176	0.11182	71.01
655	15	0.01356	19.98	0.27098	0.000189	0.12358	80.94
695	15	0.01356	40.02	0.54277	0.000189	0.13113	91.13
725	16	0.01447	30	0.43400	0.000201	0.14591	105.78
755	15.5	0.01401	30	0.42043	0.000195	0.14720	111.13
775	16	0.01447	19.98	0.28904	0.000201	0.15597	120.87
795	17	0.01537	20.04	0.30803	0.000214	0.17000	135.15
815	17.5	0.01582	19.98	0.31614	0.000220	0.17940	146.21
845	18	0.01627	30	0.48825	0.000226	0.19132	161.66
875	19	0.01718	30	0.51537	0.000239	0.20911	182.97
905	20	0.01808	30	0.54250	0.000252	0.22767	206.04
935	21	0.01899	30	0.56962	0.000264	0.24697	230.92
965	21	0.01899	30	0.56962	0.000264	0.25490	245.98
995	22	0.01989	30	0.59675	0.000277	0.27534	273.96
1025	23	0.02080	30	0.62387	0.000289	0.29653	303.95
1055	24	0.02170	30	0.65099	0.000302	0.31848	336.00
1085	24	0.02170	30	0.65099	0.000302	0.32754	355.38
1115	24.5	0.02215	30	0.66456	0.000308	0.34361	383.12
1145	25	0.02260	30	0.67812	0.000314	0.36005	412.26
1175	25	0.02260	30	0.67812	0.000314	0.36949	434.15
1205	25	0.02260	30	0.67812	0.000314	0.37892	456.60
1235	25.5	0.02306	30	0.69168	0.000321	0.39612	489.21
1265	25.5	0.02306	30	0.69168	0.000321	0.40574	513.27
1295	25	0.02260	30	0.67812	0.000314	0.40722	527.35
1355	25	0.02260	60	1.35624	0.000314	0.42609	577.35
1415	25	0.02260	60	1.35624	0.000314	0.44496	629.61
1475	25	0.02260	60	1.35624	0.000314	0.46382	684.14
1535	24.5	0.02215	60	1.32911	0.000308	0.47304	726.11
1595	24	0.02170	60	1.30199	0.000302	0.48150	767.99
1655	24	0.02170	60	1.30199	0.000302	0.49961	826.85
1715	24	0.02170	60	1.30199	0.000302	0.51772	887.89
1775	24	0.02170	60	1.30199	0.000302	0.53584	951.11
1895	22	0.01989	120	2.38698	0.000277	0.52439	993.72
2075	21	0.01899	180	3.41772	0.000264	0.54810	1137.31
2255	20	0.01808	180	3.25497	0.000252	0.56728	1279.22
2375	19.5	0.01763	120	2.11573	0.000245	0.58253	1383.51
2555	18.5	0.01673	180	3.01085	0.000233	0.59454	1519.06
2735	17.5	0.01582	180	2.84810	0.000220	0.60203	1646.55
2855	16	0.01447	120	1.73599	0.000201	0.57458	1640.42
2975	15.5	0.01401	120	1.68174	0.000195	0.58002	1725.55
3275	13.5	0.01221	300	3.66184	0.000170	0.55612	1821.29
3575	12	0.01085	300	3.25497	0.000151	0.53961	1929.10
3695	11	0.00995	120	1.19349	0.000138	0.51124	1889.05
3875	10	0.00904	180	1.62749	0.000126	0.48741	1888.71
4175	8.5	0.00769	300	2.30561	0.000107	0.44637	1863.60
4535	7	0.00633	360	2.27848	0.000088	0.39930	1810.82
4775	6	0.00542	240	1.30199	0.000075	0.36037	1720.76
5075	5	0.00452	300	1.35624	0.000063	0.31917	1619.81
5375	4	0.00362	300	1.08499	0.000050	0.27043	1453.58
5735	3	0.00271	360	0.97649	0.000038	0.21641	1241.11
5915	2.5	0.00226	180	0.40687	0.000031	0.18600	1100.20
6095	2	0.00181	180	0.32550	0.000025	0.15333	934.54
6275	1.5	0.00136	180	0.24412	0.000019	0.11839	742.92
6515	1	0.00090	240	0.21700	0.000013	0.08195	533.89
7175	0	0.00000	660	0.00000	0.000000	0.00000	0.00
7775	0	0.00000	1260	0.00000	0.000000	0.00000	0.00
* - [RWT] = (fluorometer reading)/1106				Q =	E =	sum(t_i*E_i)	sum(t_i^2*E_i)
from calibration curve				71.88246	0.024069	22.86419	45558.08

$t_d = 950$ s, $\sigma^2 = 990421\ s^2$, $\sigma = 995$ s

Table B.7 **Actual retention time and variance calculation for tracer test no. 3**

t_i sample time (s)	fluoro-meter reading	C_i - RWT conc. (mg/L)[a]	$(t_i - t_{i-1})$ (s)	$Q_i = (t_i - t_{i-1}) * C_i$ (s*mg/L)	$E_i = C_i/Q$ (s^{-1})	$(t_i * E_i)$	$(t_i^2 * E_i)$ (s)
35	0	0.0000	35	0.0000	0.000000	0.00000	0.00
65	0	0.0000	30	0.0000	0.000000	0.00000	0.00
95	0	0.0000	30	0.0000	0.000000	0.00000	0.00
125	0	0.0000	30	0.0000	0.000000	0.00000	0.00
155	0	0.0000	30	0.0000	0.000000	0.00000	0.00
195	0	0.0000	40.02	0.0000	0.000000	0.00000	0.00
215	4	0.0036	19.98	0.0723	0.000033	0.00709	1.52
230	7	0.0063	15	0.0949	0.000058	0.01327	3.05
235	10	0.0090	4.98	0.0450	0.000082	0.01937	4.55
245	15	0.0136	10.02	0.1359	0.000124	0.03029	7.42
255	22	0.0199	10.002	0.1990	0.000181	0.04624	11.79
265	28	0.0253	9.978	0.2526	0.000231	0.06116	16.21
275	29	0.0262	10.02	0.2627	0.000239	0.06574	18.08
285	25	0.0226	10.02	0.2265	0.000206	0.05874	16.74
289	21.5	0.0194	3.96	0.0770	0.000177	0.05121	14.80
293	21	0.0190	4.02	0.0763	0.000173	0.05072	14.86
315	21	0.0190	22.02	0.4181	0.000173	0.05453	17.18
325	21	0.0190	9.96	0.1891	0.000173	0.05626	18.28
335	21	0.0190	10.02	0.1903	0.000173	0.05799	19.43
365	23	0.0208	30	0.6239	0.000190	0.06920	25.26
380	22	0.0199	15	0.2984	0.000181	0.06891	26.19
395	19	0.0172	15	0.2577	0.000157	0.06186	24.44
410	17	0.0154	15	0.2306	0.000140	0.05745	23.56
425	14	0.0127	15	0.1899	0.000115	0.04905	20.84
440	16	0.0145	15	0.2170	0.000132	0.05803	25.53
455	14	0.0127	15	0.1899	0.000115	0.05251	23.89
470	12	0.0108	15	0.1627	0.000099	0.04649	21.85
485	10	0.0090	15	0.1356	0.000082	0.03998	19.39
500	11	0.0099	15	0.1492	0.000091	0.04534	22.67
515	11	0.0099	15	0.1492	0.000091	0.04670	24.05
530	11	0.0099	15	0.1492	0.000091	0.04806	25.47
545	11.5	0.0104	15	0.1560	0.000095	0.05166	28.16
560	11.5	0.0104	15	0.1560	0.000095	0.05309	29.73
575	12.5	0.0113	15	0.1695	0.000103	0.05925	34.07
590	14	0.0127	15	0.1899	0.000115	0.06809	40.17
605	17	0.0154	15	0.2306	0.000140	0.08478	51.29
620	21	0.0190	15	0.2848	0.000173	0.10732	66.54
635	25	0.0226	15	0.3391	0.000206	0.13086	83.09
650	28	0.0253	15	0.3797	0.000231	0.15002	97.52
665	30	0.0271	15	0.4069	0.000247	0.16445	109.36
680	32.5	0.0294	15	0.4408	0.000268	0.18217	123.88
695	35	0.0316	15	0.4747	0.000289	0.20051	139.36

Table B.7 (Continued)

710	38	0.0344	15	0.5154	0.000313	0.22240	157.90
725	39	0.0353	15	0.5289	0.000321	0.23307	168.98
740	39.5	0.0357	15	0.5357	0.000326	0.24094	178.30
755	43	0.0389	15	0.5832	0.000354	0.26761	202.05
770	46	0.0416	15	0.6239	0.000379	0.29197	224.82
785	46.5	0.0420	15	0.6307	0.000383	0.30089	236.20
800	47.5	0.0429	15	0.6442	0.000392	0.31324	250.59
815	46.5	0.0420	15	0.6307	0.000383	0.31239	254.60
830	45.5	0.0411	15	0.6171	0.000375	0.31130	258.38
845	45	0.0407	15	0.6103	0.000371	0.31344	264.86
860	45	0.0407	15	0.6103	0.000371	0.31901	274.34
875	47	0.0425	15	0.6374	0.000387	0.33899	296.62
890	47	0.0425	15	0.6374	0.000387	0.34481	306.88
905	48	0.0434	15	0.6510	0.000396	0.35808	324.06
920	49	0.0443	15	0.6646	0.000404	0.37160	341.87
935	49	0.0443	15	0.6646	0.000404	0.37765	353.11
950	46	0.0416	15	0.6239	0.000379	0.36022	342.21
965	45	0.0407	15	0.6103	0.000371	0.35795	345.43
980	43	0.0389	15	0.5832	0.000354	0.34736	340.41
995	42.5	0.0384	15	0.5764	0.000350	0.34858	346.83
1010	45	0.0407	15	0.6103	0.000371	0.37465	378.39
1025	42.5	0.0384	15	0.5764	0.000350	0.35909	368.06
1040	43	0.0389	15	0.5832	0.000354	0.36863	383.37
1055	43	0.0389	15	0.5832	0.000354	0.37395	394.51
1070	45	0.0407	15	0.6103	0.000371	0.39690	424.69
1085	45	0.0407	15	0.6103	0.000371	0.40247	436.68
1100	46	0.0416	15	0.6239	0.000379	0.41710	458.81
1115	46	0.0416	15	0.6239	0.000379	0.42279	471.41
1130	44.5	0.0402	15	0.6035	0.000367	0.41450	468.39
1145	42	0.0380	15	0.5696	0.000346	0.39641	453.89
1160	42	0.0380	15	0.5696	0.000346	0.40160	465.86
1175	42	0.0380	15	0.5696	0.000346	0.40679	477.98
1190	42	0.0380	15	0.5696	0.000346	0.41199	490.26
1205	41.5	0.0375	15	0.5628	0.000342	0.41221	496.72
1220	40	0.0362	15	0.5425	0.000330	0.40226	490.76
1235	40	0.0362	15	0.5425	0.000330	0.40721	502.90
1250	40	0.0362	15	0.5425	0.000330	0.41215	515.19
1265	40	0.0362	15	0.5425	0.000330	0.41710	527.63
1280	40	0.0362	15	0.5425	0.000330	0.42204	540.22
1295	39	0.0353	15	0.5289	0.000321	0.41631	539.13
1310	38.5	0.0348	15	0.5222	0.000317	0.41574	544.62
1325	38.5	0.0348	15	0.5222	0.000317	0.42050	557.16
1340	38.5	0.0348	15	0.5222	0.000317	0.42526	569.85
1355	38.5	0.0348	15	0.5222	0.000317	0.43002	582.67
1385	38.5	0.0348	30	1.0443	0.000317	0.43954	608.76

Table B.7 (Continued)

1415	38.5	0.0348	30	1.0443	0.000317	0.44906	635.42
1475	38.5	0.0348	60	2.0886	0.000317	0.46810	690.45
1535	37	0.0335	60	2.0072	0.000305	0.46816	718.63
1595	33.5	0.0303	60	1.8174	0.000276	0.44045	702.51
1655	32	0.0289	60	1.7360	0.000264	0.43655	722.49
1715	31	0.0280	60	1.6817	0.000256	0.43824	751.58
1775	30.5	0.0276	60	1.6546	0.000251	0.44626	792.11
1895	30.5	0.0276	120	3.3092	0.000251	0.47643	902.83
2015	29.5	0.0267	120	3.2007	0.000243	0.48999	987.32
2135	27.5	0.0249	120	2.9837	0.000227	0.48397	1033.27
2255	28	0.0253	120	3.0380	0.000231	0.52046	1173.65
2375	26.5	0.0240	120	2.8752	0.000218	0.51880	1232.14
2495	24	0.0217	120	2.6040	0.000198	0.49359	1231.51
2615	22.5	0.0203	120	2.4412	0.000185	0.48500	1268.27
2735	22	0.0199	120	2.3870	0.000181	0.49598	1356.51
2855	21.5	0.0194	120	2.3327	0.000177	0.50598	1444.57
2915	20	0.0181	60	1.0850	0.000165	0.48057	1400.86
3065	19	0.0172	150	2.5769	0.000157	0.48003	1471.30
3155	18	0.0163	90	1.4647	0.000148	0.46812	1476.92
3275	18	0.0163	120	1.9530	0.000148	0.48593	1591.41
3335	17	0.0154	60	0.9222	0.000140	0.46734	1558.57
3515	17	0.0154	180	2.7667	0.000140	0.49256	1731.36
3695	15	0.0136	180	2.4412	0.000124	0.45687	1688.13
3755	14	0.0127	60	0.7595	0.000115	0.43334	1627.18
3875	14	0.0127	120	1.5190	0.000115	0.44718	1732.84
3935	13	0.0118	60	0.7052	0.000107	0.42167	1659.28
3995	12	0.0108	60	0.6510	0.000099	0.39517	1578.71
4115	13	0.0118	120	1.4105	0.000107	0.44096	1814.55
4175	13	0.0118	60	0.7052	0.000107	0.44739	1867.86
4295	11	0.0099	120	1.1935	0.000091	0.38944	1672.65
4475	10	0.0090	180	1.6275	0.000082	0.36888	1650.72
4775	9.5	0.0086	300	2.5769	0.000078	0.37392	1785.49
5075	8.5	0.0077	300	2.3056	0.000070	0.35558	1804.59
5375	7.5	0.0068	300	2.0344	0.000062	0.33230	1786.10
5675	6.75	0.0061	300	1.8309	0.000056	0.31576	1791.94
5975	6	0.0054	300	1.6275	0.000049	0.29551	1765.69
6575	4.5	0.0041	600	2.4412	0.000037	0.24389	1603.58
7175	3	0.0027	600	1.6275	0.000025	0.17743	1273.07
7775	1.5	0.0014	600	0.8137	0.000012	0.09613	747.44
8675	0.5	0.0005	900	0.4069	0.000004	0.03575	310.17
9575	0	0.0000	900	0.0000	0.000000	0.00000	0.00
				Q =	**E =**	**sum(t_i*E_i)**	**sum(t_i^2*E_i)**
				109.6877	**0.027591**	**35.48581**	**71900.18**

[a] - [RWT] = (fluorometer reading)/1106 from calibration curve

$t_d = 1286$ s, $\sigma^2 = 951780\ s^2$, $\sigma = 976$ s

Table B.8 Actual retention time and variance calculation for tracer test no. 4

t_i sample time (s)	fluoro-meter reading	C_i - RWT conc. (mg/L)*	$(t_i - t_{i-1})$ (s)	$Q_i = (t_i - t_{i-1}) * C_i$ (s*mg/L)	$E_i = C_i/Q$ (s^{-1})	$(t_i * E_i)$	$(t_i^2 * E_i)$ (s)
0	0	0.0000	0	0	0.000000	0.00000	0.00
60	22	0.0199	60	1.1935	0.000277	0.01660	1.00
120	27.5	0.0249	60	1.4919	0.000346	0.04151	4.98
180	28	0.0253	60	1.5190	0.000352	0.06339	11.41
210	32	0.0289	30	0.8680	0.000403	0.08453	17.75
240	37	0.0335	30	1.0036	0.000465	0.11170	26.81
270	43	0.0389	30	1.1664	0.000541	0.14603	39.43
300	46	0.0416	30	1.2477	0.000579	0.17358	52.07
330	49.5	0.0448	30	1.3427	0.000623	0.20547	67.80
360	52	0.0470	30	1.4105	0.000654	0.23547	84.77
390	50	0.0452	30	1.3562	0.000629	0.24528	95.66
420	50	0.0452	30	1.3562	0.000629	0.26414	110.94
450	47.5	0.0429	30	1.2884	0.000597	0.26886	120.99
480	45	0.0407	30	1.2206	0.000566	0.27169	130.41
510	42	0.0380	30	1.1392	0.000528	0.26943	137.41
570	40.5	0.0366	60	2.1971	0.000509	0.29037	165.51
630	35	0.0316	60	1.8987	0.000440	0.27735	174.73
690	32	0.0289	60	1.7360	0.000403	0.27773	191.63
750	30	0.0271	60	1.6275	0.000377	0.28301	212.26
810	29.5	0.0267	60	1.6004	0.000371	0.30056	243.45
870	28	0.0253	60	1.5190	0.000352	0.30641	266.57
900	26.5	0.0240	30	0.7188	0.000333	0.29999	269.99
930	26	0.0235	30	0.7052	0.000327	0.30414	282.85
960	25	0.0226	30	0.6781	0.000314	0.30188	289.80
990	22.5	0.0203	30	0.6103	0.000283	0.28018	277.38
1050	22	0.0199	60	1.1935	0.000277	0.29056	305.09
1110	21.5	0.0194	60	1.1664	0.000270	0.30018	333.20
1170	21	0.0190	60	1.1392	0.000264	0.30905	361.59
1230	20.5	0.0185	60	1.1121	0.000258	0.31716	390.11

Table B.8 (Continued)

1290	20.5	0.0185	60	1.1121	0.000258	0.33263	429.10
1350	20	0.0181	60	1.0850	0.000252	0.33961	458.48
1410	19	0.0172	60	1.0307	0.000239	0.33697	475.13
1470	18.5	0.0167	60	1.0036	0.000233	0.34207	502.84
1620	18.5	0.0167	150	2.5090	0.000233	0.37697	610.69
1770	18	0.0163	150	2.4412	0.000226	0.40074	709.32
1920	17.5	0.0158	150	2.3734	0.000220	0.42263	811.45
2070	15	0.0136	150	2.0344	0.000189	0.39056	808.45
2220	14.5	0.0131	150	1.9665	0.000182	0.40490	898.87
2370	13	0.0118	150	1.7631	0.000164	0.38754	918.46
2520	12	0.0108	150	1.6275	0.000151	0.38037	958.53
2670	10.5	0.0095	150	1.4241	0.000132	0.35263	941.53
2670	10	0.0090	0	0.0000	0.000126	0.33584	896.69
2820	9.5	0.0086	150	1.2884	0.000119	0.33697	950.26
2970	8	0.0072	150	1.0850	0.000101	0.29886	887.62
3270	7.5	0.0068	300	2.0344	0.000094	0.30848	1008.74
3570	6	0.0054	300	1.6275	0.000075	0.26943	961.86
3870	5	0.0045	300	1.3562	0.000063	0.24339	941.92
4170	3	0.0027	300	0.8137	0.000038	0.15735	656.17
4470	2.5	0.0023	300	0.6781	0.000031	0.14056	628.31
4770	2	0.0018	300	0.5425	0.000025	0.12000	572.39
5070	1.75	0.0016	300	0.4747	0.000022	0.11160	565.82
5370	1.5	0.0014	300	0.4069	0.000019	0.10132	544.08
5670	1.25	0.0011	300	0.3391	0.000016	0.08915	505.47
5970	1	0.0009	300	0.2712	0.000013	0.07509	448.30
6570	0.5	0.0005	600	0.2712	0.000006	0.04132	271.47
7470	0.5	0.0005	900	0.4069	0.000006	0.04698	350.94
8070	0	0.0000	600	0.0000	0.000000	0.00000	0.00
8370	0	0.0000	300	0.0000	0.000000	0.00000	0.00
				Q = 67.47288	**E = 0.01520**	**sum(t_i*E_i) 13.68022**	**sum(t_i^2*E_i) 23378.49**

[a] - [RWT] = (fluorometer reading)/1106 from calibration curve

$t_d = 900$ s, $\sigma^2 = 728037\ s^2$, $\sigma = 853$ s

APPENDIX C

SETTLING COLUMN TESTS RAW DATA

Settling Column Test no. 1

Date: *July 5, 1995*
Start Time: *9:35am* ***Finish Time:*** *9:35am, July 6*

Comments: *preliminary test for hydrite flat D sample from Debro Chemical*

Port # 1
Height: 120 cm

	Time (min)	Height (mm)	Vol. (mL)	wt filt (g)	wt fi+so (g)	wt sol (g)	Conc (mg/L)
1	0	147	50	0.4095	0.766	0.3565	7130
2	15	146.2	50	0.4175	0.911	0.4935	9870
3	45	144.6	50	0.2118	0.4724	0.2606	5212
4	60	143.2	50	0.208	0.4179	0.2099	4198
5	120	141.8	50	0.205	0.3335	0.1285	2570
6	250	140.6	27	0.202	0.2423	0.0403	1492.6
7	480	126.6	25	0.1983	0.209	0.0107	428
8	780	125.8	25	0.2192	0.2233	0.0041	164
9	1410	125	25	0.2014	0.2036	0.0022	88
10							

Port # 2
Height: 84 cm

	Time (min)	Height (mm)	Vol. (mL)	wt filt (g)	wt fi+so (g)	wt sol (g)	Conc (mg/L)
1	0	146.8	50	0.4136	0.8486	0.435	8700
2	15	145.8	50	0.4159	0.941	0.5251	10502
3	30	144.2	50	0.2164	0.6468	0.4304	8608
4	60	142.8	50	0.2059	0.469	0.2631	5262
5	120	141.4	50	0.2094	0.367	0.1576	3152
6	250	140.4	25	0.215	0.2682	0.0532	2128
7	480	126.4	25	0.2062	0.2278	0.0216	864
8	780	125.6	25	0.201	0.2198	0.0188	752
9	1410	124.8	25	0.1984	0.2109	0.0125	500

Port # 3
Height: 59 cm

	Time (min)	Height (mm)	Vol. (mL)	wt filt (g)	wt fi+so (g)	wt sol (g)	Conc (mg/L)
1	0	146.6	50	0.4208	0.8427	0.4219	8438
2	15	145.4	50	0.4139	0.8817	0.4678	9356
3	30	143.8	50	0.2035	0.6445	0.441	8820
4	60	142.4	50	0.2135	0.818	0.6045	12090
5	120	141	50	0.2125	0.4011	0.1886	3772
6	250	140.2	25	0.1975	0.4055	0.208	8320
7	480	126.2	25	0.197	0.2195	0.0225	900
8	780	125.4	27	0.2165	0.2333	0.0168	622.22
9	1410	124.6	25	0.2046	0.218	0.0134	536
10							

Port # 4
Height: 28 cm

	Time (min)	Height (mm)	Vol. (mL)	wt filt (g)	wt fi+so (g)	wt sol (g)	Conc (mg/L)
1	0	146.4	50	0.4198	0.906	0.4862	9724
2	15	145	50	0.419	0.856	0.437	8740
3	30	143.6	50	0.2032	0.6776	0.4744	9488
4	60	142	30	0.2152	0.6855	0.4703	15677
5	120	140.8	50	0.2165	0.4864	0.2699	5398
6	250	140	25	0.2133	0.2686	0.0553	2212
7	480	126	25	0.2045	0.2287	0.0242	968
8	780	125.2	25	0.207	0.2345	0.0275	1100
9	1410	124.4	25	0.2098	0.2299	0.0201	804

Settling Column Test no. 2

Date: *August 29, 1995*
Start Time: *9:05am* *Finish Time:* *9:20am, August 30*

Comments: *preliminary test for Hawthorne fire clay from Manotik, 230 g in 23 L of water*

Port # 1
Height: 120 cm

	Time (min)	Height (mm)	Vol. (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0	147.6					10000
2	15	147.4	15	1.7132	1.746	0.0328	2186.667
3	30	146.6	15	1.7774	1.8031	0.0257	1713.333
4	60	145.8	16	1.7787	1.7989	0.0202	1262.5
5	120	145	15	2.7158	2.7241	0.0083	553.3333
6	240	144.6	15	1.7342	1.7422	0.008	533.3333
7	450	143.8	16	1.7808	1.789	0.0082	512.5
8	720	143	16	2.6921	2.7	0.0079	493.75
9	1440	142.2	17	2.7046	2.7122	0.0076	447.0588
10							

Port # 2
Height: 84 cm

	Time (min)	Height (mm)	Vol. (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0						10000
2	15	147.2	15	1.7128	1.7456	0.0328	8700
3	30	146.4	16	1.7786	1.8096	0.031	1937.5
4	60	145.6	15	1.7821	1.7997	0.0176	1173.333
5	120	144.9	16	2.7017	2.716	0.0143	893.75
6	240	144.4	15	1.7134	1.7264	0.013	866.6667
7	450	143.6	16	1.7733	1.78	0.0067	418.75
8	720	142.8	16	2.6852	2.6883	0.0031	193.75
9	1440	142	16	2.6974	2.6988	0.0014	87.5
10							

Port # 3
Height: 59 cm

	Time (min)	Height (mm)	Vol. (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0						10000
2	15	147	15	1.787	1.8198	0.0328	2186.667
3	30	146.2	17	1.7852	1.8193	0.0341	2005.882
4	60	145.4	16	1.7827	1.8103	0.0276	1725
5	120	144.8	15	2.7225	2.7412	0.0187	1246.667
6	240	144.2	17	1.7977	1.8089	0.0112	658.8235
7	450	143.4	16	1.7815	1.788	0.0065	406.25
8	720	142.6	16	2.7149	2.7213	0.0064	400
9	1440	141.8	15	2.7072	2.7122	0.005	333.3333
10							

Port # 4
Height: 28 cm

	Time (min)	Height (mm)	Vol. (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0						10000
2	15	146.8	15	1.7247	1.7575	0.0328	2186.667
3	30	146	16	1.7843	1.8165	0.0322	2012.5
4	60	145.2	15	1.7208	1.7505	0.0297	1980
5	120	144.7	16	2.7103	2.7418	0.0315	1968.75
6	240	144	16	1.7192	1.747	0.0278	1737.5
7	450	143.2	15	1.7777	1.788	0.0103	686.6667
8	720	142.4	16	2.7187	2.7236	0.0049	306.25
9	1440	141.6	15	2.706	2.7121	0.0061	406.6667
10							

Settling Column Test Data Collection

Date: *April 17 - 1 , 1996*

Start Time: *9:35am* *Finish Time:* *9:35am, August 30*

Comments: *Settling test on samples taken from the sedimentation basin at the inlet of the tank #1. containing 5 inclined plates*

$d = 20$ cm, $Q = 30$ L/min

$C_o = 6570$ mg/L

Port # 1

Height: 120 cm

	Time (min)	Height (mm)	Volume (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0	148					6571
2	15	148	30	2.4916	2.6958	0.204	6806.7
3	30	146.8	31	2.4751	2.6517	0.177	5696.8
4	60	145.5	31	2.4964	2.658	0.162	5212.9
5	120	144	31	2.4984	2.6512	0.153	4929
6	240	142.6	38	2.4763	2.5934	0.117	3081.6
7	420	141.2	28	2.4969	2.5578	0.061	2175
8	680	140	26	2.4984	2.5253	0.027	1034.6
9	1440	138.8	42	2.4888	2.5141	0.025	602.38
10							

Port # 2

Height: 84 cm

	Time (min)	Height (mm)	Volume (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0						6571
2	15	147.7	30	2.4745	2.6853	0.2108	7026.7
3	30	146.5	32	2.4718	2.6622	0.1904	5950
4	60	145.2	28	2.4719	2.6191	0.1472	5257.1
5	120	143.6	29	2.5024	2.6534	0.151	5206.9
6	240	142.2	36	2.4871	2.6367	0.1496	4155.6
7	420	140.9	-29	2.4741	2.5489	0.0748	2579.3
8	680	139.7	30	2.47	2.5117	0.0417	1390
9	1440	138.5	35	2.4831	2.5049	0.0218	622.86
10							

Port # 3

Height: 59 cm

	Time (min)	Height (mm)	Volume (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0						6571
2	15	147.4	40	2.4928	2.7331	0.24	6007.5
3	30	146.2	37	2.4961	2.7083	0.212	5735.1
4	60	144.8	41	2.467	2.7005	0.234	5695.1
5	120	143.3	29	2.5099	2.6779	0.168	5793.1
6	240	141.9	38	2.4866	2.6684	0.182	4784.2
7	420	140.6	28	2.4706	2.58	0.109	3907.1
8	680	139.4	27	2.4671	2.5201	0.053	1963
9	1440	138.2	37	2.4959	2.5316	0.036	964.86
10							

Port # 4

Height: 28 cm

	Time (min)	Height (mm)	Volume (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0						6571
2	15	147.1	35.5	2.4959	2.7086	0.2127	5991.5
3	30	145.9	28	2.5021	2.6663	0.1642	5864.3
4	60	144.4	33.5	2.494	2.6915	0.1975	5895.5
5	120	143	37	2.4992	2.7029	0.2037	5505.4
6	240	141.6	27	2.465	2.5957	0.1307	4840.7
7	420	140.3	28	2.4814	2.5918	0.1104	3942.9
8	680	139.1	42	2.484	2.5822	0.0982	2338.1
9	1440	137.8	32	2.4954	2.5165	0.0211	659.38
10							

Settling Column Test Data Collection

Date: *April 17 - 2 , 1996*
Start Time: *10:05am* *Finish Time:* *9:35am, next day*

Comments: *Settling test on samples taken from the sedimentation basin at the outlet of the control.*
d = 20 cm, Q = 30 L/min
$C_o = 5151$ *mg/L*

Port # 1
Height: 120 cm

	Time (min)	Height (mm)	Volume (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0	148					5151
2	15	148	33	2.5085	2.6814	0.1729	5239.4
3	30	146.8	37	2.5009	2.6885	0.1876	5070.3
4	60	145.5	40	2.4871	2.6866	0.1995	4987.5
5	120	144.2	31	2.4895	2.6471	0.1576	5083.9
6	240	142.8	39	2.492	2.6148	0.1228	3148.7
7	420	141.4	46	2.4937	2.5685	0.0748	1626.1
8	630	140	32	2.4708	2.4969	0.0261	815.63
9	1410	138.4	34	2.4946	2.5119	0.0173	508.82
10							

Port # 2
Height: 84 cm

	Time (min)	Height (mm)	Volume (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0						5151
2	15	147.7	39	2.5023	2.7041	0.2018	5174.4
3	30	146.5	35	2.5012	2.6794	0.1782	5091.4
4	60	145.2	24	2.4726	2.5916	0.119	4958.3
5	120	143.8	35	2.5013	2.6741	0.1728	4937.1
6	240	142.4	32	2.5013	2.6364	0.1351	4221.9
7	420	141.1	43	2.493	2.5849	0.0919	2137.2
8	630	139.6	41	2.4793	2.5198	0.0405	987.8
9	1410	138	34	2.4734	2.485	0.0116	341.18
10							

Port # 3
Height: 59 cm

	Time (min)	Height (mm)	Volume (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0						5151
2	15	147.4	38	2.4825	2.6795	0.197	5184.2
3	30	146.2	35	2.4951	2.6756	0.1805	5157.1
4	60	144.9	33	2.4995	2.6728	0.1733	5251.5
5	120	143.5	33	2.4969	2.6724	0.1755	5318.2
6	240	142.1	40	2.491	2.7012	0.2102	5255
7	420	140.7	32	2.498	2.6198	0.1218	3806.3
8	630	139.2	55	2.4932	2.5908	0.0976	1774.5
9	1410	137.7	33	2.4935	2.5109	0.0174	527.27
10							

Port # 4
Height: 28 cm

	Time (min)	Height (mm)	Volume (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0						5151
2	15	147.1	36	2.4909	2.6731	0.1822	5061.1
3	30	145.9	37	2.4987	2.6854	0.1867	5045.9
4	60	144.6	30	2.5139	2.6752	0.1613	5376.7
5	120	143.1	25	2.5026	2.6445	0.1419	5676
6	240	141.7	44	2.5034	2.7174	0.214	4863.6
7	420	140.3	26	2.4839	2.5779	0.094	3615.4
8	630	138.8	25	2.494	2.5484	0.0544	2176
9	1410	137.3	29	2.5001	2.5143	0.0142	489.66
10							

Settling Column Test Data Collection

Date: *April 17 - 3 , 1996*

Start Time: *10:00am* *Finish Time:* *9:35am, next day*

Comments: *Settling test on samples taken from the sedimentation basin at the outlet of the tank #1.*
containing 5 inclined plates
d = 20 cm, Q = 30 L/min
$C_o = 5069$ *mg/L*

Port # 1
Height: 120 cm

	Time (min)	Height (mm)	Volume (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0	149					5069
2	15	149	30	2.4773	2.6404	0.1631	5436.7
3	30	147.6	29	2.4983	2.6467	0.1484	5117.2
4	60	146.4	34	2.4987	2.6745	0.1758	5170.6
5	120	145	33	2.4792	2.6505	0.1713	5190.9
6	210	143.8	35	2.5007	2.6199	0.1192	3405.7
7	450	142.4	36	2.4995	2.5498	0.0503	1397.2
8	660	141.2	36	2.4904	2.5193	0.0289	802.78
9	1380	139.6	44	2.4964	2.5204	0.024	545.45
10							

Port # 2
Height: 84 cm

	Time (min)	Height (mm)	Volume (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0						5069
2	15	148.6	35	2.4781	2.666	0.1879	5368.6
3	30	147.3	21	2.4775	2.5878	0.1103	5252.4
4	60	146	33	2.5034	2.6849	0.1815	5500
5	120	144.7	34	2.4884	2.6716	0.1832	5388.2
6	210	143.4	37	2.4783	2.6426	0.1643	4440.5
7	450	142.1	30	2.4718	2.5285	0.0567	1890
8	660	140.8	39	2.4843	2.5192	0.0349	894.87
9	1380	139.2	34	2.4745	2.4865	0.012	352.94
10							

Port # 3
Height: 59 cm

	Time (min)	Height (mm)	Volume (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0						5069
2	15	148.3	31	2.5011	2.6631	0.162	5225.8
3	30	147	31	2.471	2.638	0.167	5387.1
4	60	145.7	42	2.5107	2.7556	0.2449	5831
5	120	144.4	30	2.4877	2.6575	0.1698	5660
6	210	143	37	2.4728	2.6585	0.1857	5018.9
7	450	141.8	36	2.4677	2.5761	0.1084	3011.1
8	660	140.4	45	2.4918	2.5611	0.0693	1540
9	1380	138.8	43	2.4977	2.5205	0.0228	530.23
10							

Port # 4
Height: 28 cm

	Time (min)	Height (mm)	Volume (mL)	wt filt (g)	wt fi+sol (g)	wt sol (g)	Conc (mg/L)
1	0						5069
2	15	147.9	30	2.5029	2.661	0.1581	5270
3	30	146.7	26	2.4966	2.6358	0.1392	5353.8
4	60	145.3	32	2.5014	2.6745	0.1731	5409.4
5	120	144.1	34	2.4676	2.6531	0.1855	5455.9
6	210	142.7	34	2.4812	2.6282	0.147	4323.5
7	450	141.5	34	2.4875	2.6011	0.1136	3341.2
8	660	140	35	2.4868	2.5548	0.068	1942.9
9	1380	138.4	38	2.5106	2.529	0.0184	484.21
10							

APPENDIX D

t-TEST CALCULATIONS AND RESULTS

Table D.1 t-test calculations for comparison of mean TSS removal efficiencies between basin configurations

Basin	Condition	mean X_i	std. dev. s_i	no. of points n_i	d.f.	t-distribution[1] 90% $t_{1-\alpha/2}$	90% $t_{1-\alpha}$	95% $t_{1-\alpha/2}$	95% $t_{1-\alpha}$	99% $t_{1-\alpha/2}$	99% $t_{1-\alpha}$	Hypothesis #1	s_p[2]	$X_x - X_y$ (absolute value)	n[3]	T_{90}[4]	T_{95}[4]	T_{99}[4]	Result $X_x = X_y$ 90%	95%	99%
Control (A)	overall	31.5	8.9988	103	204	1.645	1.282	1.96	1.645	2.576	2.326	$X_a = X_b$	9.0172	0.6	0.1393	2.067	2.463	3.237	T	T	T
	Q_1	35.6	6.958	35	68	1.6693	1.2951	1.9973	1.6693	2.6543	2.3857	$X_a = X_b$	8.0072	0.3	0.2390	3.1952	3.823	5.081	T	T	T
	Q_2	32.9	8.289	33	64	1.6701	1.2955	1.9987	1.6701	2.6571	2.3879	$X_a = X_b$	8.7594	0.5	0.2462	3.6014	4.31	5.73	T	T	T
	Q_3	26.2	8.832	36	70	1.6688	1.2948	1.9967	1.6688	2.6528	2.3847	$X_a = X_b$	8.2970	2.6	0.2357	3.2636	3.905	5.188	T	T	T
	d_1	30.44	8.8727	44	86	1.6654	1.293	1.9913	1.6654	2.6414	2.3761	$X_a = X_b$	8.3384	1.31	0.2132	2.9607	3.54	4.696	T	T	T
	d_2	32.23	9.0154	60	118	1.6584	1.2892	1.9807	1.6584	2.6184	2.3591	$X_a = X_b$	9.1389	2.11	0.1826	2.7671	3.305	4.369	T	T	T
	C_1	28.63	9.7181	56	112	1.6597	1.2899	1.9827	1.6597	2.6227	2.3623	$X_a = X_b$	8.1316	1.39	0.1890	2.5505	3.047	4.03	T	T	T
	C_2	34.92	6.5536	48	94	1.6636	1.292	1.9887	1.6636	2.6356	2.3719	$X_a = X_b$	7.5291	3.16	0.2041	2.5567	3.056	4.051	F	F	T
	t_1	31.65	9.2472	48	94	1.6636	1.292	1.9887	1.6636	2.6356	2.3719	$X_a = X_b$	8.8615	0.46	0.2041	3.0092	3.597	4.767	T	T	T
	t_2	30.64	8.4111	48	94	1.6636	1.292	1.9887	1.6636	2.6356	2.3719	$X_a = X_b$	9.1288	2.23	0.2041	3.1	3.706	4.911	T	T	T
5 plates (B)	overall	32.1	9.0356	103	204	1.645	1.282	1.96	1.645	2.576	2.326	$X_b = X_c$	8.9537	3.7	0.1393	2.0524	2.445	3.214	F	F	F
	Q_1	35.3	8.934	35	68	1.6693	1.2951	1.9973	1.6693	2.6543	2.3857	$X_b = X_c$	9.2417	2.92	0.2390	3.6878	4.412	5.864	T	T	T
	Q_2	32.4	9.2057	33	64	1.6701	1.2955	1.9987	1.6701	2.6571	2.3879	$X_b = X_c$	8.1062	2.33	0.2462	3.3329	3.989	5.303	T	T	T
	Q_3	28.8	7.7251	36	70	1.6688	1.2948	1.9967	1.6688	2.6528	2.3847	$X_b = X_c$	7.2841	5.92	0.2357	2.8651	3.428	4.555	F	F	F
	d_1	29.13	7.7675	44	86	1.6654	1.293	1.9913	1.6654	2.6414	2.3761	$X_b = X_c$	7.6402	2.39	0.2132	2.7128	3.244	4.303	T	T	T
	d_2	34.34	9.2607	60	118	1.6584	1.2892	1.9807	1.6584	2.6184	2.3591	$X_b = X_c$	9.4200	4.79	0.1826	2.8522	3.407	4.503	F	F	F
	C_1	27.24	6.1485	56	112	1.6597	1.2899	1.9827	1.6597	2.6227	2.3623	$X_b = X_c$	6.7842	2.08	0.1890	2.1279	2.542	3.363	T	T	T
	C_2	38.08	8.392	48	94	1.6636	1.292	1.9887	1.6636	2.6356	2.3719	$X_b = X_c$	8.6992	5.84	0.2041	2.9541	3.531	4.68	F	F	F
	t_1	31.19	8.4582	48	94	1.6636	1.292	1.9887	1.6636	2.6356	2.3719	$X_b = X_c$	8.7693	3.82	0.2041	2.9779	3.56	4.718	F	F	T
	t_2	32.87	9.7941	48	94	1.6636	1.292	1.9887	1.6636	2.6356	2.3719	$X_b = X_c$	9.3280	3.1	0.2041	3.1676	3.787	5.018	T	T	T
3 plates (C)	overall	28.4	8.871	103	204	1.645	1.282	1.96	1.645	2.576	2.326	$X_a = X_c$	8.9351	3.1	0.1393	2.0482	2.44	3.207	F	F	T
	Q_1	32.38	9.5394	35	68	1.6693	1.2951	1.9973	1.6693	2.6543	2.3857	$X_a = X_c$	8.3491	3.22	0.2390	3.3316	3.986	5.297	T	T	T
	Q_2	30.07	6.832	33	64	1.6701	1.2955	1.9987	1.6701	2.6571	2.3879	$X_a = X_c$	7.5955	2.83	0.2462	3.1229	3.737	4.968	T	T	T
	Q_3	22.88	6.8147	36	70	1.6688	1.2948	1.9967	1.6688	2.6528	2.3847	$X_a = X_c$	7.8881	3.32	0.2357	3.1027	3.712	4.932	F	T	T
	d_1	26.74	7.5108	44	86	1.6654	1.293	1.9913	1.6654	2.6414	2.3761	$X_a = X_c$	8.2200	3.7	0.2132	2.9186	3.49	4.629	F	F	T
	d_2	29.55	9.5767	60	118	1.6584	1.2892	1.9807	1.6584	2.6184	2.3591	$X_a = X_c$	9.3003	2.68	0.1826	2.816	3.363	4.446	T	T	T
	C_1	25.16	7.3653	56	112	1.6597	1.2899	1.9827	1.6597	2.6227	2.3623	$X_a = X_c$	8.6223	3.47	0.1890	2.7044	3.231	4.274	F	F	T
	C_2	32.24	8.996	48	94	1.6636	1.292	1.9887	1.6636	2.6356	2.3719	$X_a = X_c$	7.8701	2.68	0.2041	2.6725	3.195	4.234	F	T	T
	t_1	27.37	9.0697	48	94	1.6636	1.292	1.9887	1.6636	2.6356	2.3719	$X_a = X_c$	9.1589	4.28	0.2041	3.1102	3.718	4.927	F	F	T
	t_2	29.77	8.8374	48	94	1.6636	1.292	1.9887	1.6636	2.6356	2.3719	$X_a = X_c$	8.6269	0.87	0.2041	2.9295	3.502	4.641	T	T	T

1 - The t-distribution values were obtained from Himmelblau (1990).
Each value corresponds to a specified confidence interval and number of degrees of freedom (d.f. = $n_x + n_y - 2$)

2 - $S_p = [((n_x-1)^2 s_x + (n_y-1)^2 s_y^2)/(d.f.)]^{1/2}$

3 - $n = ((n_x+n_y)/(n_x n_y))^{1/2}$

4 - $T = t_{1-\alpha/2} * s_p * n$

5 - If hypothesis #1 was proven true then the test is complete. However, if hypothesis #1 was proven false, another test will confirm that one value is significantly greater than the other.

6 - $U = t_{1-\alpha} * s_p * n$

Table D.1 (Continued)

Hypothesis #2[5]	U_{90}[6]	U_{95}[6]	U_{99}[6]	Results $X_x < X_y$ or $X_y < X_x$			Summary
				90%	95%	99%	
							X_a is equal to X_b
							X_a is equal to X_b
							X_a is equal to X_b
							X_a is equal to X_b
							X_a is equal to X_b
							X_a is equal to X_b
							X_a is equal to X_b
$X_a < X_b$	1.9856	2.5567		T	T		X_a is smaller than X_b at 90 & 95% only
$X_b > X_c$	1.5995	2.0524	2.9021	T	T	T	X_b is greater than X_c at 90, 95, 99%
							X_b is equal to X_c
							X_b is equal to X_c
$X_b > X_c$	2.223	2.8651	4.0943	T	T	T	X_b is greater than X_c at 90, 95, 99%
							X_b is equal to X_c
$X_b > X_c$	2.2172	2.8522	4.0573	T	T	T	X_b is greater than X_c at 90, 95, 99%
							X_b is equal to X_c
$X_b > X_c$	2.2942	2.9541	4.2118	T	T	T	X_b is greater than X_c at 90, 95, 99%
$X_b > X_c$	2.3127	2.9779		T	T		X_b is greater than X_c at 90 & 95% only
$X_a > X_c$	1.5962	2.0482		T	T		X_a is greater than X_c, at 90 & 95% only
							X_a is equal to X_c
							X_a is equal to X_c
$X_a > X_c$	2.4073			T			X_a is greater than X_c at 90% only
$X_a > X_c$	2.266	2.9186		T	T		X_a is greater than X_c, at 90 & 95% only
							X_a is equal to X_c
$X_a > X_c$	2.1018	2.7044		T	T		X_a is greater than X_c, at 90 & 95% only
$X_a > X_c$	2.0756			T			X_a is greater than X_c at 90% only
$X_a > X_c$	2.4155	3.1102		T	T		X_a is greater than X_c at 90 &AD22 95% onl'

Table D.2 t-test calc. for comparison of mean TSS removal efficiencies between different variable settings for individual basins

Basin	Condition	mean X_i	std. dev. s_i	no. of points n_i	d.f.	t-distribution[1] 90% $t_{1-\alpha/2}$	90% $t_{1-\alpha}$	95% $t_{1-\alpha/2}$	95% $t_{1-\alpha}$	99% $t_{1-\alpha/2}$	99% $t_{1-\alpha}$	Hypothesis #1	s_p^2 [2]	$X_x - X_y$ (absolute value)	n[3]	T_{90}[4]	T_{95}[4]	T_{99}[4]	Result $X_x = X_y$ 90%	95%	99%
Control (A)	t_1	31.65	9.2472	48	94	1.6636	1.292	1.9887	1.6636	2.6356	2.3719	X(t1)=X(t2)	8.8390	1.01	0.2041	3.0016	3.588	4.755	T	T	T
	t_2	30.64	8.4111	48																	
	Q_1	35.6	6.958	35	66	1.6697	1.2953	1.998	1.6697	2.3868	2.6557	X(Q1)=X(Q2)	7.6324	2.7	0.2426	3.0922	3.7	4.42	T	T	T
	Q_2	32.9	8.289	33	67	1.6695	1.2952	1.9977	1.6695	2.3863	2.655	X(Q2)=X(Q3)	8.5769	6.7	0.2410	3.4509	4.129	4.933	F	F	F
	Q_3	26.2	8.832	36	69	1.6691	1.295	1.997	1.6691	2.3852	2.6536	X(Q1)=X(Q3)	7.9639	9.4	0.2374	3.1554	3.775	4.509	F	F	F
	d_1	30.44	8.8727	44	102	1.6619	1.2911	1.986	1.6619	2.6376	2.6299	X(d1)=X(d2)	8.9555	1.79	0.1985	2.954	3.53	4.688	T	T	T
	d_2	32.23	9.0154	60																	
	C_1	28.63	9.7181	56	102	1.6619	1.2911	1.986	1.6619	2.6376	2.6299	X(C1)=X(C2)	8.4092	6.29	0.1967	2.7489	3.285	4.363	F	F	F
	C_2	34.92	6.5536	48																	

Basin	Condition	mean X_i	std. dev. s_i	no. of points n_i	d.f.	t-distribution[1] 90% $t_{1-\alpha/2}$	90% $t_{1-\alpha}$	95% $t_{1-\alpha/2}$	95% $t_{1-\alpha}$	99% $t_{1-\alpha/2}$	99% $t_{1-\alpha}$	Hypothesis #1	s_p^2 [2]	$X_x - X_y$ (absolute value)	n[3]	T_{90}[4]	T_{95}[4]	T_{99}[4]	Result $X_x = X_y$ 90%	95%	99%
5 plates (B)	t_1	31.19	8.4582	48	94	1.6636	1.292	1.9887	1.6636	2.6356	2.3719	X(t1)=X(t2)	9.1506	1.6807	0.2041	3.1074	3.715	4.923	T	T	T
	t_2	32.87	9.7941	48																	
	Q_1	35.3	8.934	35	66	1.6697	1.2953	1.998	1.6697	2.3868	2.6557	X(Q1)=X(Q2)	9.0668	2.9	0.2426	3.6733	4.396	5.251	T	T	T
	Q_2	32.4	9.2057	33	67	1.6695	1.2952	1.9977	1.6695	2.3863	2.655	X(Q2)=X(Q3)	8.4646	3.6	0.2410	3.4057	4.075	4.868	F	T	T
	Q_3	28.8	7.7251	36	69	1.6691	1.295	1.997	1.6691	2.3852	2.6536	X(Q1)=X(Q3)	8.3427	6.5	0.2374	3.3055	3.955	4.724	F	F	F
	d_1	29.13	7.7675	44	102	1.6619	1.2911	1.986	1.6619	2.6376	2.6299	X(d1)=X(d2)	8.6627	5.21	0.1985	2.8574	3.415	4.535	F	F	F
	d_2	34.34	9.2607	60																	
	C_1	27.24	6.1485	56	102	1.6619	1.2911	1.986	1.6619	2.6376	2.6299	X(C1)=X(C2)	7.2688	10.84	0.1967	2.3761	2.84	3.771	F	F	F
	C_2	38.08	8.392	48																	

Basin	Condition	mean X_i	std. dev. s_i	no. of points n_i	d.f.	t-distribution[1] 90% $t_{1-\alpha/2}$	90% $t_{1-\alpha}$	95% $t_{1-\alpha/2}$	95% $t_{1-\alpha}$	99% $t_{1-\alpha/2}$	99% $t_{1-\alpha}$	Hypothesis #1	s_p^2 [2]	$X_x - X_y$ (absolute value)	n[3]	T_{90}[4]	T_{95}[4]	T_{99}[4]	Result $X_x = X_y$ 90%	95%	99%
3 plates (B)	t_1	27.37	9.0697	48	94	1.6636	1.292	1.9887	1.6636	2.6356	2.3719	X(t1)=X(t2)	8.9543	2.3996	0.2041	3.0407	3.635	4.817	T	T	T
	t_2	29.77	8.8374	48																	
	Q_1	32.38	9.5394	35	66	1.6697	1.2953	1.998	1.6697	2.3868	2.6557	X(Q1)=X(Q2)	8.3373	2.31	0.2426	3.3777	4.042	4.828	T	T	T
	Q_2	30.07	6.832	33	67	1.6695	1.2952	1.9977	1.6695	2.3863	2.655	X(Q2)=X(Q3)	6.8230	7.19	0.2410	2.7452	3.285	3.924	F	F	F
	Q_3	22.88	6.8147	36	69	1.6691	1.295	1.997	1.6691	2.3852	2.6536	X(Q1)=X(Q3)	8.2703	9.5	0.2374	3.2768	3.92	4.683	F	F	F
	d_1	26.74	7.5108	44	102	1.6619	1.2911	1.986	1.6619	2.6376	2.6299	X(d1)=X(d2)	8.7654	2.81	0.1985	2.8913	3.455	4.589	T	T	T
	d_2	29.55	9.5767	60																	
	C_1	25.16	7.3653	56	102	1.6619	1.2911	1.986	1.6619	2.6376	2.6299	X(C1)=X(C2)	8.1573	7.08	0.1967	2.6666	3.187	4.232	F	F	F
	C_2	32.24	8.996	48																	

Table D.2 (Continued)

Hypothesis #2[5]	U_{90}[6]	U_{95}[6]	U_{99}[6]	Results $X_x < X_y$ or $X_y < X_x$ 90%	95%	99%	Summary
							$X(t_1) = X(t_2)$
							$X(Q_1) = X(Q_2)$
$X_{Q2} > X_{Q3}$	2.6772	3.4509	5.488	T	T	T	$X(Q_3) < X(Q_2)$
$X_{Q1} > X_{Q3}$	2.4482	3.1554	5.0165	T	T	T	$X(Q_3) < X(Q_1)$
							$X(d_1) = X(d_2)$
$X_{C2} > X_{C1}$	2.1356	2.7489	4.3501	T	T	T	$X(C_1) < X(C_2)$

Hypothesis #2[5]	U_{90}[6]	U_{95}[6]	U_{99}[6]	Results $X_x < X_y$ or $X_y < X_x$ 90%	95%	99%	Summary
							$X(t_1) = X(t_2)$
							$X(Q_1) = X(Q_2)$
$X_{Q2} > X_{Q3}$	2.6422			T			$X(Q_3) < X(Q_2)$ at 90% only
$X_{Q1} > X_{Q3}$	2.5646	3.3055	5.2552	T	T	T	$X(Q_3) < X(Q_1)$
$X_{d2} > X_{d1}$	2.2199	2.8574	4.5217	T	T	T	$X(d_1) < X(d_2)$
$X_{C2} > X_{C1}$	1.846	2.3761	3.7601	T	T	T	$X(C_1) < X(C_2)$

Hypothesis #2[5]	U_{90}[6]	U_{95}[6]	U_{99}[6]	Results $X_x < X_y$ or $X_y < X_x$ 90%	95%	99%	Summary
							$X(t_1) = X(t_2)$
							$X(Q_1) = X(Q_2)$
$X_{Q2} > X_{Q3}$	2.1297	2.7452	4.3657	T	T	T	$X(Q_3) < X(Q_2)$
$X_{Q1} > X_{Q3}$	2.5423	3.2768	5.2095	T	T	T	$X(Q_3) < X(Q_1)$
							$X(d_1) = X(d_2)$
$X_{C2} > X_{C1}$	2.0716	2.6666	4.2198	T	T	T	$X(C_1) < X(C_2)$

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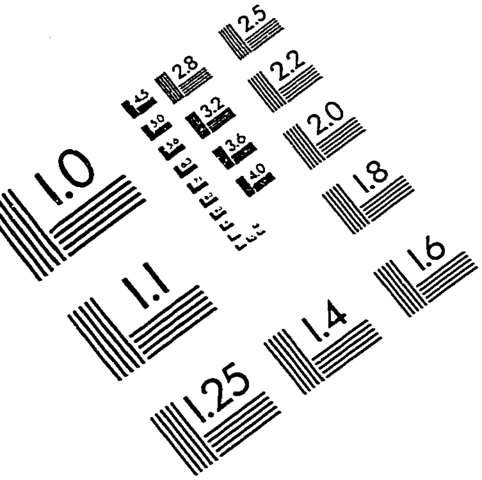
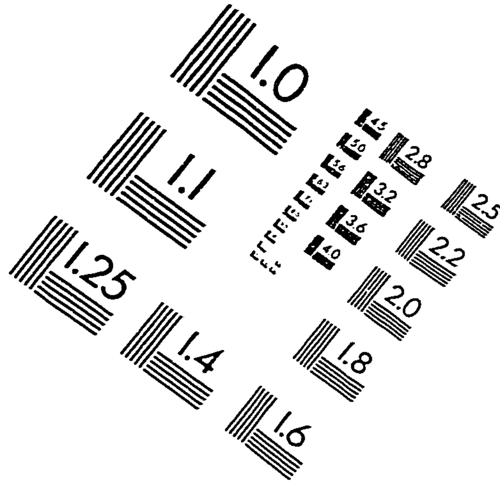
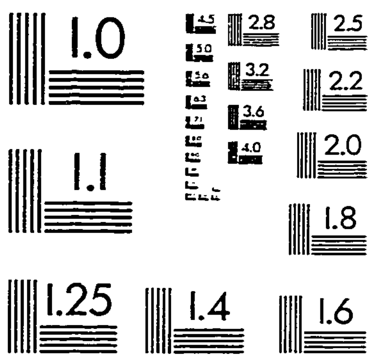
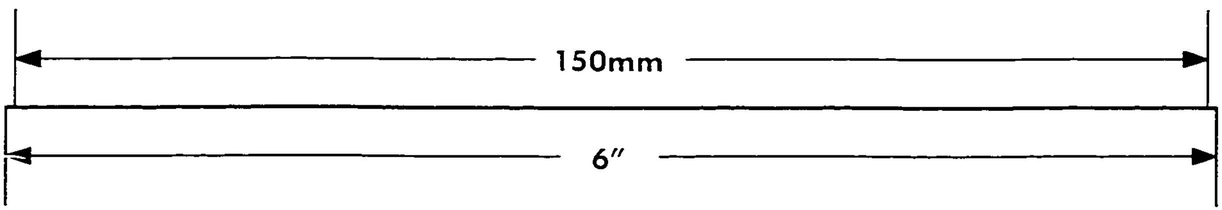
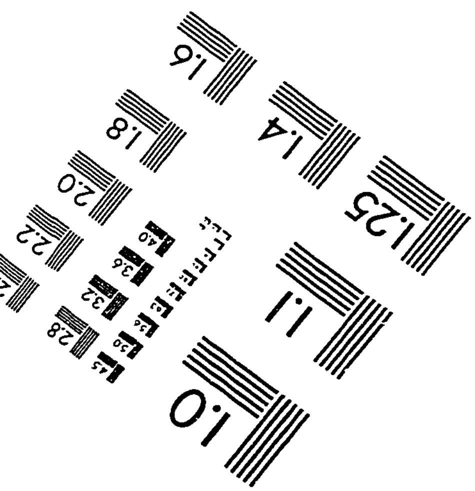
IMAGE EVALUATION TEST TARGET (QA-3)

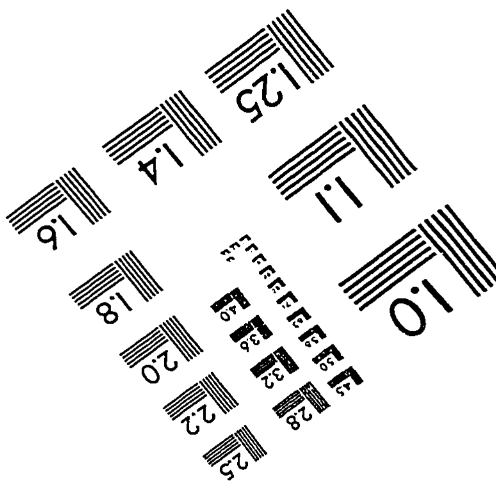












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