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Evaluation of Factors Responsible for High Effluent Suspended Solids Events in the Kuwahee Wastewater Treatment Plant

Patricio Alejandro Moreno
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To the Graduate Council:

I am submitting herewith a thesis written by Patricio Alejandro Moreno entitled "Evaluation of Factors Responsible for High Effluent Suspended Solids Events in the Kuwahee Wastewater Treatment Plant." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

Gregory D. Reed, Major Professor

We have read this thesis and recommend its acceptance:

Bruce Robinson, Chris Cox

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Evaluation of Factors Responsible for High Effluent Suspended Solids Events in the Kuwahee Wastewater Treatment Plant

A Thesis
Presented for the
Master of Science Degree
The University of Tennessee, Knoxville

Patricio Alejandro Moreno
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Abstract

The potential factors causing high effluent suspended solids (ESS) in Kuwahee Wastewater Treatment Plant (WWTP) are studied in order to properly identify the reason or reasons that might lead to focus future studies in proper remedial actions in the facility. In this document an analysis protocol is established, and several factors are evaluated for potential associations with high ESS events. From the protocol some of the factors were collected from regular operational procedure and others were collected during a study sampling period.

The analysis of those factors included in the protocol showed no biological, or hydraulic, or settling parameters causing the suspended solids content to rise in the plant effluent. However, some flow distribution problems were found when the inflow to each clarifier was sampled and evaluated. This leaded to clarifier differences in performance that were corrected during the study period, after adjusting the flow openings to each clarifier.

One of the most important evaluations carried out during the analysis, showed that the average suspended solid concentration taken at the effluent weir of the secondary clarifiers was smaller than the average ESS concentration taken at the overall plant effluent. This suggests the presence of another source of suspended solids contributing to the final ESS at the plant discharge flow.

As part of the sampling procedure DSS/FSS testing was carried out on selected clarifiers. The clarifiers sampled during the sampling period were different from each other. The results showed that those clarifiers with flocculation well had a better performance than the one that has a conventional center well. However, the final statement could not be related for sure to the better performance of the flocculator clarifiers due to operational differences.

In Kuwahee WWTP a secondary diversion is used when the inflow exceeds the maximum hydraulic capacity of the biological reactor. Since the diversion carries the flow from the primary clarifier effluent to the chlorination basin influent, it was thought to be one of the sources of high suspended solids events. In that, a simulation of different flows was run, in order to understand the incidence of the bypass in the final suspended solids concentration. The simulation showed that during bypass mode (secondary diversion is open) the overall plant ESS concentration increases with increasing diverted flow. Further study is suggested, along with possible solutions to high ESS problems.

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Nomenclature and Abbreviations

Nomenclature

Q	Influent Flow to the Aeration Basin
Q_w	Flow of Settled Solids Wasted from the Secondary Treatment System
r_g	Net Rate of Microorganism Growth
S_o	Substrate Concentration in the Influent to the Aeration Basin
V	Volume of the Aeration Basin
X	Mixed Liquor Suspended Solid Concentration in the Aeration Basin
X_e	Suspended Solid Concentration at the Effluent of the Secondary Clarifiers
X_o	Suspended Solid Concentration of Influent to the Aeration Basin
X_r	Suspended Solids Concentration of Returned Activated Sludge
μ	Specific Growth Rate of Bacterial Cell

Abbreviations

BOD	Biochemical Oxygen Demand
CBOD	Carbonaceous Biochemical Oxygen Demand
DAF	Dissolved Air Flotation
DSS	Dispersed Suspended Solids
ESS	Effluent Suspended Solids
F/M	Food to Microorganism Ratio
FSS	Flocculated Suspended Solid
GPD	Gallons per Day
MGD	Million Gallons per Day
MLSS	Mixed Liquor Suspended Solids
RAS	Returned Activated Sludge
SLR	Solid Loading Rate

SOR	Surface Overflow Rate
SRT	Solid Retention Time
SS	Suspended Solids
SVI	Sludge Volume Index
TSS	Total Suspended Solids
WAS	Wasted Activated Sludge
WWTP	Wastewater Treatment Plant

Chapter 1: Introduction

1.1 Background

Suspended solids are present in municipal wastewater and in many industrial wastewaters, and they are one of the most important physical characteristics to be measured in wastewater. All particles in water that are suspended, and will remain as residue after evaporation at 103 to 105ºC in a standardized filter, are considered total suspended solids (TSS).

“As levels of TSS increase, a water body begins to lose its ability to support a diversity of aquatic life. Suspended solids absorb heat from sunlight, which increases water temperature and subsequently decreases levels of dissolved oxygen (warmer water holds less oxygen than cooler water). Some cold-water species, such as trout and stoneflies, are especially sensitive to changes in dissolved oxygen. Photosynthesis also decreases, since less light penetrates the water. As less oxygen is produced by plants and algae, there is a further drop in dissolved oxygen levels” (Department of Environmental Quality of Michigan, 2004).

Because of the above and many other reasons, adequate treatment is necessary to insure that suspended solids are not present at levels of concern in waters. Therefore treatment of wastewaters should prioritize the reduction of suspended solids in the discharge effluent. According to the National Pollutant Discharge Elimination System (NPDES) effluent limits for wastewater treatment plants in Knoxville, TSS should not exceed the following levels of concentration:

- Monthly average: 30 mg/L
- Weekly average: 40 mg/L
- Daily maximum:45 mg/L

The Kuwahee Wastewater Treatment Plant (Kuwahee WWTP) falls under these requirements. It is because of this regulation; the removal of suspended solids will be studied in Kuwahee WWTP as a whole, including all possible sources of TSS within the plant. Kuwahee WWTP had 20 violations to the daily maximum in the period 2001-2004. From these violations more than 50% occurred between January and March.

During the first phase of the analysis of the study, two possible sources of TSS in the final effluent were identified. The first one, and the more obvious, concerns the performance of the six existing secondary clarifiers. The second one concerns the suspended matter that is transported when the plant bypass is in use, due to high flow events. The secondary treatment in Kuwahee WWTP is designed to treat flows no greater than 70 MGD. For this reason when incoming flows exceed 70 MGD, they are diverted. The flow that doesn't receive secondary treatment is combined with the biologically treated portion just before disinfection and then discharged into the Tennessee River. Therefore, bypassed flows might be a source for high suspended solids events, as well.

1.2 Research Objectives

The objectives of this research are to identify the cause of high TSS events in the effluent flow of Kuwahee WWTP. With this in mind, there will be a review of existing operational data and collection of new data necessary to correlate them to high effluent suspended solids (ESS) events. Furthermore evaluation and recommended practice improvements will be suggested as part of the scope of this study.

The existing secondary system was evaluated with the purpose of finding out if the analysis of available data would correlate to high-suspended solids events. For this reason, a diagnostic approach is employed as a tool to analyze the performance of the clarifiers. The diagnostic approach will be used to suggest the least-cost technology for reducing ESS. Kuwahee WWTP had the initiative of deeper study of high ESS events, to avoid permit violations.

Chapter 2: Literature Review

2.1 Suspended Solids

Those solids present in water bodies that can be trapped in filters, under standard methods, are called total suspended solids (TSS). TSS can include materials from several sources. High concentrations of suspended solids can cause problems to streams environment and their aquatic life.

Photosynthesis in submerge vegetation can be slowed down due excessive amounts of suspended solids in the water that can block incoming light. Since rates of photosynthesis diminish, oxygen produced by these plants will diminish as well. Eventually if the loads of suspended solids are extreme plants will die, originating a bacterial decomposition scenario that will increase the oxygen required from water. Since no oxygen is being produced and greater amounts of them are being required, a depletion of oxygen can cause fish to die. Not only this, but also water temperature can increase as well. The latter can occur due to the absorption of heat of suspended mater from sunlight. This can cause oxygen levels to drop even more, causing major problems in the stream environment and aquatic life (Murphy, 2002).

High TSS can originate several problems in fish environment owing to the reduction in visibility (clarity of water) that may cause fish difficulties to catch their food, solids can clog fish gills, reduce fish growth rates, and prevent eggs and larval to develop. Another problem caused by high TSS present in water bodies is the generation of higher concentrations of bacteria, nutrients, heavy metals and pesticides, which can be attached to the suspended solids. This can cause great harm not only to animals and environment, but it can affect human health as well (Murphy, 2002). All of the above reasons sustain the importance of control and limitation of TSS discharges in water bodies.

In a wastewater treatment plant, there are many sources of suspended solids. In activated sludge processes the main unit used to obtain a solid free effluent is secondary clarification. If secondary clarifiers do not work correctly high suspended solids concentrations can be expected at the plant effluent.

In case of high flow events due to heavy rain or snow melting, some wastewater treatment facilities provide primary treatment to the complete influent, but biological treatment up to their maximum capacity, determined by the minimum solids retention time (SRT) in which bacteria are not wasted from the system faster than they can reproduce (called washout). When the inflow of a treatment plant is big enough that SRT can fall under its minimum, EPA, under the Blending Policy, allows the diversion of excess flows from the secondary treatment unit, and then blended with the fully treated flow before disinfection is held (EPA, 2004). If blending practices are being held in the plant as part of high flow events strategies, flows contributing to the blended effluent become potential sources of high ESS.

2.2 Potential Source Parameters of High ESS Events

There are several potential sources of high ESS events. Some of them can be analyzed from existing plant operational data, which can be classified in accordance to their impact on performance. Therefore they can be classified into biological performance parameters, hydraulic performance parameters or settling performance parameters. In the following subsections they will be described according to their potential implication in the final ESS.

2.2.1 Biological Parameters

Variations in the biological performance of a wastewater treatment plant, which can lead to high ESS events, are susceptible to occurred because of: variations of influent flow, return activated sludge management, mixed liquor suspended solids management, specific growth rate, wasted activated sludge management, variations on influent suspended solids, and food to microorganisms ratio.

Primary Effluent BOD

For study purposes, the loading of organic matter will be analyzed with respect to the influent of the secondary treatment unit, it is to say, the operational data from primary effluent BOD is to be analyzed as a potential source of high ESS events. BOD is the most widely used parameter that measures organic matter in wastewater. BOD measurements indicate the dissolve oxygen used by microorganisms present in water in the biochemical oxidation of organic matter (Metcalf & Eddy, 2003). Even though it has several limitations, it is a good measurement to determine the oxygen needed for stabilization or the organic matter, and it is a major parameter for treatment design.

Drastic variations in the influent organic matter will be reflected in the BOD measurements. These variations may cause changes in the sludge retention time (SRT) and therefore changes in the characteristics of biomass, such as growth of filamentous bacteria, and changes in nutrient composition; causing eventually a change in suspended solids concentration.

Return Activated Sludge (RAS)

RAS control is a very important operational strategy since variation in this parameter will cause major changes in sludge retention time and biomass concentration being a key factor for clarification performance. RAS pumping capacity has to be able to handle high flow events that will avoid overloading clarifiers (sludge blanket build up) and a change in the characteristics of sludge. In summary RAS management influence the settleability of floc, sludge blanket levels in clarifiers, aeration basin performance and sludge quality (Metcalf & Eddy, 2003)

Mixed Liquor Suspended Solids (MLSS)

MLSS is nothing more than the concentration of microorganisms present in the biological reactor. It is a measure of the quantity of suspended solids in a volume of wastewater. The concentration of biomass in the biological reactor is essential for sludge characteristics. Any change in MLSS concentration will produce changes in the time of sludge residence, and consequently in the ESS due to variations in sludge characteristics that would generate density currents and short circuiting in the sedimentation basin (Ekama et al., 1997). Typical values for MLSS range from 1500 to 4000 mg/L (Metcalf & Eddy, 2003)

Specific Growth Rate

Any biological change will be reflected in the kinetics of bacterial growth. The specific growth rate of degrading bacteria is inversely proportional to the sludge retention time, thus any change in cell growth will change the process performance. Since settling characteristics of activated sludge, percent of dispersion of solids and zone settling velocity are dependent of SRT (Bisogni and Lawrence, 1971), variations of growth rate will impact the concentration of suspended solids in the plant effluent. Hence, there is no doubt that this is a key parameter to be analyzed in this study.

The specific growth rate can be calculated from the following a system mass balance of solids, considering the secondary treatment as a system boundary:

$$\frac{dX}{dt}V = QX_o - [(Q - Q_w)X_e - Q_w X_r] + r_g V \qquad (1)$$

Where

X = Mixed liquor suspended solid concentration in the aeration basin

V = Volume of the aeration basin

Q = Influent flow to the aeration basin

X_o= Suspended solids concentration of influent to the aeration basin

Q_w= Flow of settled solids wasted from the secondary treatment system

X_e= Suspended solids concentration of the effluent of the secondary clarifiers

X_r= Suspended solids concentration of RAS

r_g= Net rate of microorganism growth

Assuming that the treatment performance is under steady state conditions, this means no change in biomass occurs, and that the suspended solids concentration at the influent and effluent are negligible, the following equation is obtained:

$$r_g = \frac{-Q_w X_r}{V} \qquad (2)$$

From literature the specific growth rate of bacterial cells can be defined by the following relationship (Metcalf & Eddy, 2003):

$$\mu = \frac{r_g}{X} \qquad (3)$$

Where:

μ = Specific growth rate of bacterial cell

Finally, replacing equation 2 in equation 3, the specific growth rate of bacterial cell can be obtained.

$$\mu = \frac{-Q_w X_r}{VX} \qquad (4)$$

Waste Activated Sludge (WAS)

The amount of sludge wasted from activated sludge process will cause a direct impact in the time of residence of degrading biomass in the system. Therefore WAS will determine the amount of activated sludge return to the system, and consequently it will determine the sludge characteristics implying changes in ESS concentration.

The idea in activated sludge process it to maintain a steady state condition in order to obtain values predicted in design. The steady state concept is accomplish when no accumulation of biomass or substrate occur in the system. If steady state is to be achieved with in the system the excess biomass produced each day must be wasted. In that SRT can be maintained (Metcalf & Eddy, 2003). If WAS is increased until SRT has an decreases (inverse relationship), MLSS concentration will decrease as well. Short SRT will generate dispersed growth. In the other hand, if WAS is decreased enough that SRT increases notoriously, MLSS will increase as well. At long SRT pin point floc will form, and there will be a high probability for filamentous bulking to form, which will cause solids to have a detrimental in their settling characteristics, and consequently, a higher solid concentration in the effluent. As one can see, WAS can alter the process in a way that flocculation performance can be affected causing solids to be lost in the effluent.

Food to Microorganisms ratio (F/M)

According to Metcalf & Eddy (2003), F/M ratio is commonly used to characterize process design and operation performance. Low F/M ratios will generate bulking scenarios, where the increase of filamentous bacteria will decrease the settling properties of floc, generating mayor solid losses that will be carried over the effluent weir of secondary clarifiers and eventually producing an increase in solids in the plant effluent. There is no clear definition in literature for low F/M ratio (Ekama et al., 1997). In the other hand, high F/M ratios may cause dispersed growth because of the high availability in substrate that causes exponential growth. These reasons make the behavior of F/M ratio a very important matter to be analyzed for possible biological responsibility in high ESS events.

The “food” in the ratio is the CBOD entering the process. The “microorganisms” are the activated sludge solids in the aeration tanks, which are usually measured as mg/L of MLSS. Typical values for F/M ratios in conventional activated sludge systems range between 0.25-0.5 lb CBOD5/lb MLSS (Lee, 1999)

The F/M ratio is defined in Metcalf & Eddy (2003) as:

$$\frac{F}{M} = \frac{QS_o}{VX} \qquad (5)$$

Where:

F/M = Food to microorganisms ratio

So = Substrate concentration in the influent to the aeration basin

2.2.2 Hydraulic Parameters

Hydraulics is one of the most studied and complex issues in secondary settling tanks. Hydraulic characteristics in the plant can be affected drastically when flow regimes or flow patterns change. Clarification and thickening functions in the clarifier can be altered because of changing flows affecting BOD and solids removal. High flows can cause excessive turbulence and as a result floc breakup will be a major issue. Floc breakup, then, will affect flocculation and finally making ESS concentration to rise. Parameters such as surface over flow, solids loading rate, RAS, sludge blanket levels will be affected, as well, causing a major operational issue (Ekama et al., 1997). Two major hydraulic parameters are measured in Kuwahee WWTP: influent flow, and rainfall, which can be considered as closely related to high flow events.

Influent Flow

As mentioned in the introductory paragraph of hydraulic parameters, high flow events are of great consideration due to the implications in effluent quality detriment. Hence, it is very important to analyze the potential correlation of flow behavior versus plant effluent solids quality.

Rainfall

Rainfall events should be closely related to high flow events, and therefore closely related to the hydraulic changes going on in the secondary unit process, more specifically in the secondary clarification tanks. It is a parameter to be studied for potential high ESS correlation.

2.2.3 Settling Parameters

Settling characteristics tests are based in two major approaches: "first of all the use of volume of sludge occupied in a defined period of time, and secondly the use of the subsidence velocity of the liquid/solid interface during the zone settling stage" (Ekama et. al., 1997). Since secondary clarifiers have as a major purpose the separation of solids from liquid, the settling characteristics of the mixed liquor should be considered in the design.

Sludge Volume Index

Sludge volume index (SVI) is the most commonly used test for establishing the settling characteristics of the mixed liquor. SVI is defined as the volume of 1 g of sludge after 30 minutes of settling. Even though, SVI is strongly criticized mainly due to its dependency on activated sludge concentration and because SVI is not a measure of effluent clarity or sludge thickening, it will be used as a factor in this study, because SVI is a commonly used reference parameter in literature. Values below 100 are desired, while SVI values above 150 are associated with filamentous growth (Metcalf & Eddy), thus with poor settling characteristics.

Settleable Solids

All solids that settle out within a specified period of time in an imhoff cone are considered settleable solids (Metcalf & Eddy, 2003). Settleable solids will indicate the volume of solids settled after one hour. This is a good parameter for determining what percentage of the total solids suspended in wastewater is able to settle in the mentioned period of time. If this parameter decreases, more suspended solids can be discharged in the final effluent, because of the decrease in the settling properties of the incoming wastewater.

2.3 Specific Clarifier Performance Parameters

Secondary clarifiers require the consideration of several factors in order to achieve a successful design. Some of these factors are clarifier physical parameters, surface overflow rate (SOR), solids loading rate (SLR), rising sludge, and sludge blanket height.

2.3.1 Physical Parameters

Physical parameters such as inlet structure of clarifiers, flocculation devices, sludge collection system, tank side water depth can affect notoriously the performance of the sedimentation process (Ekama et al., 1997). Kuwahee WWTP has clarifiers with different physical parameter designs, which will be used to study to identify any variation in performance :

Clarifier Inlet Structure

The inlet design, as well as weir loading and placement are important factors for the hydraulics of the tank. A well designed inlet will distribute the flow evenly into the clarifier, maximizing the potential for flocculation and therefore minimizing the floc breakup.

Flocculation Center Well

Because of floc breakup in the aeration basin due to aeration shearing, high levels of dispersed particles are transported to the secondary clarifiers. These dispersed particles don't settle well because of their small size, thus being carried over the weir. Because of this phenomenon, an extra flocculation step is suggested in literature. Flocculation in conventional, center feed, circular clarifiers occur mainly in the center well, however center well detention times are too short. Wahlberg et al. (1994) states that good flocculation of activated sludge can be performed in 20 minutes of residence time in a completely mixed reactor. Conventional circular clarifiers have center well residence times that vary from 3 to 6 minutes (Parker, 1983). Therefore the addition of an enlarged center well will increase the residence time, enhancing flocculation of small dispersed particles and as a result reducing the concentration of suspended solids in the effluent weir. Clarifiers that incorporate enlarged center wells and other features for the addition of dispersed particles into the settled floc are called flocculator-clarifiers. There are different designs of flocculation clarifiers that have been used in municipal and industrial wastewaters. One of the most commonly used is the one showed in Figure 1. The influent enters the clarifier through the pipeline to the inlet center well. The inner well is closed at the bottom and has diffuser ports and gates that distribute the influent of the clarifier tangentially into the next chamber, called flocculation well. Diffuser ports and gates dissipate inlet energy enhancing flocculation in the following chamber. The flocculation center well allows enough time for the smaller particles to adherer together with other particles and settle. Velocity gradient were found to be very low ($G < 5\ sec^{-1}$) in flocculator wells, as the one showed in Figure 1, which was determined to be significant enough for good flocculation (Parker et al., 1996). At the same time it is recommended in literature that the skirt of the flocculation well should go, as a maximum, through one half of the side water depth.

The sizing of the flocculation center well is very important for better performance of the clarifier. Flocculation wells too small will enhance density currents. In the other hand, if the flocculation well is too large, excessive recirculation will enhance density currents, as well. Therefore experience and hydraulic studies over time

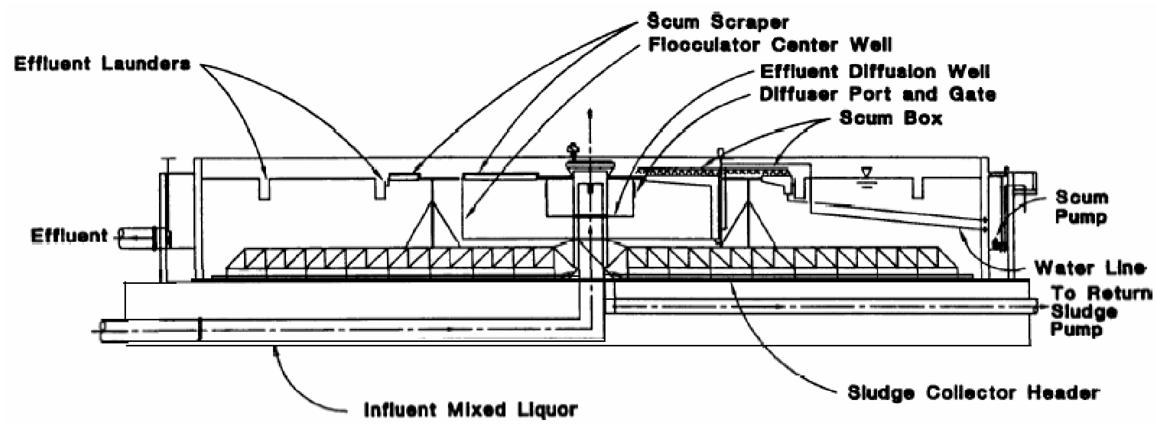

Figure 1: Cross sectional view of flocculator clarifier

persuaded Parker et al. (1996) to suggest that minimum concentrations of suspended solids at the effluent weir can be achieved using flocculation center wells with diameters ranging from 32 to 35 percent of the clarifier diameter.

Sludge Collection System

Return activated sludge (RAS) is a very important factor that can impact overall performance in the wastewater treatment plant. For that reason sludge collection systems and RAS pumping are very important actors in clarifier's performance.

There are two major sludge removal devices used in circular secondary clarifiers: hydraulic suction and scrapers. According to Wahlberg (1995b) better performance can be obtained with draft tube sludge removal devices than scraper devices. The reason for the latter is that scrappers will collect the settled solids on the bottom surface of the settler and transport them to the center of the clarifier, where they will be pumped out. This may allow some excess sludge blanket build up in places where the flocculator well or the inlet well are located. As the sludge blanket gets closer to the bottom of the skirt high velocities will develop in the gap between the sludge blanket and the skirt, hence resuspending the settled solids and causing an increase in ESS.

Incline Plates and Tube Settling

Incline plates and tube settling have been used to enhance the settling characteristics of sedimentation basins. Frequently they are used in drinking water treatment applications, but they also have been used in wastewater treatment (Metcalf & Eddy, 2003). Some studies have reported very good suspended solids removal results for rectangular secondary clarifiers (Saleh and Hamoda, 1999). The idea of incline settling systems is to increase the effective settling area so effluent quality can be significantly improved. At the same time, the flow rate applied to the clarifier can be increased significantly.

For self cleaning purposes, the inclination of the settlers should be between 45 and 60° above the horizontal (Metcalf & Eddy, 2003), otherwise solids will tend to accumulate inside of the incline plates or tubes.

Incline plates and tubes can be set for use in three ways with respect to the direction of the flow relative to the direction of the particle settling: (1) countercurrent, that is wastewater passes upward through the incline system and the cleared effluent leaves from the top of the basin; (2) cocurrent, the wastewater is distributed from the top of the inline system and the water passes through it; and (3) cross flow, in which the flow is introduced in the basin horizontally (Water Quality & Treatment, 1999).

Side Water Depth

Side water depth in a secondary clarifier is usually measured at the sidewall in circular sedimentation tanks from the bottom of the clarifier up to the height of water surface. Water depth is a very important factor to be considered when designing and operating a secondary clarifier due to the influence that this parameter has in the suspended solids removal and in the return activated sludge concentration. Temporary flow changes and deterioration in sludge characteristics will more likely affect the performance of shallow clarifiers than deeper ones (Ekama et al., 1997). The reason being is the fact that deeper clarifiers will store bigger volumes of solids during flow changes.

Weir Loading

The weir loading rates are a design parameter in a secondary clarifier. Nonetheless, the hydraulic loading to the clarifier is considered a much important factor when designing. Since parameters such as SOR and SLR will be studied weir loading will not be considered in further analyses.

2.3.2 Surface Overflow Rate (SOR)

SOR corresponds to the flow applied to the sedimentation basin relative to its surface area. It is a common and controversial parameter that is based on the theoretical vertical velocity of the flow when distributed in the clarifier. It is a controversial parameter because according to studies made by Wahlberg et al. (1994b) in full scale facilities, there is no relationship between ESS and SOR. The main issue of SOR as a design parameter is that even though it is a correct mathematical interpretation of forces interacting in the floc particle (upward flow velocity), ideal conditions are assumed in the tank. This is not that true in a circular secondary clarifier where flow conditions vary because of design and loading characteristics, generating conditions that are not represented in the theory. Usually SOR values as related to high ESS events in secondary clarifiers are associated to hydraulic problems due to the clarifier design or as an indirect evidence of high SLRs at high SORs (Ekama et al., 1997). In this study SOR will be used and analyzed to since it is such a commonly used parameter.

2.3.3 Solids Loading Rate (SLR)

SLR is considered as a crucial design parameter for secondary clarifiers. This is supported by Wahlberg et al. (1994b), who found a direct relationship between ESS concentrations and SLR. Solids loading rate corresponds to the total amount of solids applied to the surface of the clarifier. This includes solids carried in the influent flow and those carried in the return activated sludge withdrawn from the bottom clarifier and carried into the aeration basin in the activated sludge system. The solids loading rate can be calculated using equation 6 (Metcalf & Eddy, 2003).

$$SLR = \frac{(Q + Q_r)X}{A} \qquad (6)$$

Where

A = Surface area of secondary clarifier

2.3.4 Denitrification

Denitrification can be identified by examination of the surface of the sedimentation tank. If small refractile gas bubbles are observed, under good light conditions, to be carrying floc attached to them all the way to the to the clarifier surface, denitrification is occurring in the settling tank. This can be corrected by altering the mode of operation in the secondary system; an example would be the application of higher rates of air in the aeration basin. When a wastewater treatment plant is required to nitrate at nitrification and nitrification/denitrification facilities is a concern, because of the potential for denitrification to occur in secondary clarifiers, which can result in the rising of solids from the sludge blanket (Henze et al., 1993)

2.3.5 Sludge Blanket Height

The next question of concern is whether high blanket levels are being generated in the clarifier. If sludge blankets build high enough, already settled particles will get resuspended by the clarifier's internal flow currents, and eventually they will end up in the clarifier effluent. High blanket levels can be detected easily using a Sludge Judge or more complex electronic methods such as blanket detection by light interference techniques. If high blankets are detected, the solid flux approach is used to analyze the problem (Parker et al., 2000). One of the most recommended methods to solve this problem is the state point of analysis, because of its ability to verify overloads due to drastic changes in the inflow characteristics and how design or operational changes will reduce sludge blanket heights.

2.4 Identification of Flocculation and Hydraulic Problems in Secondary Clarifiers

Activated sludge operation conditions vary unexpectedly many times leaving wastewater treatment plant operators with little chance to fight back when clarifier performance and capacity are limited. On the other hand many treatment facilities have had to deal with new and more stringent effluent requirements. These two reasons have caused engineers to focus on the improvement in performance of secondary clarifiers (Parker et al., 2000). Activated sludge secondary clarifiers perform two functions: solid separation from liquid and solids thickening. Clarification is important in that one of its two major functions is to attain a relatively solids free effluent. Ideally clarification will be well performed if a sufficient flocculation level has been reached in the aeration basin, in addition to any complementary flocculation incorporated during settling. The thickening function is defined fundamentally in terms of the velocity that solids entering the secondary clarifier travel to the bottom of the basin for further removal in the return sludge flow. "The overall performance of the activated sludge process essentially rests on the efficiency of the secondary clarifier to accomplish these two functions" (Wahlberg et al., 1995a)

It is unlikely that the profession can reduce process variability below a certain amount given the highly variable nature of wastewater treatment plant influents. The design and operations communities must target activated sludge secondary clarifier performance at 10 mg/L of suspended solids (SS). There are essentially four reasons why an activated sludge secondary clarifier will not produce an effluent of 10 mg/L SS (Wahlberg, 1995b):

1. Denitrification
2. High sludge blankets
3. Flocculation problems
4. Hydraulic problems

Denitrification and high sludge blankets have been already discussed. Flocculation and hydraulic problems will be discussed in the following subsection.

2.4.1 Flocculation Problems

The environment in the aeration basin is necessarily turbulent. Much of the success of the activated sludge process depends on the ability of the solids to flocculate after leaving the turbulence of the aeration basin. Flocculation is necessary to produce floc of dispersed solids that do not otherwise have sufficient mass to settle in the secondary clarifier (Wahlberg et al., 1994a). These dispersed biosolids exist as a result of three possible mechanisms:

1. They have not been incorporated into a floc particle due to unreactive surface chemistry between flocculating particles.
2. They have not been incorporated into a floc particle due to insufficient time for flocculation to occur.

3. They have been sheared form a floc particle due to excessive, localized turbulence in the mixed liquor transport system between the aeration basin and secondary clarifier.

Poor flocculation between particles could be due to biological toxicants and/or chemical substances in amounts high enough to produce toxic effects in bacteria. Therefore, if the source of these chemicals and/or toxicants can be identified, they should be prevented. The other reason for poor flocculation between particles can be the result of unfavorable operational and loading conditions in the aeration basin (Wahlberg, 1995b).

It is known from the literature that the kinetics of flocculation is dependent on two phenomenon taking place during flocculation: floc aggregation and floc breakup. For most sludges the high flocculation performance can be obtained when a flocculation zone with a minimum of 20 minutes of hydraulic retention time is added to the field capacity (Wahlberg et al., 1994). The latter suggests that an extra flocculation step should be added in the process, typically fitting in a flocculation zone in the secondary clarifier, with the purpose of giving the time required for flocculation to occur to obtain better clarification.

Das et al. (1993) studied floc breakup in activated sludge plants, finding several sources for the poor performance to occur, such as degree of intensity in aeration in the aeration basin, type of aeration system (coarse, fine bubble, etc), distance of discharge point to aerators in the aeration basin, and shearing due to pipelines and free falls in mixed liquor transport systems from the aeration basin to the secondary clarifier. All of these cause performance problems that can be improved when an extra flocculation step is incorporated.

2.4.2 Hydraulic Problems

Hydraulics problems in secondary clarifiers have been a recurring topic for a long time. This is an important and controversial issue due to the non-ideal flows generated in secondary clarifiers (e.g., Crosby, 1980). Non-ideal flow is directly related to density flows that form in the clarifier, causing short circuiting and high velocity currents that result in turbulence and the carry over of solids through the effluent weir. Therefore, the reduction of non-ideal flows within the clarifier will result in the deterioration of performance causing high ESS events. For this, it is important to control the hydraulics of the tank, since this will have influence on the achievement of flow splitting, flocculation, energy dissipation, minimization of density currents, uniform flow in effluent launders, minimization of short circuiting, and the avoidance of adverse internal currents due to sludge removal mechanisms (Ekama et al., 1997).

There is abundant literature that suggests the use of physical inlet structures could have a positive impact in the reduction of non-ideal flows in secondary sedimentation basins. These structures are inlet structures, baffles, sludge withdrawal devices, and effluent weirs (Ekama et al., 1997).

2.4.3 DSS/FSS Testing

There are four potential sources of high ESS concentrations in the clarifier effluent, which were mentioned in section 2.4. From these potential sources two, denitrification and sludge blanket, are easy to identify. Denitrification can be recognized by simple examination of the surface of the sedimentation tank, while high blanket levels can be detected easily using a Sludge Judge or more complex electronic methods. Both are easy to correct, mainly with operational changes. Conversely, it is difficult to make a distinction between hydraulic and flocculation problems, and since the corrective actions are totally different, their correct identification becomes a transcendental issue (Wahlberg, 1995). To identify and differentiate from hydraulic and flocculation problems, there is a very useful test called the DSS/FSS test. DSS stands for Dispersed Suspended Solids and FSS stands for Flocculated Suspended Solids. The DSS/FSS testing was first proposed by Wahlberg, (1995), and republished later along with some case examples.

Dispersed Suspended Solids (DSS) Test

Disperse suspended solids (DSS) are defined by Wahlberg et al. (1995) as "those suspended solids remaining in the supernatant after 30 minutes of settling. The DSS test quantifies a mixed liquor's state of flocculation at the moment and location that the sample is taken". For this to be accomplished a sample of the supernatant is taken from the specific location to be tested, using a Kemmerer sampler (Figure 2), and then the sample is allowed to settle for 30 minutes. After the settling period a sample is withdrawn from the sampling container for TSS analysis.

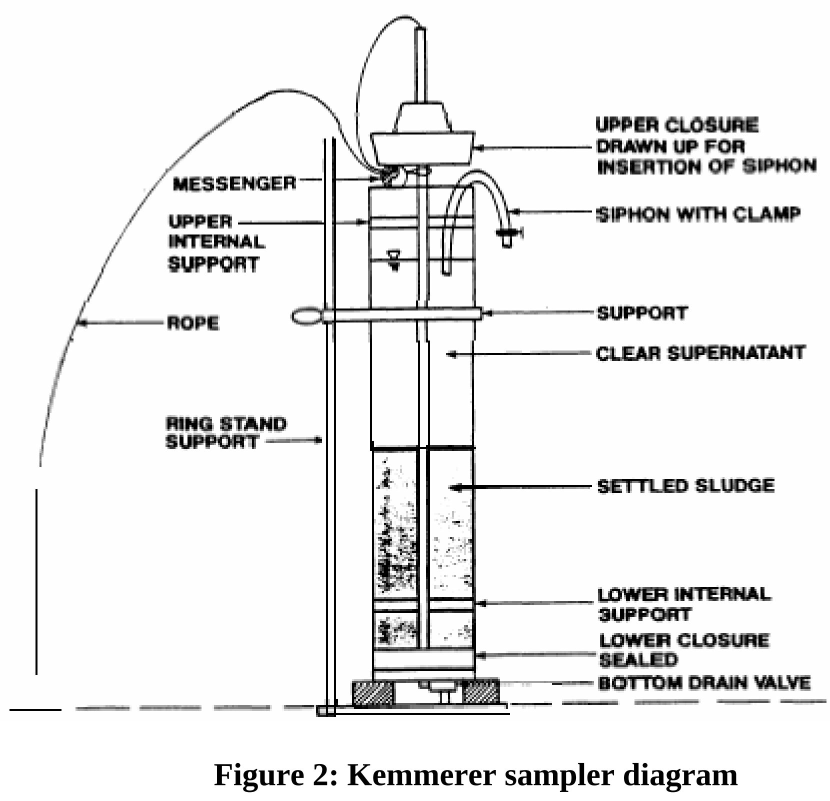

Figure 2: Kemmerer sampler diagram

The total suspended solid (TSS) analysis withdrawn from the DSS test should be very similar to the ESS concentration taken from a well design and operated secondary clarifier (Parker and Stenquist, 1986).

Flocculated Suspended Solids (FSS) Test

FSS is defined by Walberg. (1995) as "those suspended solids remaining in the supernatant after 30 minutes of settling proceeded by 30 minutes of flocculation. The FSS test attempts to simulate the optimum degree to which the sample can be flocculated". The testing procedure is carried out in a six-paddle stirrer with mixed liquor sample contained in a square flocculation jar with a volume of at least 1.5 liters. After the settling period a sample is withdrawn from the sampling container for TSS analysis. Some precautions should be taken in account during the test, due to the small volume of the sample jars, so no drastic variations in temperature take place.

Interpretation of DSS/FSS testing

For DSS/FSS testing an additional ESS sample should be taken at the effluent weir of the clarifier, so a comparison analysis can be made later. It is very important to mention that FSS as well as DSS and ESS should be taken within a reasonable period of time from each other, for further interpretation of results. Knowing these three test results, there are four case scenarios to consider. Other combinations do not relate to hydraulic or flocculation problems in the clarifier:

1. **High ESS, High DSS, Low FSS**: In this case the results of the DSS/FSS testing indicate two potential problems diminishing the performance of the clarifier. The first one could be that the time given for flocculation to occur is not sufficient. The other one is the potential for floc breakup due to convoluted transport from the aeration basin to the inlet of the sedimentation basin, because of shearing in the pipeline and/or free falls. In the case of flocculation deficiencies, the incorporation of an extra flocculation step will be the suggested solution. On the other hand if floc breakup is occurring, free falls and tortuous pipeline

transportation should be replaced for a transportation conduct that minimizes shearing.

2. **High ESS, Low DSS, Low FSS:** This indicates that flocculation is being performed correctly during clarification in the sedimentation basin. However, solids are being carried over the weir. The reason for this to occur, once high sludge blankets have been discarded as a potential source, is the existence of hydraulic currents that have re suspended the solids already settled at the bottom of the secondary clarifier, and transporting them through the effluent causing high suspended solid events in the overflow. This can be checked through comparison of DSS at the effluent weir and ESS. If the latter is significantly greater than DSS concentration, a hydraulic problem has been confirmed. Wahlberg (1995) recommends a study of the clarifier's hydraulic characteristics using either the multipoint dispersion and flow pattern/solids distribution tests (Protocol of the ASCE Clarifier Research Technical Committee, Wahlberg et al., 1994b) or clarifier hydraulic models. Usually these kinds of problems are solved using inlet structures such as baffling or revising the management of sludge blankets.

3. **High ESS, High DSS, High FSS:** In this case high FSS indicates that clarifier performance cannot be improved by extra flocculation. It is very likely that the source of poor performance in the aeration basin is due to biological problems or because of the presence of inhibitor substances (chemicals or toxicants) in the plant influent. If biological problems are the cause of poor flocculation, parameters such as solids retention time (SRT) or process loading intensity should be revised. In the presence of inhibitors, the sources should be identified and their toxicant discharge limited or prohibited.

4. **High ESS, Low DSS, High FSS:** When this result is obtained, it means that FSS and DSS samples where taken at different times or at inadequate locations, samples were taken in an erroneous manner, some external condition during

sampling procedure where inappropriate, or TSS samples where mistaken. In summary if this happens it is suggested to repeat the sampling.

2.5 Temperature

The settling of particles is affected by the particle velocity, particle diameter, fluid density and fluid viscosity (Metcalf & Eddy, 2003). The density and viscosity of water will vary with temperature. Variations in the physical properties of water can cause convection currents in the sedimentation basin. These currents can carry solids from the settling area and therefore increase the suspended solids concentration at the effluent of the clarifier, generating short circuiting and dead zones in the clarifier. Consequently, temperature is a parameter to be considered as a potential source of high ESS concentrations.

Chapter 3: Methodology of Evaluation and Analysis of Performance

3.1 Overview of Kuwahee Wastewater Treatment Plant

The overview of the Kuwahee WWTP is a very useful description of every process unit in the facility in order to understand how the facility works and what potential sources of high suspended solids are in the plant. The following description was provided by the Knoxville Utilities Board, the entity in charge of the operation of Kuwahee WWTP.

3.1.1 The Collection System

The Kuwahee WWTP collection system served approximately 150,000 residents in 2000 and approximately 50 industrial dischargers. Included in the industrial dischargers are four large hospitals, several motels and hotels, the University of Tennessee area, two packing plants, a metal fabrication plant, and a plastics plant.

The collection system consists of 1,200 miles of pipe with size ranges from 8 inches to 84 inches in diameter. Forty-seven pump stations also help to operate the collection system. Because of the ridge and valley topography, the large interceptor lines follow the creeks as they flow toward the Tennessee River. The First Creek and Second Creek trunk lines intersect the 72-inch diameter main line along Neyland Drive near the river. The 72-inch main line flows west and increases to an 84-inch line before reaching the treatment plant.

The old Third Creek interceptor collects from most of the western part of the city along the middle and east fork of Third Creek, including the flow from the Cheowa

Circle Pump Station. This trunk line follows Third Creek to the river and turns east along Neyland Drive as 48-inch line before reaching the plant.

A new Third Creek interceptor has also been built to carry the flow that was previously diverted by the Third Creek Pump Station (off Sutherland Avenue) to the Fourth Creek Treatment Plant. This line follows the west fork and main channel of Third Creek; then through a deep tunnel at Concord Street and east along Neyland Drive to reach the plant as 48-inch line.

In conclusion, the Kuwahee WWTP receives flow from two different directions; with the flows combining and entering the plant through an 84-inch plant influent line.

3.1.2 Kuwahee Wastewater Treatment Plant

Kuwahee WWTP is an advanced plant that includes primary sedimentation, a combined secondary and nitrification system, anaerobic sludge digestion, and high pressure filter press dewatering. The average daily dry weather design flow of the facility is 40 million gallons per day with a maximum hydraulic capacity of 120 MGD. The plant was designed to meet the effluent requirements showed in Table 1.

Table 1: Kuwahee WWTP effluent requirements

	Monthly Average	Daily Maximum	Typical
CBOD	25 mg/L	40 mg/L	10 mg/L
Suspended Solids	30 mg/L	45 mg/L	18 mg/L
Ammonia-Nitrogen	5 mg/L	10 mg/L	0.5 mg/L
Fecal Coliform	200 colonies per 100 ml	1000 Colonies	10 calonies
Residual Chlorine	0.6 mg/L	-	0.2 mg/L

3.1.3 Pollutant Removal

Influent

When the raw wastewater reaches the plant via the 84-inch influent line, the flow is split into two bar screen channels. Four mechanically cleaned bar screens seven feet wide remove debris from the raw wastewater and lift the screenings to the ground level and dump them into holding bins before ultimate disposal in the sanitary landfill.

Grit Chamber

Following screening, the raw wastewater is pumped by four 40 MGD variable speed pumps to the grit chamber. Within the channel aerated grit chamber, heavy inorganic particles such as sand, gravel, and cinders are removed. The diffused air used in the grit removal process assists in keeping the wastewater in an aerobic state and enhances grease removal in the primary clarifiers. The raw wastewater pumps and grit chambers are sized to handle a maximum hydraulic flow of 120 MGD (during storm conditions). After the grit chamber, the flow has to be split so it doesn’t overload the primary clarifiers, which are capable of treating only 70 MGD.

Pre-aeration

All flows between 70 MGD and 120 MGD are sent to the pre-aeration tank and then on to the secondary aeration basins. The main purpose of the pre-aeration tank is to remove scum and grease that could hinder the secondary treatment process. After aeration by a series of dome type fine bubble diffusers, the wastewater passes to a quiescent settling zone to allow the scum and grease to rise to the surface. A mechanical skimmer removes scum, which is pumped, along with scum from the primary clarifiers, to the dissolved air flotation (DAF) units.

Pre-aeration is not intended to provide solids treatment or removal; however, a sludge mechanism is included to clean the bottom of the tank of any heavy solids as they accumulate.

Primary Clarifiers

The primary clarifiers are designed for a maximum flow of 70 MGD. The wastewater flows through a double Parshall flume into nine double-bay primary settling tanks that are 40 feet wide by 144 feet long by 15 feet deep. These tanks are used to settle out discreet organic particles and to skim the scum and grease from the wastewater surface within the tank. Two primary sludge pumps are used to transfer sludge from the primary clarifiers and pre-aeration basin to the gravity thickener. If the gravity thickener is out of service, primary sludge will be pumped to the thickened sludge wet-well in the dissolved air flotation building for further treatment in the anaerobic digesters. During storm events, a portion of the 70 MGD treated in the primary clarifiers will be routed to the secondary aeration basin (to combine with the flow from the pre-aeration) to provide a total flow of no more than 70 MGD to the remainder of the plant. Any remaining flow treated in the primary clarifiers receives disinfection and is discharged to the river after being previously diverted from the secondary treatment unit.

Secondary Treatment and Nitrification Treatment

Primary clarifier and pre-aeration effluent flows to the intermediate pump station wet well. At this point, five 16,000 GPM intermediate pumps transport the wastewater through the 54-inch secondary effluent line to the aeration system.

The 48-inch return sludge line combines with the 54 inch secondary effluent line to form a 72-inch line before reaching the nitrification influent channel.

Flow is distributed to the six nitrification activated sludge reactors by the influent channel. Each reactor is divided into five compartments containing fine bubble diffusers, with air flow provided by one to two horizontally split 2,000 horsepower blowers. In these tanks, wastewater is combined with mixed liquor (a culture containing thousands of pounds of microorganisms) and wastes are consumed by the microbes.

Final Clarifiers

Following aeration the mixed liquor flows by gravity to six 135-foot diameter circular final clarifiers with 12-feet side water depths. From the total clarifiers present at

Kuwahee WWTP, five of them were constructed at the time that the facility was build. Clarifier #4 was upgraded recently, incorporating a flocculation well and a different sludge collection system. In the year 2000 a new clarifier was added to increase the secondary treatment capacity and to improve effluent quality. This last clarifier, #6, has a flocculation well and suction devise for sludge collection. The settled nitrification sludge is returned by gravity through telescopic valves to the nitrification return sludge wet well. One of two 40 MGD return sludge pumps returns the sludge to the reactor via the return sludge line. Sludge wasting is conducted from the return sludge wet well by one of two 600 GPM waste-activated sludge pumps to the dissolved air flotation units. Wasting is required to maintain optimal microbes' population to consume incoming wastes.

Disinfection

The main purpose for disinfection is to remove or kill all disease-producing organisms present in wastewater before treated wastewater can be discharged to the receiving stream. The Kuwahee WWTP uses chlorination for disinfection because it has been found to be the most economical method. In chlorine contact tank #1, chlorine solution is applied by a submerged diffuser system. The chlorinators are capable of feeding 8000 pounds of chlorine per day. After half hour's detention time in contact tank #1, the flow continues, by gravity, under Neyland Drive in an 84-inch line to chlorine contact tank #2. After another half hour of contact time, sodium bisulfite solution (NaH_2SO_2) is added for de-chlorination. Finally, the plant effluent is discharged through an underwater 48-inch effluent diffuser spanning the Tennessee River.

3.1.4 Solids Disposal

Gravity Thickener

The 70-foot diameter gravity thickener has a 10-feet side water depth. The thickened primary sludge is collected by rotating sludge rake arms along the bottom of the tank while scum is collected by a skimming blade at the tank surface. The purpose of the gravity thickener is to thicken the primary sludge form 1 percent solids to about 8 percent solids.

Dissolved Air Flotation (DAF)

The DAF system thickens scum and waste activated sludge from 1 percent solids to about 4 percent solids. The facility provides 1,500 square feet of effective flotation area with three 500 square foot units. The cleaned DAF subnatant flows by gravity to the 48-inch sewer and then flows to the plant influent. The thickened sludge combines with the gravity thickened primary sludge and is pumped from the DAF wet well to the anaerobic digesters where it receives further treatment.

Anaerobic Digestion

The anaerobic digesters consist of five 90-foot diameter units with a maximum side water depth of 37 feet. Anaerobic digesters utilize bacteria to reduce the volume of sludge and convert the sludge into a relatively stable material that is more easily dewatered in the filter press. It also reduces the number of pathogens in the sludge, making it safe for land application. This treatment plant normally uses three primary digesters and two secondary digesters. The raw sludge is pumped into the primary digesters from the DAF wet well. The sludge in the primary digesters is quiescent conditions allow better separation of the sludge (solids) and liquid (supernatant). Digester sludge for dewatering and disposal is drawn only from the secondary digesters. Supernatant (a relatively clear liquid above the sludge) is periodically withdrawn from the secondary digesters and returned to the plant influent to provide increased detention time for the process.

Sludge Dewatering and Disposal System

The primary functions of this system are to condition the sludge (prepare the sludge before dewatering), dewater the sludge after conditioning, and dispose of the dewatered sludge efficiently. After 30 days in the anaerobic digesters, sludge is pumped to the dewatering system where lime and ferric chloride are added. Fast filling the filter and high pressure pumping of the sludge against the filter media, results in a cake with optimum solids content. A final dewatering filtration pressure of 225 psi produces a filter cake of at least 40 percent solids. When the press plates are opened the cakes fall by gravity into two sludge transport trailers. The trailers are hauled by diesel tractors to farms for ultimate disposal by spreading on land for soil amendment. Kuwahee WWTP has received national recognition for its use of biosolids in strip-mines site reclamation projects.

Water Quality Analysis

Wastewater flowing into and water flowing out of Kuwahee WWTP is continuously being analyzed for pollutants that could harm the Tennessee River and its users. The laboratory performs thousands of tests monthly to determine the quality of water being discharged from Kuwahee.

Water Quality Laboratory

Many of these tests are extremely sophisticated, requiring measurements of parts per billion. Several tests are performed daily at various stages in the treatment process to ensure optimum plant performance.

A chart flow of the Kuwahee WWTP can be observed in Figure 3.

3.2 Collection of Data

According to the literature review and Kuwahee WWTP design configuration and its operation procedures, two flows contributing TSS in the final effluent were identified: (1) the flow treated in the aeration basin and processed through secondary clarifiers, and (2) the flow diverted when the plant bypass is in use (secondary diversion), from the

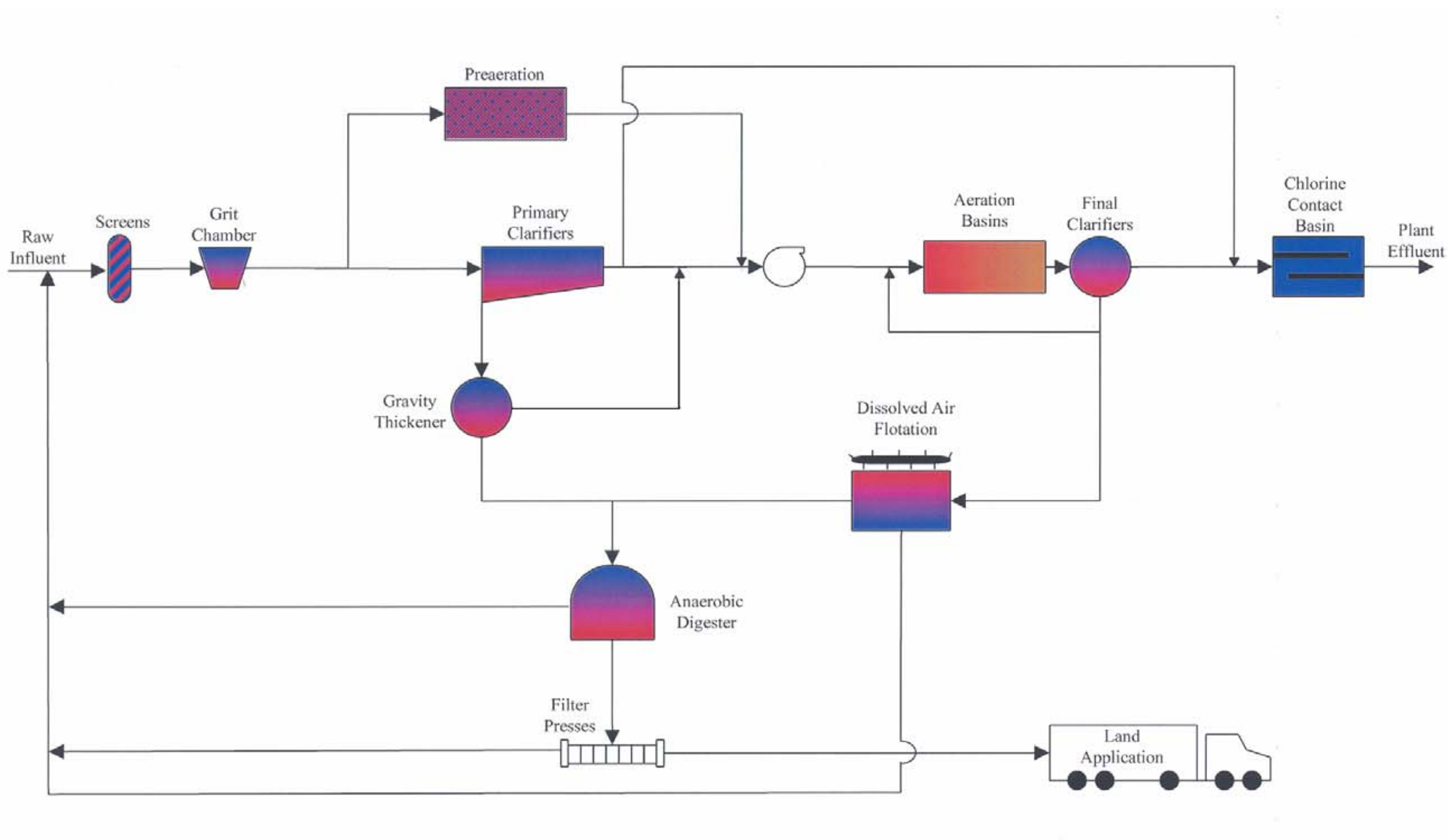

Figure 3: Flow chart of the Kuwahee WWTP

primary sedimentation effluent channel to the influent channel of disinfection units. Since the aim of this thesis was to identify the potential source or sources of high ESS, an evaluation protocol was established to have a methodology for assessing plant performance relative to ESS.

From those factors discussed in the literature review, there are known and unknown parameters. Those that are known form part of the operational data collected periodically in Kuwahee WWTP that will be analyzed relative to the primary evaluation procedure mentioned previously. The unknown ones should be sampled, so essential data can be obtained for a complete analysis of the effluent solids content, which may give useful information about the causes of deficiencies in the effluent quality, described in chapter 2. Therefore, a second approach for analysis should be established.

Before hand, the two potential sources of high ESS events were identified and presented in previous paragraphs. From this initial step an extra data collection and analysis procedure was set up to obtain useful information that is not currently measured in Kuwahee WWTP.

Relative to the existing operational observations taken by the personnel in Kuwahee WWTP, preliminary data were collected with the purpose of analyzing potential correlations with high effluent TSS events. The parameters were taken by Kuwahee WWTP personnel from January 1, 2001; up to December 30, 2002. During this period of time, and following the order establish in the literature review, the following operational data were known:

3.2.1 Suspended Solids

The overall plant effluent TSS concentration was measured on a daily basis in Kuwahee WWTP at the effluent of #2 chlorine contact tank. This was the only ESS measurement taken in the facility as part of their operational strategy.

3.2.2 Potential Source Parameters of High Effluent Suspended Solids Events

As described in the literature review, there are several factors that may cause high ESS events. For study purposes they were grouped into several categories described in the preceding chapter.

3.2.2.1 Biological Parameters

As described in chapter 2, some of the parameters causing high concentrations of ESS have been gathered into a biological parameter section, these parameters are mentioned in Table 2. In order to investigate the secondary treatment system performance with respect to effluent solid quality, the primary effluent BOD will be analyzed instead of the plant influent BOD, because our interest to know the substrate that is coming into the aeration basin.

Table 2: Biological parameters description

Parameter	Description
Primary Clarifier Effluent BOD	Primary effluent BOD is sampled from a 24 hour composite and collected from intermediate wet well. The sampler is turned off on Friday mornings and turned back on Sunday mornings.
Return Activated Sludge (RAS)	RAS is a grab sample taken from RAS wet well
Mixed Liquor Suspended Solids (MLSS)	MLSS is a grab sample taken from center well of #3. If clarifier #3 is down, the sample will be taken at another clarifier.
Specific Growth Rate (μ)	μ will be calculated from existing data using equation 4 in the literature review.
Wasted Activated Sludge (WAS)	WAS is measured in gallons per minute (GPM) from RAS wet well. Solids concentration is the same as RAS
Food to Microorganisms ratio (F/M)	F/M ratio will be calculated from existing data using equation 5 in the literature review.

3.2.2.2 Hydraulic Parameters

Only two hydraulic parameters were analyzed from the existing operational data collected from Kuwahee WWTP, primary effluent flow and rainfall, as described in Table 3. For study of the secondary treatment system performance with respect to effluent solid quality, the primary effluent flow will be analyzed, since this is the influent flow in the aeration basin during regular flow events.

3.2.2.3 Settling Parameters

As discussed in the previous chapter, the settling parameters affecting the quality of the effluent flow relative to its solid content are described in Table 4. SVI and Settleable solids are the two parameters collected regularly in Kuwahee WWTP.

Table 3: Hydraulic parameters description

Parameter	Description
Primary Effluent Flow	Primary effluent flow is a daily average derived from a computer report (SCADA). The reading is taken at the Parshall flume at the primary clarifier effluent.
Rainfall	Rainfall samples are taken in a rain gage located in the plant property.

Table 4: Settling parameters description

Parameter	Description
Sludge Volume Index (SVI)	SVI is a grab sample taken from center well of #3 final clarifier. The sample may be taken at another clarifier if #3 is down for repair or has foam build up in the center well.
Settleable Solids	Imhoff settleable solids sample is taken from a 24 hour composite sample collected at the effluent of #2 chlorine contact tank.

3.2.3 Specific Clarifier Performance Parameters

There are several clarifier performance parameters that are specific to each analyzed clarifier, such as the physical parameters, SOR, SLR, denitrification in the secondary clarifier, and the sludge blanket heights. All of them will be described in the following subsections.

3.2.3.1 Physical Parameters

According to literature specific performance parameter in the clarifiers such as inlet structure, flocculation wells, sludge collection systems, side water depth and sludge blanket levels are mandatory in the attempt to achieve the optimal functioning of solid-liquid separation and solids thickening in the final settler. These parameters are described in Table 5.

Table 5: Physical parameters description

Parameter	Description
Clarifier Inlet Structure	There are four clarifiers with the same inlet structures (#1,2,3 and 5), and two clarifiers that differ from each other and the rest of the clarifiers (#4 and #6). Differences in the inlet structures are determined from existing drawings.
Flocculation Center Well	Clarifiers #4 and #6 are flocculator clarifiers. The rest of the clarifiers have conventional inlet center wells.
Sludge Collection System	Clarifier #4, which was updated from its original configuration, has a spiral scrapper collection system. Clarifiers #1, 2, 3. 5 and 6 have hydraulic suction as collection system.
Side Water Depth	There is no difference of side water depth between clarifiers. All of them have 12 feet of side water depth.
Sludge Blanket Height	Each clarifier is measure for blanket levels using a sludge judge. This sample is taken, at least once a day, in the morning.

3.3 Sampling and Analysis Procedure

From those parameters necessary for the adequate analysis of high ESS events, several were not considered in the normal operational sampling procedure of Kuwahee WWTP. The importance of these parameters is the influence that each of them has over the final ESS quality of the treated wastewater. The particular influence and importance of each of the factors is stated throughout chapter 2. The parameters to be sampled as potential sources of ESS problems are describe in the following pages.

3.3.1 Suspended Solids

During a preliminary study of Kuwahee WWTP design and operation procedure two potential sources of high TSS events were identified. The first one was the solids carried over the effluent of the secondary clarifiers; and the second one was the solids carried through the secondary by pass flow, which receives primary treatment and then is blended with the secondary treatment effluent before chlorination. Therefore, three suspended solid data measurements should be analyzed: the overall plant effluent suspended solids, the suspended solids present in the effluent of the secondary clarifiers, and the suspended solids transported in the secondary deviation during by pass mode. The overall plant effluent suspended solid concentration was sampled in a regular basis in Kuwahee WWTP. The other two measurements need to be collected during the sampling period of the present study.

3.3.1.1 Clarifiers Effluent Suspended Solids

Secondary treatment effluent suspended solids is a necessary parameter that needs to be known in order to verify the optimal performance of secondary clarification. A well-mixed grab sample taken at the effluent of each secondary clarifier in the treatment train, filtered through a weighed standard glass-fiber filter and then dried to a constant temperature of 103 to 105°C, was used to obtain the clarifiers solids content at the effluent. Data obtained in this sampling procedure will allow an analysis of performance of every clarifier in the secondary system. Additionally, observations taken during high flow events, when by pass mode was being used, will allow one to quantify the solids contribution of the secondary treated effluent versus the flow diverted in the by pass, in the final blending discharged in the Tennessee River after disinfection.

3.3.1.2 Suspended Solids during Bypass Mode

In Kuwahee WWTP, during bypass mode, the secondary diversion is opened. This happens with high flow events that cannot be handled through the secondary treatment due to its design limitation of 70 MGD, because of “washout” of microorganisms from the system (as explained in 2.1). Consequently, it is essential for the study to use suspended solids concentration data for every time period in which the secondary diversion is used. A well-mixed grab sample will be taken from the secondary diversion flow during bypass mode, filtered, weighed and dried according to the standard methods. These observations will help quantify the amount of solids contributed by the bypass in the plant effluent.

3.3.2 Specific Clarifier Performance Parameters

From specific clarifier performance the following data of performance is important to be known, and since it has not been included in a regular parameter collection strategy, they were collected for this study.

3.3.2.1 Surface Overflow Rate (SOR)

SOR will be calculated from the values of flow taken every day by Kuwahee WWTP, and the known area of the clarifiers (diameter of 135 ft on six clarifiers). The flow measurement will be compensated in accordance to the distribution and the real flow that every clarifier is receiving. The flow distribution will be quantified through the measurement of the flow gate openings of the clarifiers. After the aeration basin, wastewater is transported gravitationally to the six secondary clarifiers through a concrete channel. From this center channel the flow is distributed to three clarifiers on each side of the channel. The influent wastewater enters the clarifier piping through the clarifier gate. This gate can be controlled manually or from the computer in the control room of Kuwahee WWTP. The opening of each gate was measured daily with respect to the surface level of water coming into the clarifier. Once the openings for each of the six clarifiers (three on the left and three on the right of the distribution channel) were measured, and knowing the theoretical total opening (overall sum of the six clarifiers openings with respect to the surface water on each of them) the proportional percentage of flow entering each clarifier can be calculated. In that way the proportional percentage of flow entering each clarifier can be multiplied with the total effluent flow from the aeration basin, obtaining the equivalent flow for each of the six secondary sedimentation tanks. This will allow the comparison between clarifier's flows, and check the assumption of equivalent flow loading. Consequently the specific SOR can be calculated for each sedimentation basin.

3.3.2.2 Solids Loading Rate (SLR)

Similarly from SOR, SLR will be calculated from the proportional percent of flow coming into each clarifier. SLR is a function of the incoming flow (including RAS), the MLSS concentration and all divided by the area of the clarifier. Therefore, the SLR can be calculated from operational existing data (RAS, MLSS and area of the clarifier), plus data coming from the measurement of flow opening gates to each clarifier relative to surface level of water entering each clarifier. The calculation of SLR was achieve using equation 6 in section 2.3.3 of the literature review.

3.3.2.3 Denitrification

Denitrification will be identified by simple observation of the surface of the sedimentation tank. If small refractile gas bubbles are observed, under good light conditions, to be carrying floc attached to them all the way to the clarifier surface, denitrification is occurring in the settling tank (as explained in section 2.3.4).

3.4 Identification of Flocculation and Hydraulic Problems in Secondary Clarifiers

Unlike denitrification and sludge blanket levels, hydraulic and flocculation problems are difficult to differentiate, and specific testing is needed to identify them.

3.4.1 DSS/FSS Testing

ESS in final clarifier effluent, DSS and FSS comparisons will allow the identification of hydraulic and flocculation problems in the clarifier performance, according to Wahlberg et al. (1995), Ekama et al. (1997) and Parker et al. (2000). The latter can be achieved only if the samples (ESS, DSS and FSS) are taken approximately at the same time period (Ekama et al., 1997), otherwise, results will be useless, since they do not represent the loading characteristics on that time frame. DSS/FSS testing will be carried out in three of the six secondary clarifiers. The idea is to sample clarifiers that are different from each other so as to analyze their performance relative to their particular design. In Kuwahee WWTP there are three different types of circular clarifiers. Four of them (clarifiers #1, 2, 3, and 5) have the same characteristics, while clarifiers #4 and #6 are different from the rest. Clarifier #4 is a circular clarifier that was updated from its original design. An inlet and flocculation well were placed in replacement of the conventional center well present in clarifiers #1, 2, 3 and 5. The sludge collection system was equally modified, from a sludge suction arm with squeegees to a spiral scraper system. Clarifier #6 was built the last, and it is different from the rest of the clarifiers since it has a flocculation well (different diameter than clarifier #4) with hydraulic suction as sludge collection system. Therefore clarifiers #4 and #6 where chosen for DSS/FSS testing, in addition to clarifier #1, which will be representative from the other group of clarifiers (clarifiers #1, 2, 3 and 5). The difference between clarifiers is shown in Table 6.

Table 6: Clarifiers design characteristics

	Clarifier					
	#1	**#2**	**#3**	**#4**	**#5**	**#6**
Diameter (ft)	135	135	135	135	135	135
Center well type	Conven. center well	Conven. center well	Conven. center	Flocc. well	Conven. center well	Flocc. well
Center well diameter (ft)	20	20	20	10 (inlet well)	20	15 (inlet well)
Flocculation well diam. (ft)	-	-	-	32	-	34
Sludge collection system	hydraulic suction	hydraulic suction	hydraulic suction	Spiral scrapers	hydraulic suction	hydraulic suction
Side water depth (ft)	12	12	12	12	12	12

Conv: Conventional
Flocc: Flocculation

3.4.1.1 Dispersed Suspended Solids (DSS) Test

DSS testing was first designed by Parker et al. (1970), and it consists of the collection of wastewater samples and later settling, for 30 minutes, in the same container, so floc breakup or flocculation effects are avoided from transfer of samples from intermediate containers. Samples of DSS were collected in three specific locations on each of the clarifiers chosen for DSS/FSS testing. These three locations were: the center well influent, the upstream side of the center well effluent (or flocculation well when sampling clarifiers #4 and #6), and the upstream side of the clarifier effluent weir. The test was performed in a 4.2 liters Kemmerer sampler (shown in Figure 2). This sampler consisted of an acrylic tube with upper and lower closures.

The advantage of the Kemmerer sampler is that the closures will remain open until a lead messenger hits the upper closure, once the sampler has been submerged in the location desired for sampling. After the closures have been secured, the sampler was pulled up from its string and settled in a safe place where the water level was lowered just below the upper internal support, using the bottom drain valve.

Then the sampler was placed in a vertical position and the 30 minutes of settling were initiated (see Figure 4). After 30 minutes, approximately 50 ml were wasted through the siphon (this was done to avoid solids adhered to the siphon that may alter the real suspended solids value present in the supernatant of the sampler), and afterward a 500 ml sample was withdrawn from the supernatant and analyzed for suspended solids concentration. The flow rate at which the sample is withdrawn should be low enough so the settled particles are not disturbed. The water level after the 500 ml sample had been taken should not be less than 0.25 inches above the sampling siphon, so no floating debris is added in the withdrawn sample.

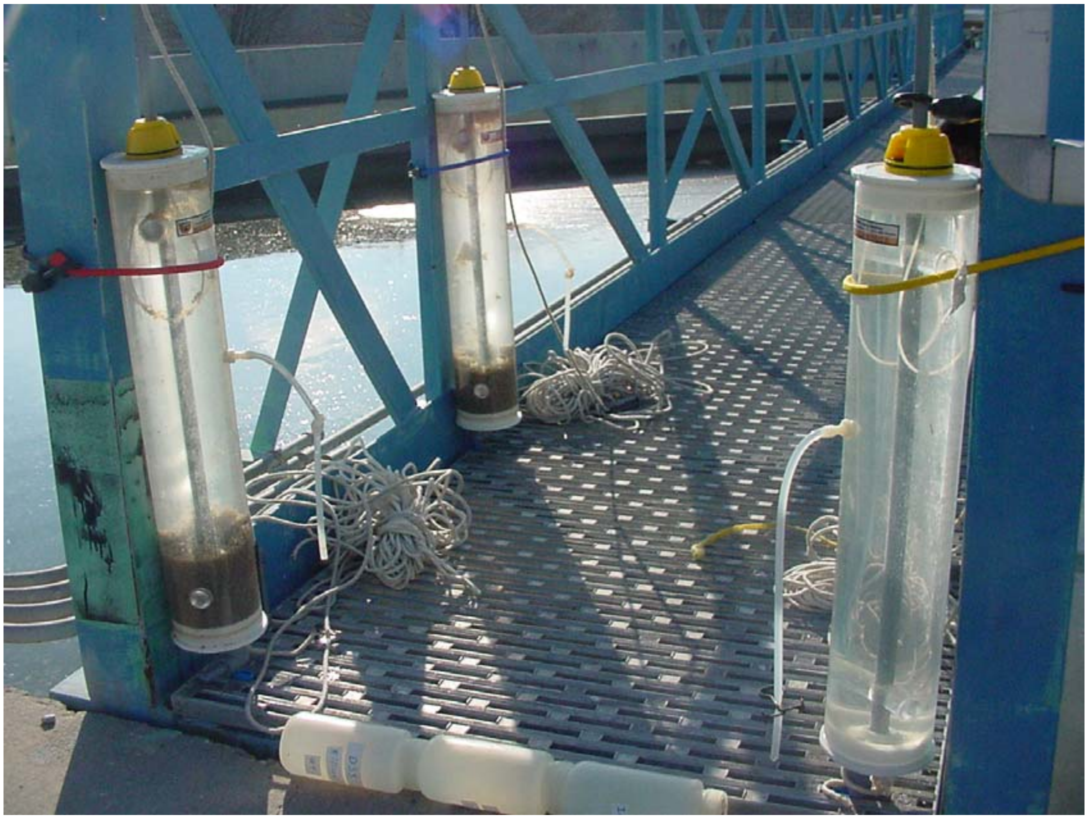

Figure 4: DSS samples taken in Kemmerer samplers during settling

3.4.1.2 Flocculated Suspended Solids (FSS) Test

FSS test was operationally defined by Wahlberg et al. (1995) as the suspended solids concentration from a sample withdrawn after 30 minutes of settling, preceded by 30 minutes of flocculation at a stirring velocity of 50 rpm. A six paddle stirrer will be used in addition to square flocculation jars filled with 1.5 liters of sampled wastewater (see Figure 5). The importance of the square jars lays in the avoidance of in-vessel baffling. The FSS sample will be taken on each clarifier at the closest location where the inflow to the settler enters in to each of the sampled clarifiers. After one hour period (once flocculation and settling have been carried out), a 500 ml supernatant sampled is taken for standard suspended solids concentration measurement. It is important to let the

Figure 5: FSS samples during flocculation period

sample siphon open so 50 ml of liquid are wasted, before the 500 ml sample is taken, in order to avoid debris to alter the suspended solids result.

3.5 Statistical Analysis Tools

Two software tools were used during the analysis of the collected data. The first one was Microsoft Excel 2002, which was used for organizing and summarizing data and to build the necessary calculations and unit transformations for further analysis. Tables and some bivariate graphs were applied to the collected data using Excel.
The other software tool was JMP 5.0. This is statistical analysis software. Data collected and entered in excel sheets was imported to JMP 5.0. JMP 5.0 was used for multivariate

regressions, where correlations and coefficients can be obtained. The two statistical functions used from JMP 5.0 were for assessing multivariate graphs, and multiple comparisons of means. The first one is nothing more than plotting two variables against each other. The multiple comparisons of means consisted basically in two types of parametric tests: the Tukey-Kramer Method and the Hsu Method for Comparisons with the Best (MCB). The data entered was previously proven to fit a normal distribution using a normal quantile plot.

In the case of the multivariate regression the variable selection method used was the stepwise regression with mixed direction. In this way the software will enter or remove variables with a probability of 0.25.

The Tukey-Kramer Method is a very helpful, not conservative method for mean comparison. It is used to determine statistically if one or more sample populations have means that are significantly different. If there is evidence of differences when comparing sample means the next step would be to determine which of those means is significantly larger of smaller than the rest. This task can be accomplished using the Hsu Method.

A graphical representation of sample comparison was used to summarize and plot the data. JMP 5.0 has an option of side by side box plots. They are especially useful for visually compare multiple sample distributions in terms of their means and skewnesses.

Chapter 4: Data Analysis

As previously mentioned the Kuwahee WWTP design configuration and operation procedures suggest the existence of two potential sources contributing TSS in the final effluent: fully treated wastewater, and wastewater diverted from secondary treatment when high flows exceed the maximum biological treatment capacity. In the preceding chapter, variables already collected periodically in Kuwahee WWTP, and those that need to be collected during the study were described. In the present chapter the evaluation of known and unknown parameters were conducted using Excel and Jump as statistical tools.

4.1 Evaluation of high Effluent Suspended Solid Events

According to the evaluation protocol established in the literature review, many parameters can cause ESS concentrations to rise in the plant effluent. From the described parameters, a portion has already been collected by Kuwahee WWTP as part of their operational strategy of treatment control. However, another group of parameters had to be measured. In this section those factors considered important when evaluating high ESS concentration issues in the literature have been addressed. The sampling procedure for those parameters to be measured, started on January 18th of 2004, and finished on March 31st of the same year.

The evaluation will be presented in the order described in chapter 3, hence each of the mentioned existing parameters will be shown separately in the following subsections. A summary table containing the relationships analyzed with the existing parameters is shown in Table 7, where yellow colored boxes indicate that that particular relationship

Table 7: Summary table of analyzed existing parameter relationships

	ESS	Prim Eff BOD	RAS	WAS	Prim Eff Ave Flow	SVI	Rainfall	MLSS	µ	Settleable Solids	Blanket height	F/M
ESS												
Prim Eff BOD												
RAS												
WAS												
Prim Eff Ave Flow												
SVI												
TVA rainfall												
MLSS												
µ												
Settleable Solids												
Blanket height												
F/M												

was analyzed. The operational data collected covers a sampling period that started the first day of year 2001, and finished on December 30th of 2002.

4.1.1 Suspended Solids

The only suspended solids measurement taken as part of the normal operational and regulatory strategy was the overall plant effluent concentration, which was measure in a daily basis in Kuwahee WWTP.

As mentioned before, high influent flow events over 70 MGD, cannot be treated through the biological treatment unit, because microorganisms will be wasted faster than the rate at witch they grow. Kuwahee WWTP relies on EPA's blending policy as the high flow operational strategy. Hence, every time a high flow event occurs, the secondary diversion bypass is open, and the flows exceeding the limit are run through the primary clarifiers and carried to the influent channel of the disinfection units.

High suspended solids events can be tied to the solids carried from the primary clarifier to the blending point. On the other hand, if clarifiers are performing deficiently, excess suspended solids might be getting into the discharge point of the treatment facility. Another option is that high overall plant ESS may be caused because of both, bypass and poor clarifier solids-liquid separation. Because of all of these reasons Kuwahee WWTP arranged a sample collection strategy when secondary diversion was in use, while overall plant ESS concentration was still being taken in a regular basis. At the same time, and as part of the sample protocol, TSS analysis of each of the six clarifiers will be carried out.

These three TSS measurements will be evaluated in the following subsections.

4.1.1.1 Overall Plant Effluent Suspended Solids

As mentioned in chapter 3, TSS samples of the overall plant effluent suspended solids were taken at the effluent of #2 chlorine contact tank during the sampling period.

During the operational data collection, period prior to year 2004, there were 19 TSS values greater than 45 mg/L (NPDES daily discharge limit). However, from January to the end of March of 2004, no values over 45 mg/L were discharged into the Tennessee River. The mean value for the sampling time previous the year 2004 had an average value of 15 mg/L, which is a very good concentration. Nevertheless, some isolated events contained solid loss higher than normal in the final effluent. The information gathered was analyzed using JMP 5.0. A stepwise regression was used for the selection of the predictor candidates of ESS. Than a linear regression model was generated. The results of the multivariable regression show that the variables that could represent the ESS behavior are rainfall, SVI, primary clarifier effluent flow, and WAS. However the value R^2=0.06169, suggests that the predicted values using the equation obtained from the multivariate regression don't have a good match with the real values. The output report obtained from JMP 5.0 can be seen in Analysis A.1, Appendix A. In Table 8, those parameters that have an X on the enter column were considered by the stepwise regression.

The most commonly used standard transformations were applied to the model after careful inspection of the residual plots of the predictors. None of them improved the correlation of the linear model.

A correlation matrix of the dependent and independent variables was also analyzed with the intent of using those variables that were independent between them as predictor candidates of the model (see Table B 1, in Appendix B).

Data collected in the sampling period that went from January to March of year 2004, was analyzed for multivariate regression as well. Following the procedure for the analysis of the operational data collected prior the sampling on year 2004, a stepwise regression was used for the selection of the predictor candidates of ESS. Further a linear regression model was generated. Standard transformations were applied as well to this model according to the residual plot analyses. However, none of them improved the correlation of the model. The predictor variables in this model turned out to be: plant influent average flow, the plant influent suspended solids concentration, the plant effluent settleable solids, and the average SLR (see Table 9). Even though the correlation for this

Table 8: Stepwise output for operational data

RSquare		RSquare Adj
0.0617		**0.053**
Entered	**Parameter**	**Estimate**
X	Intercept	16.1095799
	Prim Inf BOD (mg/l)	0
X	WAS (gpm)	-0.0130424
X	SVI	0.02873532
	Settleable Solids (ml/L)	0
	MLSS (mg/l)	0
	µ (1/d)	0
X	Rainfall (in)	3.32670669
X	Prim Eff Avg Flow (mgd)	-0.1076847
	F/M ratio	0
	RAS (mgd)	0

Table 9: Stepwise output for sampling data

RSquare		RSquare Adj
0.6134		**0.56**
Entered	**Parameter**	**Estimate**
X	Intercept	-15.425105
	Rainfall (in)	0
X	Influent aver flow (MGD)	0.737583
	Infl Temp (°C)	0
	Inf BOD (mg/L)	0
	Eff BOD (mg/L)	0
X	Infl SS (mg/L)	0.00583952
X	Eff Set Solids (ml/L)	79.2190242
	Inf pH	0
	Eff pH	0
	MLSS (mg/L)	0
	RAS mgd	0
	Ave SOR	0
X	Ave SLR	-17.428704
	SVI	0

model was much higher (R^2 = 0.613353) than the previous model, the prediction capability of the model is still low. It is to say that if the four predictor parameters in the model are carefully controlled during operation, 40 percent of the variance will still be unexplained by the model. The output report obtained from JMP 5.0 can be seen in Analysis A.1, Appendix A.

As in the previous model, a correlation matrix was obtained from the JMP report. The correlation matrix (see Table B 2) was useful for the selection of independent variables (no collinear parameters). Temperature had some correlation to the ESS (-0.4158), however when entered into the stepwise regression, temperature was discarded as a predictor. This implies that variations of temperature at A stepwise regression was used for the selection of the predictor candidates of ESS. Than a linear regression model was generated the influent to the plant was not an incident variable of high ESS at the overall plant.

4.1.1.2 Clarifiers Effluent Suspended Solids

Suspended solids data collected from each of the six circular secondary clarifiers on Kuwahee WWTP was analyzed almost every day during the sampling period. A data summary with ESS (effluent suspended solids taken from secondary clarifiers) can be seen in Table B 3, in Appendix B.

The graph ESS concentration versus date is shown in Figure 6. This graph shows the behavior of each secondary clarifier relative to their solids free effluent. Clarifier #2, is the one that had more frequent high suspended solid concentrations. At the beginning of the sample period, flows on each clarifier were assumed to be, if not exactly equal, very similar. But once the first week’s results showed an evident difference between clarifier performances, the statement was suspected to be untrue. Recalling that clarifiers #1, 2, 3 and 5 were designed equally, they were expected to behave equally, however Figure 6 shows that it wasn’t that way. Because of these

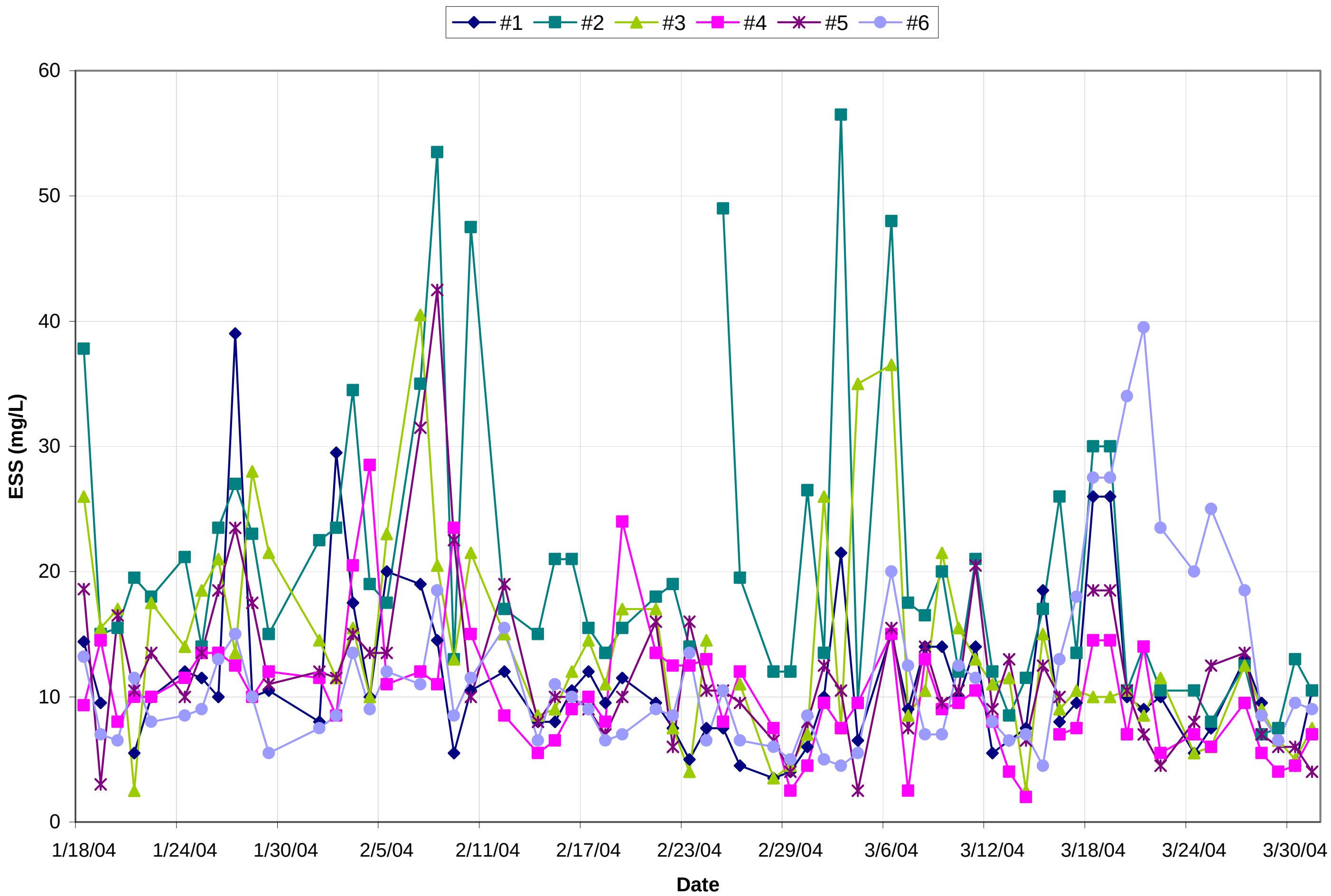

Figure 6: Daily ESS values for each clarifier

unanticipated results a flow measurement strategy was developed, in order to measure proportionally the flow that each clarifier was receiving. Therefore poor performance because of overloading of some clarifiers could be determined.

As described in chapter 3, the gate opening of each clarifier was measured from the bottom of the gate up to the surface water flow. The measurement was carried out using a measuring pole. Samples were taken during DSS/FSS testing, so as to have a consequent parameter for comparison. Figure 7 shows the different values taken per day in each clarifier, from the day the gate openings were started to be measured (data is shown in Table B 4, in Appendix B). Proportional opening measurements started on February 7th, and ended on March 31st. From Figure 7, it can be observed that clarifier #2 was being critically overloaded in comparison with the rest of the clarifiers. Figure 7 has more missing observations (zero opening values). The reason for this, besides the cleaning or repairing of a clarifier (when cleaning or repairing incoming flow to the specific clarifier is shut down), was the amount of scum floating on the surface of the incoming flow over the gate. Since the measurement was taken visually in accordance to the level of water in the measuring pole, scum made it impossible for the reading to be taken. Clarifiers #1 and #2 were usually the most affected, since the scum would stay in the first gate openings, rather than going further away in to the distribution channel (see Figure 8).

On March 15th, a change in gate openings was made in Kuwahee WWTP, in order to even the flow into the existing clarifiers. On Sunday, March 14th, the gates were set in different positions while measuring the flow levels in the gates, so the flows could be set even. After the measurements taken on Sunday, on Monday the gates were evened out, as Figure 7 shows for dates after the change was made (proportional flows are shown in Table B 5 in Appendix B). The most noticeable change can be observed in clarifier #2, which leveled out its performance relative to ESS concentrations with respect to the other clarifiers, after the new gate adjustments. Figure 8 shows the design distribution of the clarifiers in the facility.

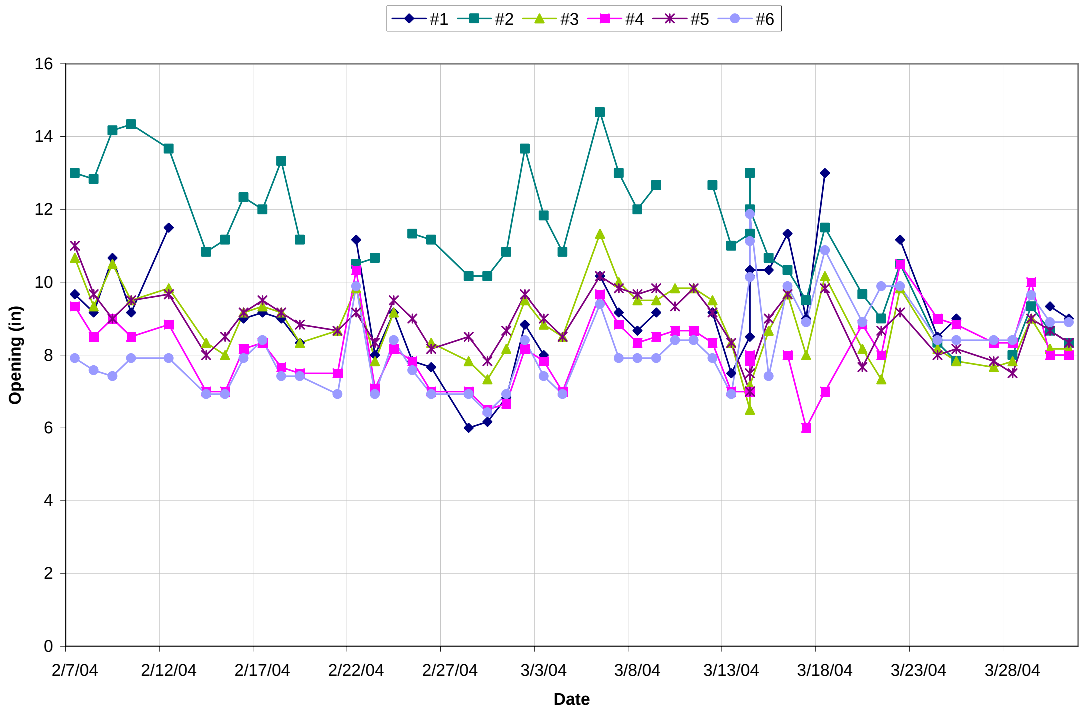

Figure 7: Daily opening measurement values for each clarifier

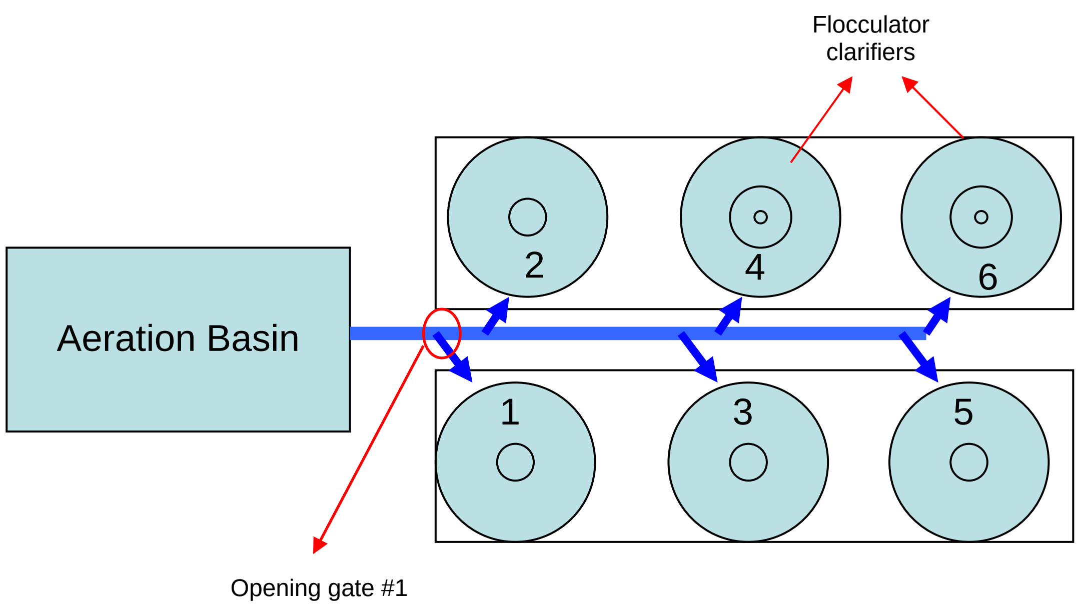

Figure 8: Secondary treatment plant view

In order to establish a more accurate evaluation of flows entering each clarifier a statistical analysis was carried out using the Tukey-Kramer Method in JMP 5.0, so that statistical difference of flows between clarifiers could be found. In addition, a statistical analysis for the best fit, using the Hsu's MCB method in JMP 5.0, was used to find if there was an average value from a specific clarifier that was significantly larger or smaller than the rest of the values. The box plot generated during the analysis is shown in Figure 9. The data showing the analysis output from JMP 5.0 can be seen in Analysis A.2, in Appendix A.

From the Tukey-Kramer report (see Analysis A.2, Appendix A), clarifier #2 mean flow value was significantly different from the rest of the clarifiers mean flows. This was expected according to the measurements taken from gate openings. The Hsu's MCB output report (see Analysis A.2, Appendix A) shows that the mean flows of clarifiers #1, 3, 4, 5 and 6 are significantly less than the max (mean flow of clarifier #2). Therefore, the mean flow of clarifier #2, was significantly greater than the rest of the clarifiers, for the observations taken from the beginning of February until the last day of March of 2004.

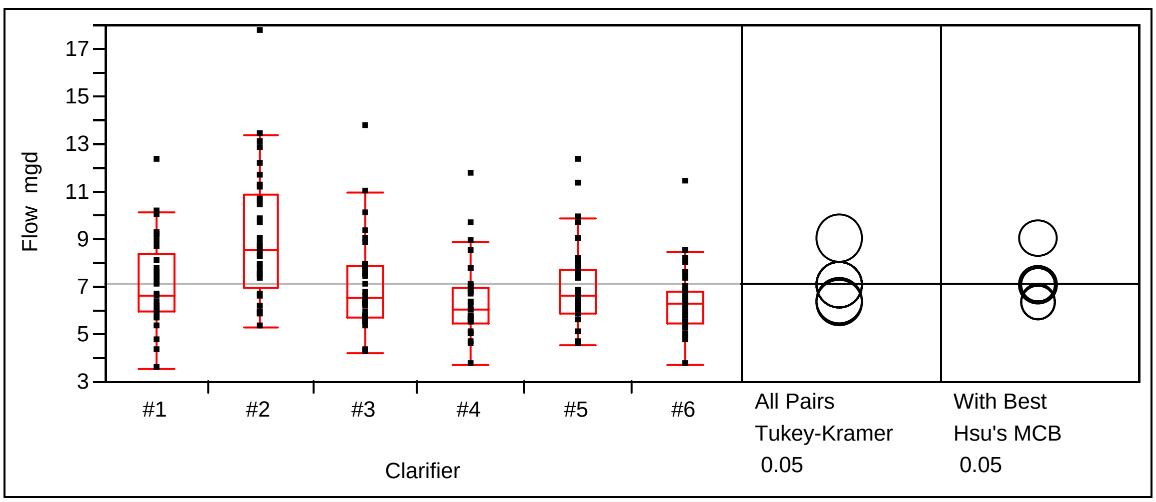

Figure 9: Side by side box plot for flow comparison between clarifiers

4.1.1.3 Suspended Solids during Bypass Mode

Unfortunately the data collected during bypass mode was erroneous and very limited, so it couldn't be used for further analysis, since it would lead to erroneous and confusing conclusions. Instead a flow-TSS simulation was generated in order to understand what effects the plant effluent will suffer when the secondary diversion is in use.

The simulation contemplates a variety of operational considerations. First of all, even though the primary clarifiers and the secondary treatment have a flow limit of 70 MGD, operational data shows that in Kuwahee WWTP, the bypass mode is activated at flows lower than the limit. Most of the times, the bypass is used when flows get closer to 60 MGD. This means that the pre aeration channel is activated, which diverts the flow away from the primary clarifier, and blends it back in the influent channel of the aeration basin. At the same time secondary diversion is opened, which redirects the flow from the primary effluent channel, before the pre aerated flow is blended into the aeration basin influent, and transports it into the chlorination basin influent channel. The flows redirected in the pre aeration channel and the secondary diversion are proportional, so a flow balance is kept with in the plant. From the last discussion it is reasonable to suggest that at plant influent flows over 55 MGD the bypass mode is activated (pre aeration and secondary diversion channels are opened).

At flows larger than 55 MGD, for simulation purposes, primary clarifiers and the secondary treatment unit (aeration basin and secondary clarifiers) will be receiving a constant flow of 55 MGD, for as long as the high flow event lasts. Hence, even though flows can still be increasing these two process units will treat no more than 55 MGD, which is what actually happens in Kuwahee WWTP. From this, it can be concluded that the TSS value for the primary effluent will stay constant relative to the 55 MGD flow, as well as the secondary clarifier effluent TSS, during bypass.

The secondary diversion channel will divert the flow right from the primary clarifiers' effluent, and therefore, the TSS concentration in the diversion channel should be the same as the one at the primary settling effluent.

Flow rates from 25 MGD to 120 MGD, which is the maximum design flow that can be treated in Kuwahee, will be simulated relative to the TSS concentration performance. In order to predict the TSS values for the plant influent, the primary effluent, the secondary treatment effluent and the plant effluent, operational data collected in the Kuwahee WWTP was used.

The plant influent suspended solids will be used as a reference, because it doesn't affect the calculations of the plant effluent solids content. A graph of TSS as a function of plant influent flow was generated from the operational data collected in Kuwahee WWTP from January 1st to March 31st of 2004. From the latter an average TSS projection was obtained using linear regression and used in the simulation (see Figure B **1** in the Appendix). In the same way a predicted TSS concentrations for primary effluent (Figure B 2 in Appendix B), secondary treatment (Figure B 3 in Appendix B), and the overall plant effluent (Figure B 4 in Appendix B), were obtained using the regression from plotting TSS as a function of the plant influent flow. The data plotted using the overall plant effluent was taken from the 2 years of operational observations, since the data were available and makes the prediction more accurate. The secondary diversion TSS was assumed to be the same as the primary effluent TSS.

The simulation is plotted in Figure 10, and the simulation data is in Table B 6 in Appendix B. This figure shows the estimated TSS concentration as a function of flow variation. There are two plant ESS simulations: one based in the blending of the secondary diversion TSS concentration and flow, with the secondary clarifiers effluent TSS concentration and flow during bypass mode; and the other one is the predicted plant ESS according to the operational data collected in Kuwahee from January 2001 until April of 2003. The estimation of TSS using the flow blending is over estimating the real average operational values of TSS at the plant effluent. It is very probable that there is a dilution factor that has not been taken in account in this simulation, because of the lack of data for higher flows, since the TSS-flow curve was extrapolated up to 120 MGD.

In Figure 10, one can see that because of the flow diversion the secondary clarifiers should keep a very stable TSS concentration (18 mg/L in the simulation, for

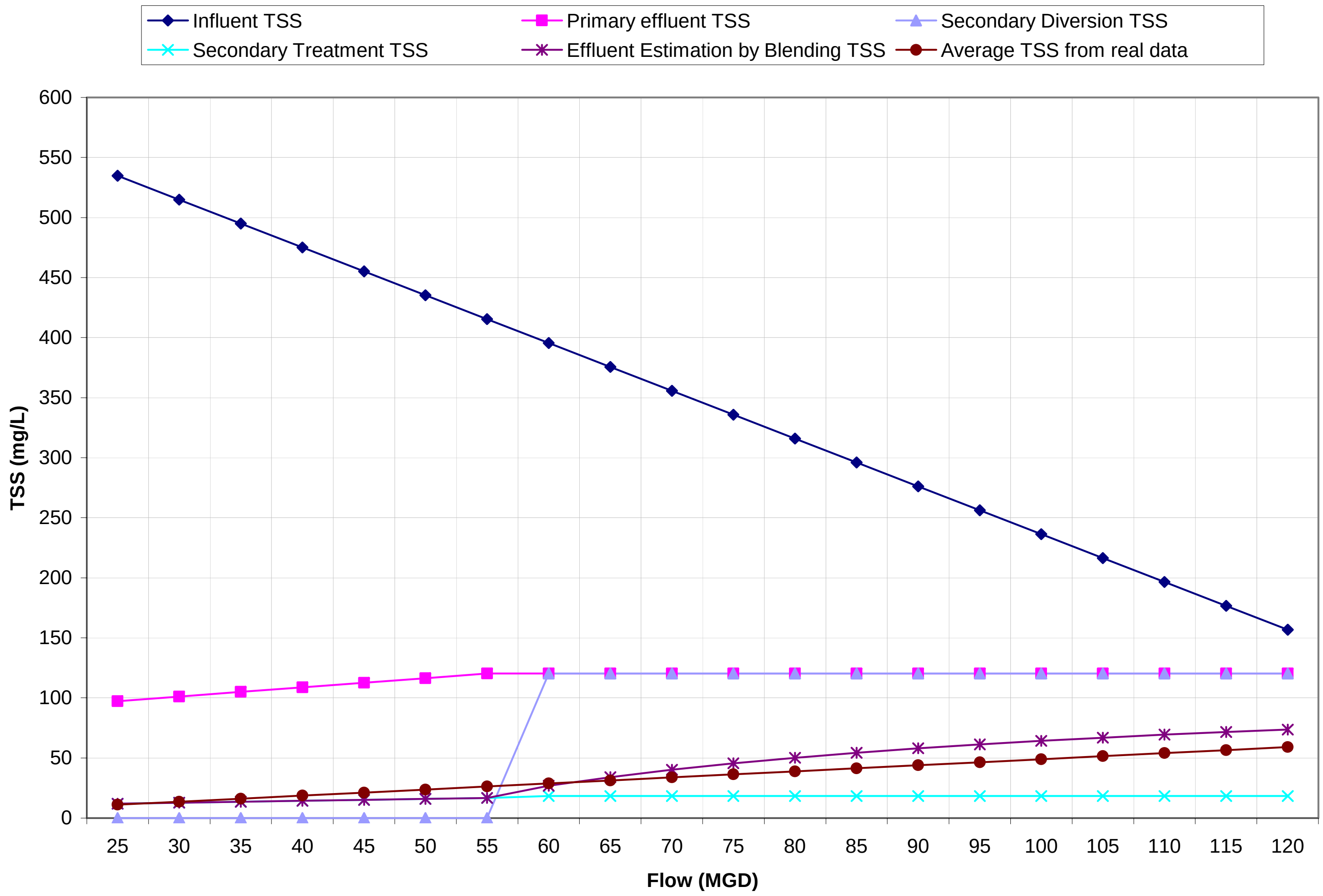

Figure 10: TSS simulation as a function of plant influent flow

flows of 55 MGD), while the secondary diversion would as well have a constant concentration of 120 mg/L at a flow rate of 55 MGD. The NPDES daily limit of 45 mg/L is violated at flows larger than 90 MGD according to the operational data prediction. Instead, the daily limit would be violated at flows over 75 MGD, according to the blending TSS estimation criteria.

During the operational data collection (January 2001 to April 2003) there were 20 TSS concentration values equal of greater than the NPDES daily limit. As it can be seen in Figure B 4 in the Appendix, from those 19 daily violation values 8 of them were at flows greater than 55 MGD, and the rest were at lower flows. This implies that almost 58 percent of the violations were caused by problems other than high flow events, while the other 42 percent is related to high flows. From the graph it is also noticeable that the secondary diversion influence on the blended effluent TSS concentration increases with increasing flow during bypass mode, since the secondary clarifiers keep a constant ESS concentration because of the constant flow rates applied during high flow events.

Even though the concentration of the secondary diversion is constant, because of the constant primary effluent TSS concentration, its contribution increases for the reason that more flow is diverted, and therefore a greater part of the blended effluent will have high concentrations coming from the primary effluent. When the plant influent flow is over 110 MGD, more than half of the blended effluent will be contributed by the secondary diversion. Consequently, no matter how good secondary clarifiers are performing, during high flow events, there will likely be high ESS concentrations because of the suspended solids concentration contribution from the secondary diversion.

4.2 Potential Source Parameters of High Effluent Suspended Solids Events

As described in the literature review, there are several factors that may cause high ESS events. For study purposes they were grouped into several categories described in the preceding chapters.

4.2.1 Biological Parameters

In agreement with the literature review and data collection procedures, the following biological parameters were analyzed relative to the solid content at the plant effluent.

Primary Effluent BOD

Primary effluent BOD was analyzed relative to the overall plant ESS, specific growth rate, WAS and F/M ratio. Graphs related to this analysis carried out in JMP 5.0 are shown in the following figures. The ESS concentration is plotted in Figure 11 as a function of the primary effluent BOD collected during the sampling period. The horizontal line drawn across the graph shows an ESS limit of 30 mg/L, used as a reference. There was no pattern in the graph, ESS over 30 mg/l occurred at normal influent BOD values. The plot shows no relationship between high ESS events and the organic content of the wastewater entering the aeration basin, since at normal BOD values high suspended solids were observed in the plant effluent, therefore no

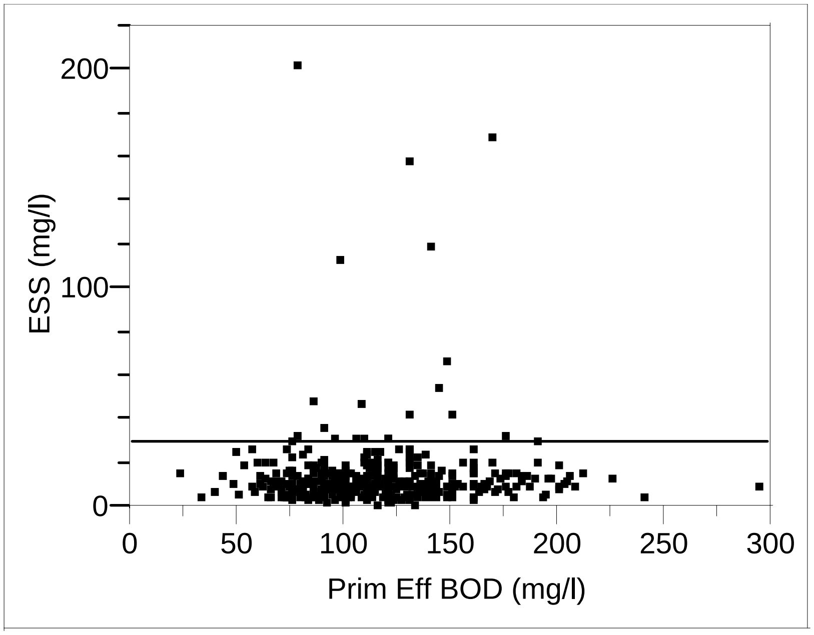

Figure 11: ESS vs. primary effluent BOD

relationship exists between these two parameters, and BOD has no influence on ESS final concentration.

Figure 12 is a plot of specific growth rate of microorganisms as a function of the influent BOD to the aeration unit. It is well known that the limiting factor for biological growth is the substrate provided to the microbial population. Therefore, any biological effect in the rate of bacterial growth due to substrate concentration changes should be recognized in this graph. However, the plot shows no pattern at all between organic loadings into the aeration basin and the specific growth rate of the bio-population. WAS is the daily excess of biomass generated in the system, relative to a steady state operation procedure. This is the key operational control parameter for maintaining the SRT in the treatment plant. There was no relationship between the WAS and the primary effluent BOD (see Figure 13). This can be expected according to Figure 12, since SRT and specific growth rate are inversely proportional, hence if no relation exist between

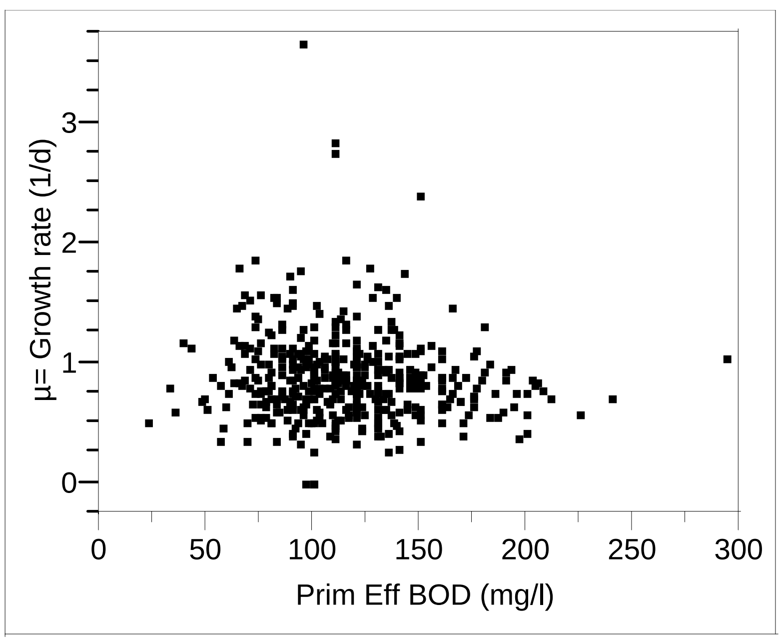

Figure 12: Growth rate vs. primary effluent BOD

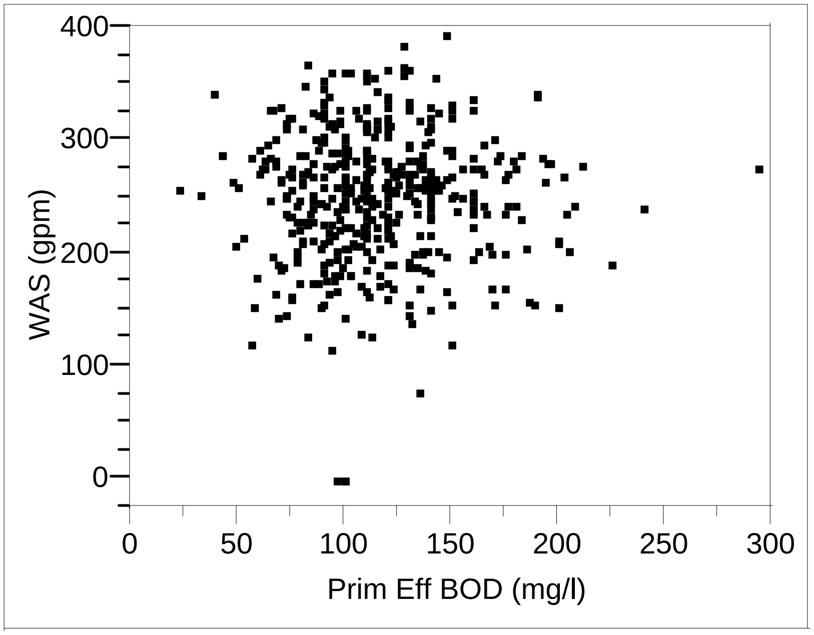

Figure 13: WAS vs. primary effluent BOD

growth rate, no relationship will be anticipated for SRT and primary effluent BOD. Since WAS has a strong relationship with SRT, no pattern should exist between wasted sludge and BOD loading in the aeration tank. The F/M ratio as a function of primary effluent BOD shows a sort of logical trend. Even though the ratio varies widely as BOD increases, with more food (BOD), the bigger the ratio gets. Consequently, F/M ratio seems to be operationally maintained in an acceptable manner (see Figure 14).

Return Activated Sludge (RAS)

Figures 15 to 19 show the relationship that return sludge concentration (mg/L) has with respect to different parameters. The first to be looked at is the plant effluent solid concentration as a function of RAS (Figure 15). High ESS occurs mostly when RAS is between 600-1800 mg/l, which is a normal operational value for RAS in Kuwahee WWTP. Hence return sludge, doesn't seem to have any influence on ESS changes.

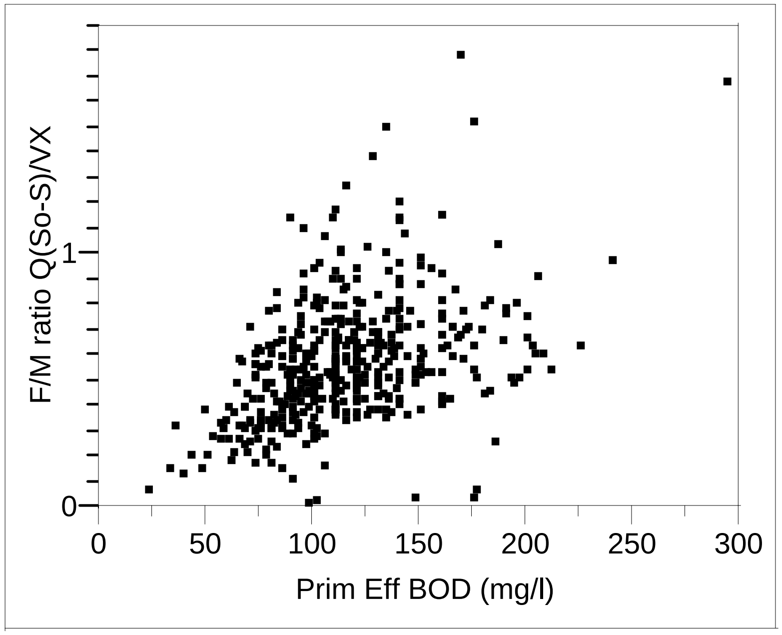

Figure 14: F/M ratio vs. primary effluent BOD

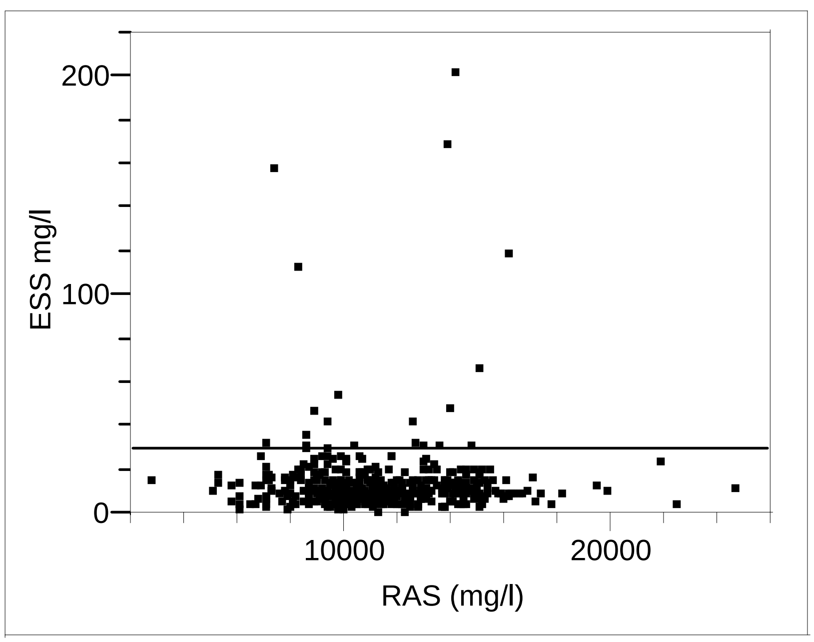

Figure 15: ESS vs. RAS

The specific growth rate of microorganisms in the aeration basin is plotted as a function of the RAS concentration in Figure 16. No pattern can be observed from the graph, and therefore no relationship exists between the mentioned parameters.

The same occurs when looking at Figure 17. There is no pattern since both values are independent from each other. For the same RAS the WAS varies from 100 to 400 GPM.

An increase in returned sludge seems to increase the MLSS concentration in the aeration basin. This relationship behavior can be anticipated, since the mixed liquor concentration would be expected to rise every time a higher concentration of activated sludge is returned, and added to the existing microbial population (see Figure 18).

Continuing to look into the operational parameters collected in Kuwahee WWTP, a plot of F/M ratio is shown as function of RAS. Although, with high RAS (mg/L) less RAS flow is returned, one would have expected the F/M ratio to increase, because of a smaller amount of population added to the aeration basin, however, no relationship was found between parameters, according to Figure 19.

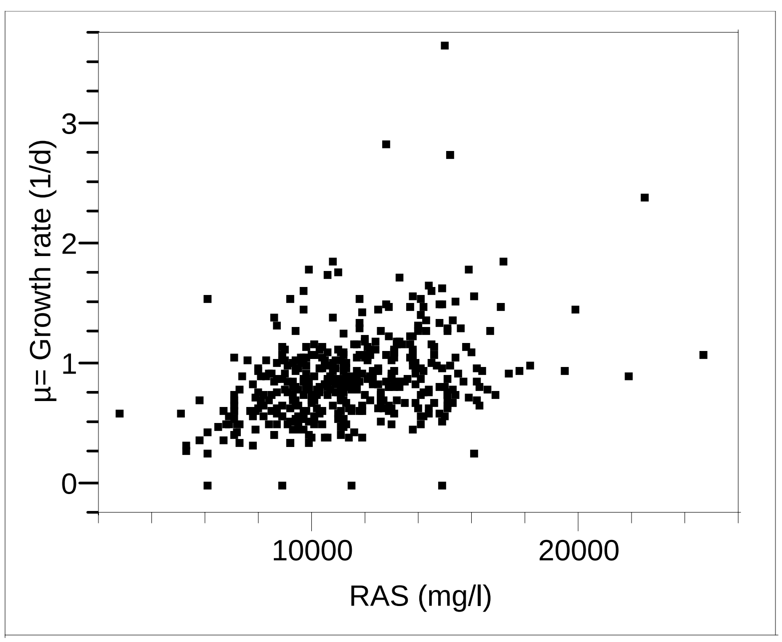

Figure 16: Growth rate vs. RAS

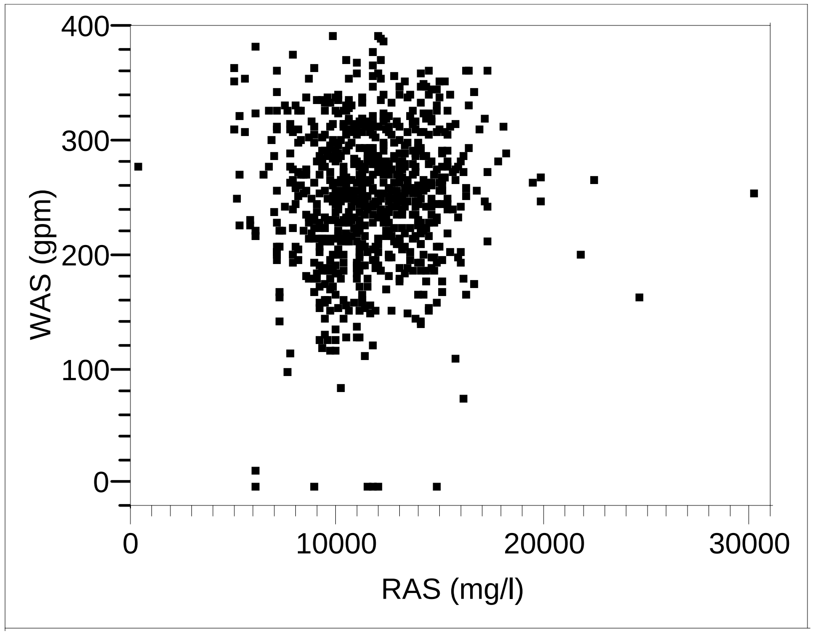

Figure 17: WAS vs. RAS

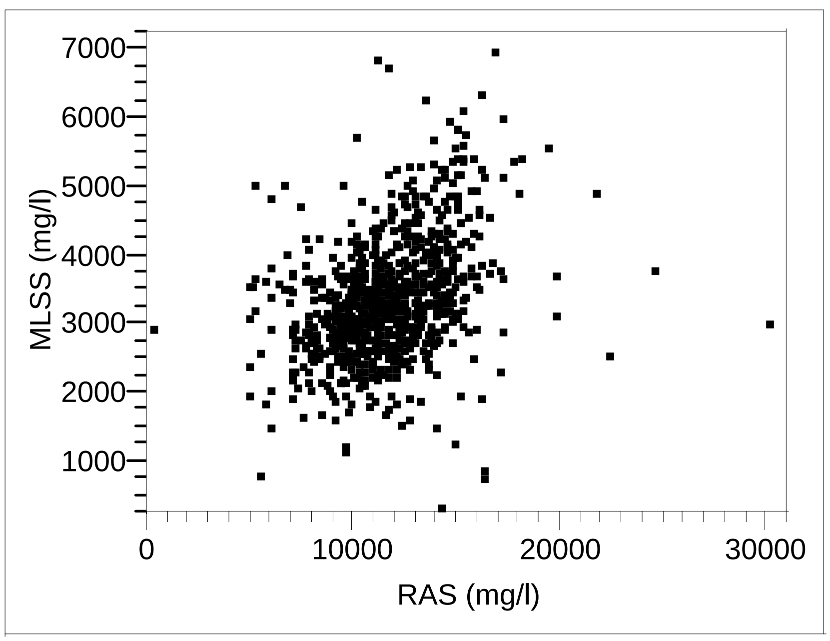

Figure 18: RAS vs. MLSS

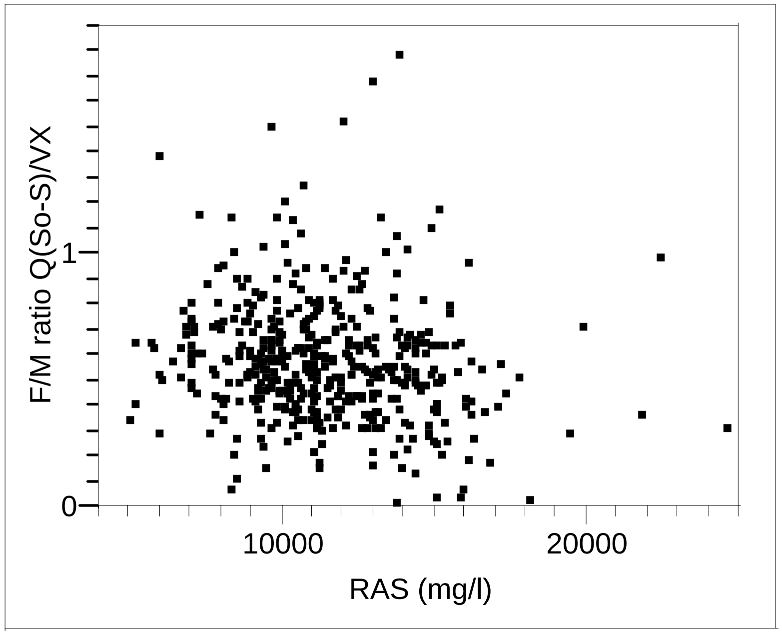

Figure 19: F/M ratio vs. RAS

Mixed Liquor Suspended Solids (MLSS)

No relationship exists between MLSS and ESS values. MLSS varies widely, 1000-7000 mg/l, but high ESS occur at normal MLSS values. In fact, high MLSS values don't seem to affect the suspended solid quality of the plant effluent (see Figure 20).

Major variations on growth rate occur when MLSS is optimal, according to literature 2500 - 4000 mg/l (Metcalf & Eddy, 2003). No strong correlation exists between specific microbial growth rate and biomass concentration in the Kuwahee aeration basin, as shown in Figure 21. As a matter of fact, microbial growth rate varies greatly at a specific MLSS concentration.

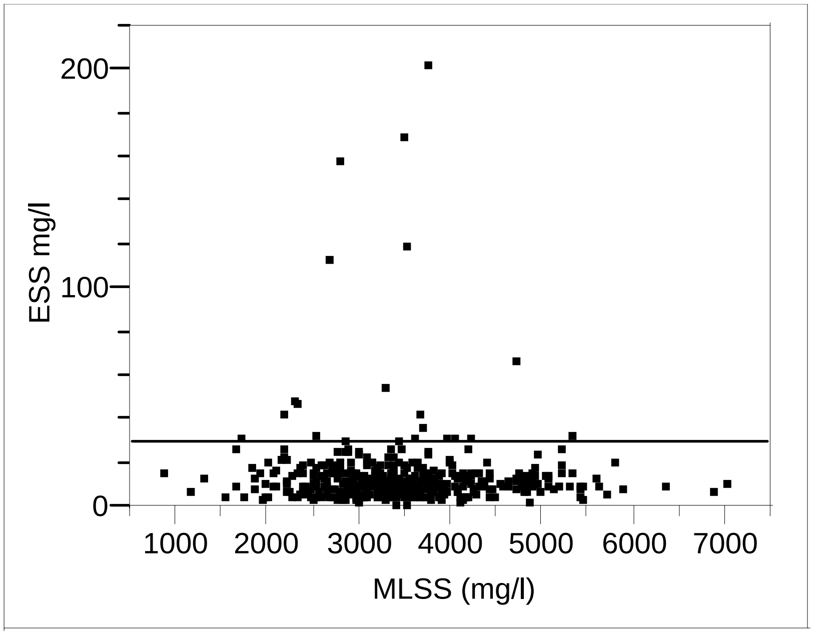

Figure 20: ESS vs. MLSS

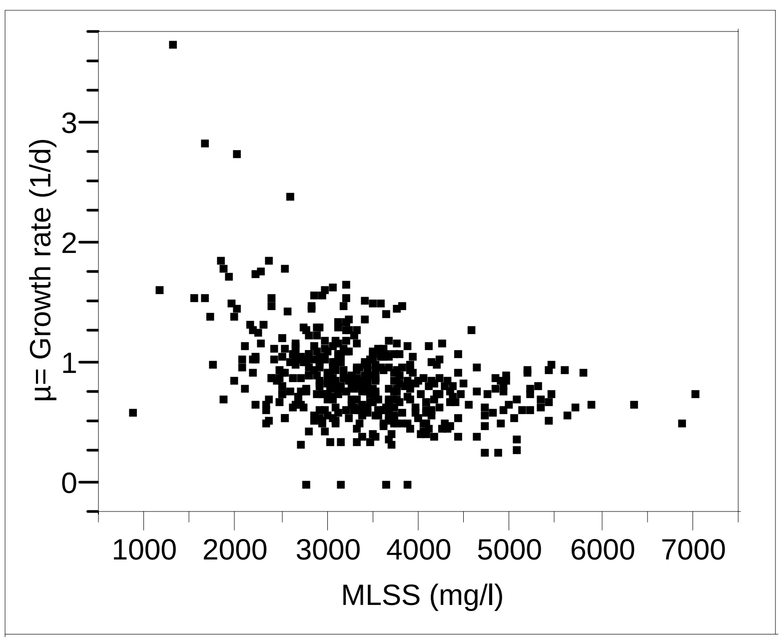

Figure 21: Growth rate vs. MLSS

In Figure 22 WAS is plotted against MLSS concentration. WAS doesn't appear to be function of MLSS. This suggests that there is something unstable when optimal operation is being performed, because data are not consistent all of the time.

In Figure 23, the F/M ratio is plotted against the mixed liquor concentration in the aeration unit. This graphical representation shows a logical trend. As MLSS concentration increases (microorganisms), more substrate (food) will be degraded, and therefore the F/M ratio will decrease. The same analogy can be applied to low MLSS concentrations in the aeration basin. If the amount of microorganisms present in the system decrease, and the same amount of food is being fed into the secondary system, the F/M ratio will increase.

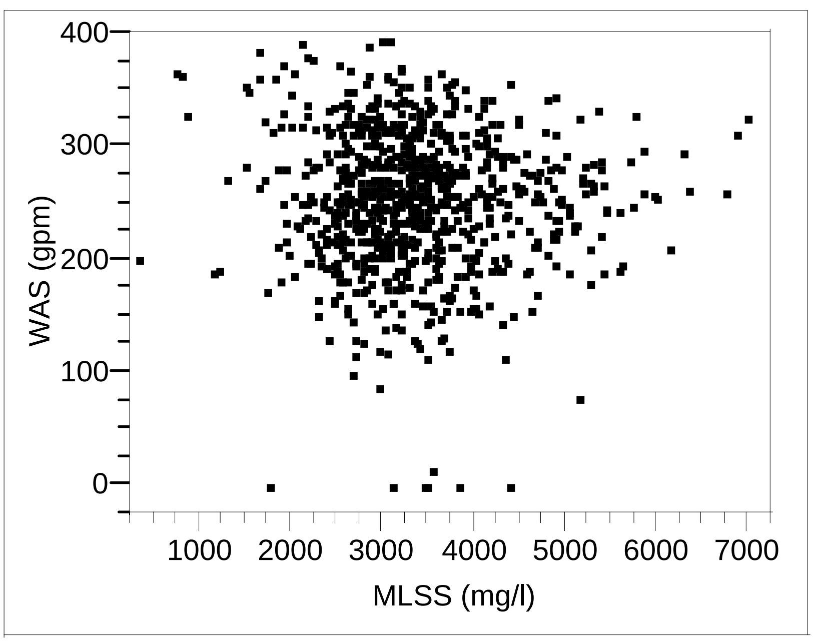

Figure 22: WAS vs. MLSS

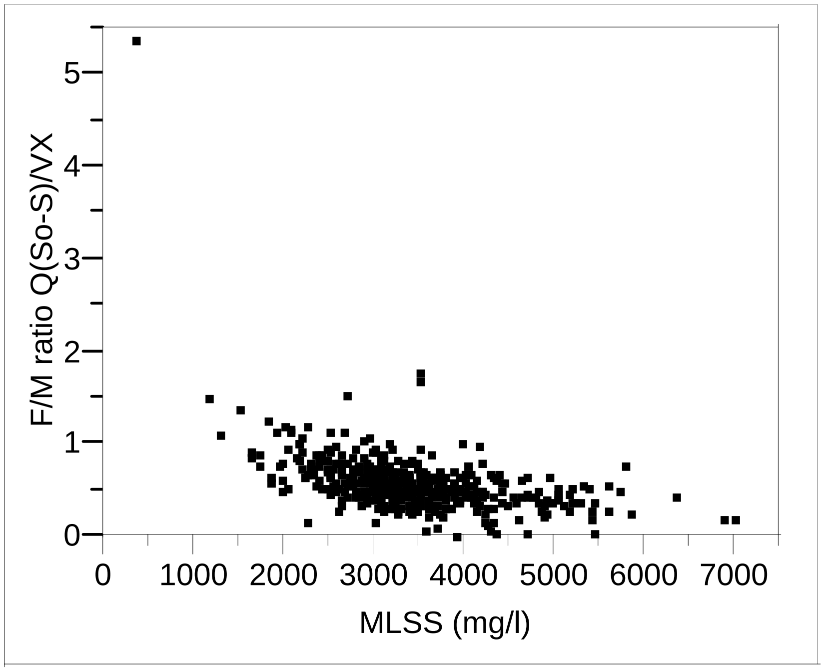

Figure 23: F/M vs. MLSS

Specific Growth Rate

In Figure 24, at smaller rates of microbial growth there is a tremendous variation in settleable solids content. The latter varies from 100 to 700 ml/L. Instead, when the bio-population in the biological reactor is growing at high rates, solids with good settling characteristics seem to diminished. This appears to be logical, given that at higher growth rates, young populations of microorganisms will tend to stay dispersed, which will be a detriment to floc formation and therefore most of the solids will need a longer time to settle.

When looking at ESS concentrations as a function of microbial growth rates, no relationship or pattern is observed. High ESS concentrations happened when growth rates were near 1, normal and optimal growth rate (see Figure 25). Furthermore, at very high rates of microbial growth, more young microbes will be expected; therefore more disperse solids will be expected, which will diminish settling. However, according to the plot no high ESS concentrations occurred in this situation.

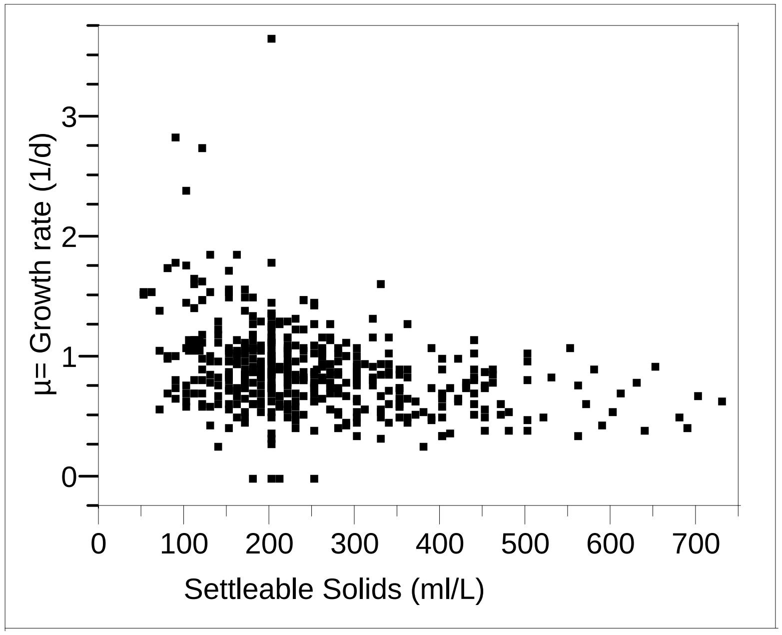

Figure 24: Growth rate vs. settleable solids

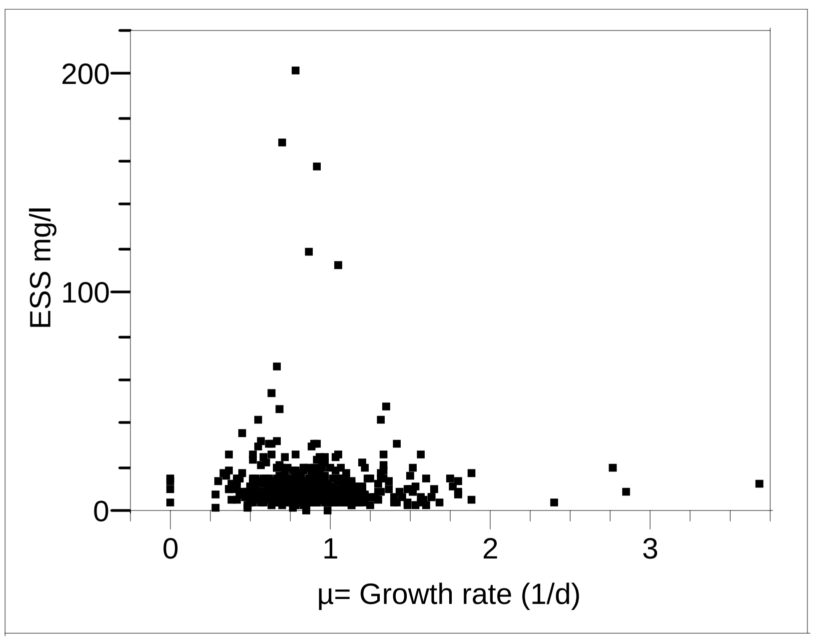

Figure 25: ESS vs. growth rate

The trend between growth rate and wasted sludge, shown in Figure 26, makes good sense. Every time that higher growth rates were observed, more biomass was generated. In order to keep steady state operational conditions, excess biomass must be wasted. Consequently, when microorganisms grow faster, a bigger amount of them must be taken out of the process. Therefore, SRT can be kept with in the required range.

It can be expected that at very high rates of bacterial growth, a more disperse population will exist in the aeration basin, due to inherent properties of fast growing microbes. Figure 27 shows nothing similar. From the plot sludge characteristics will vary widely when low growth rates are happening. There is no clear pattern that can be observed in the mentioned plot, thus no clear relationship can be stated. And finally Figure 27, shows total independence of sludge wasted from rainfall events.

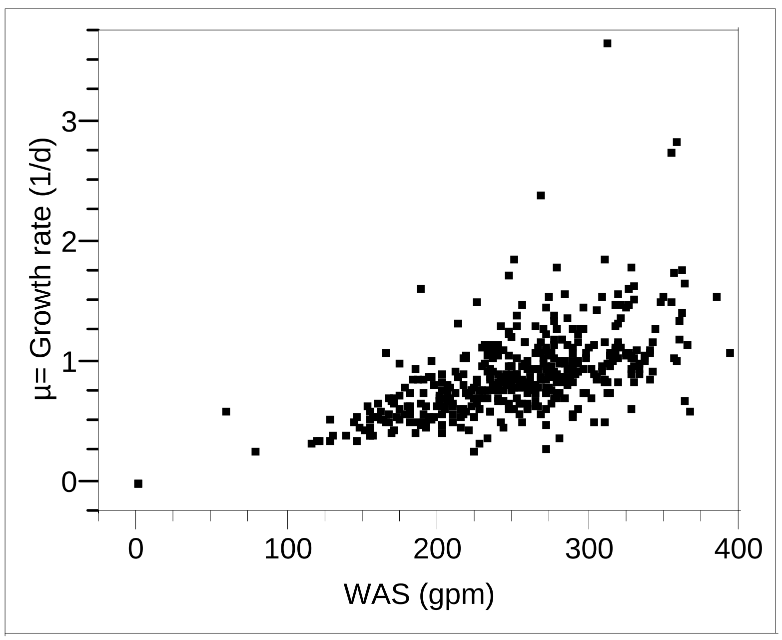

Figure 26: Growth rate vs. WAS

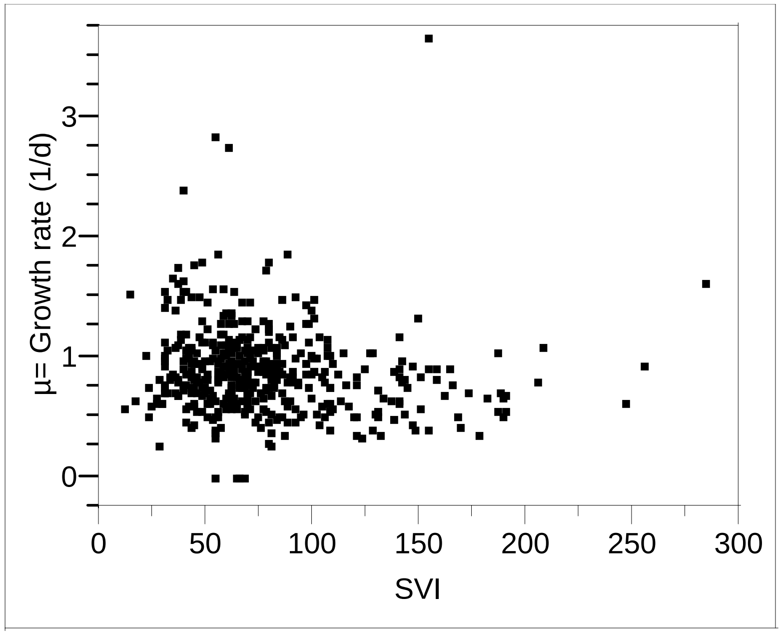

Figure 27: Growth rate vs. SVI

Wasted Activated Sludge (WAS)

From Figure 28 no relationship can be made between plant effluent solids quality and wasted sludge. Recall that WAS is the very key parameter for the control of time in which biomass stays in the system. This suggests a null association between SRT and ESS under the studied conditions.

In the same way, no relationship between wasted sludge versus SVI and F/M can be seen in Figure 29 and Figure 30 respectively. Therefore no trend in sludge characteristics can be expected from the variations made during the data sampling, because SVI varies widely no matter what amount of sludge is withdrawn from the system. In the other hand, in Figure 30, no significant variations on F/M ratio occurred with very different amounts of WAS.

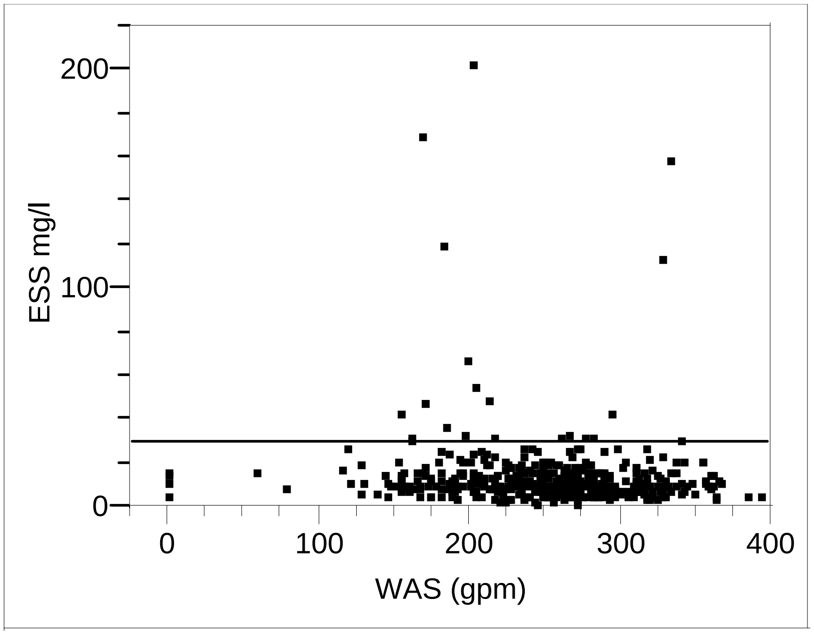

Figure 28: ESS vs. WAS

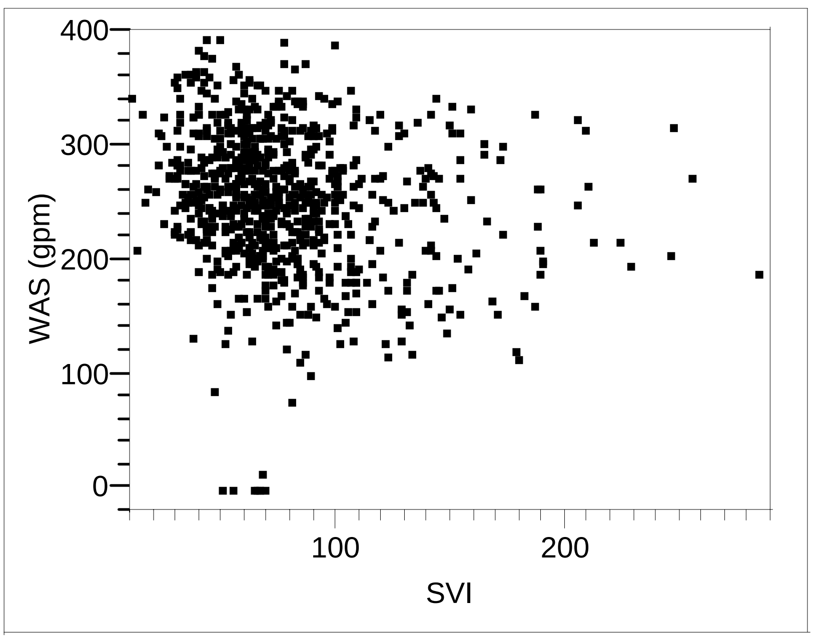

Figure 29: WAS vs. SVI

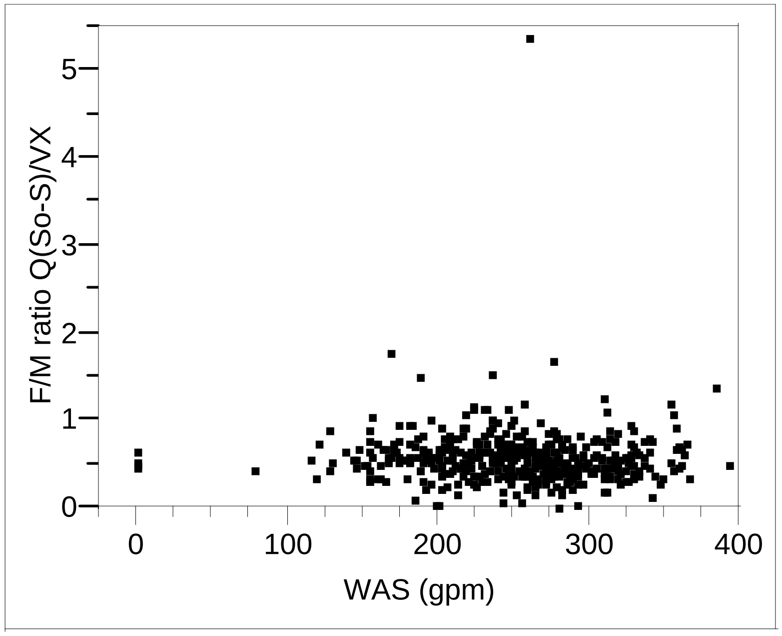

Figure 30: F/M vs. WAS

Food to Microorganism ratio (F/M)

The F/M ratio is a very useful parameter that gives information of control performance in the treatment facility. Figure 31 and Figure 32 are analyzed in this section.

As in other ESS plot, Figure 31 shows that there was no tendency for high ESS values due to changes in F/M ratio. Even more, low ESS values are obtained at very low and very high F/M values. ESS concentrations greater than 30 mg/L can be observed at F/M ratios in the range of 0.2 to 0.6, which are recommended values for plug flow type of facilities. This is shown in Figure 31.

F/M ratio values as a function of SVI are plotted in Figure 32. There is no relation between the two parameters; at least not an evident one. Once again low and high values of F/M ratio reach SVI of over 100, which are considered bad sludge characteristics. Therefore SVI varies widely no matter what F/M ratios are maintained in Kuwahee WWTP, according to the collected data.

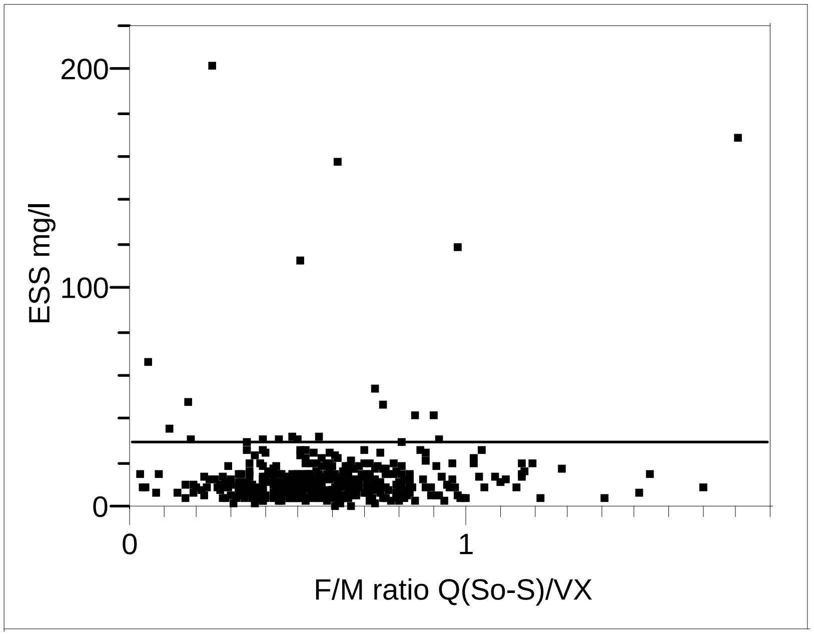

Figure 31: ESS vs. F/M

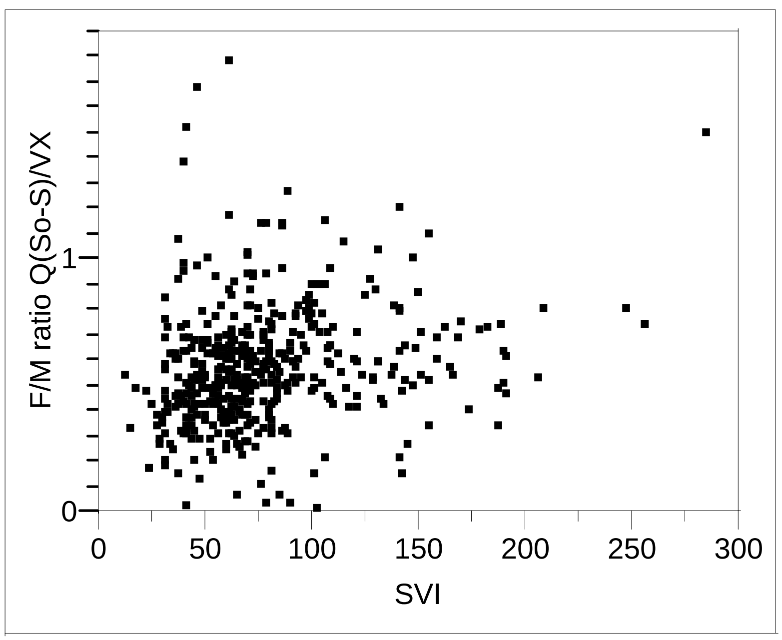

Figure 32: F/M vs. SVI

4.2.2 Hydraulic Parameters

As commented in chapter 3, two hydraulic parameters are analyzed from the existing operational data collected from Kuwahee WWTP: primary effluent flow and rainfall. The following figures show the influence they have, according to collected data, on ESS concentrations, and in the biological parameters that could be a function of poor liquid-solid separation.

Primary Effluent Flow

Flow entering the aeration basin was collected from Kuwahee WWTP. These data show no relationship when compared to high ESS events in Figure 33. High ESS values are present at low flows, as well as in higher flows, leaving no doubt about the lack of a relationship between influent flow to the aeration basin, and plant effluent solids quality, according to data collected. Figure 34 shows no pattern with respect to RAS as well. No matter the amount of incoming flow from primary clarifier, RAS is not varied. The same issue can be observed in Figure 35, no matter the amount of incoming flow

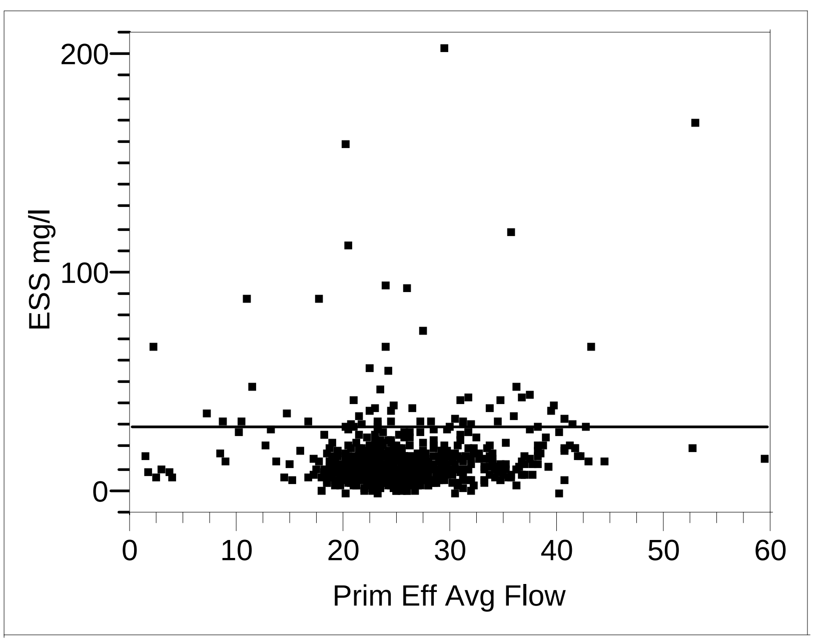

Figure 33: ESS vs. primary effluent average flow

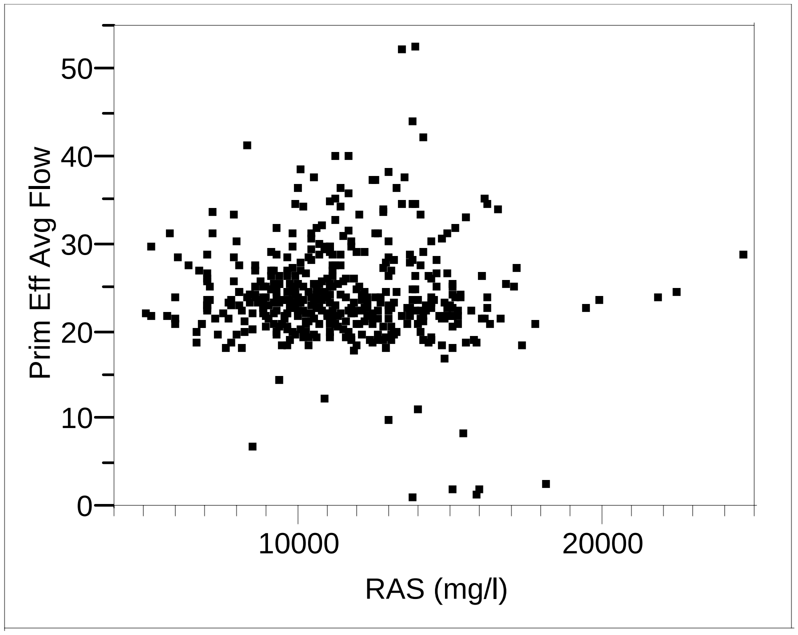

Figure 34: Primary effluent average flow vs. RAS

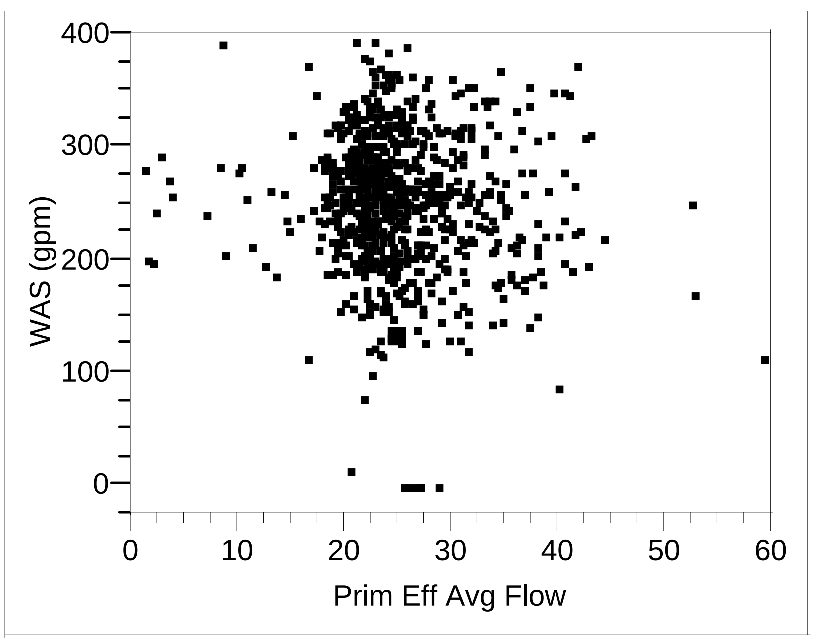

Figure 35: WAS vs. effluent average primary flow

from primary clarifiers, WAS was not varied. This might be explained by the fact that, at a certain flow (close to 70 MGD) a secondary diversion is opened, therefore the secondary treatment does not see flows greater than that, so no RAS or WAS changes are made.

Rainfall

Rainfall is another indicator of hydraulic conditions varying in treatment performance. The precipitation in the plant is measured by a gage and data collected by Kuwahee WWTP personnel. ESS, specific microbial growth rate in the aeration basin and WAS were plotted as a function of precipitation (in inches) in Figure 36, Figure 37 and Figure 38 respectively. From the first graph, Figure 36, it can be seen that rainfall effects did not influence the majority of ESS violations. In Figure 37, one can observe no real change in growth rate when rainfall increased. And finally Figure 38, shows total independence of sludge wasted from rainfall events.

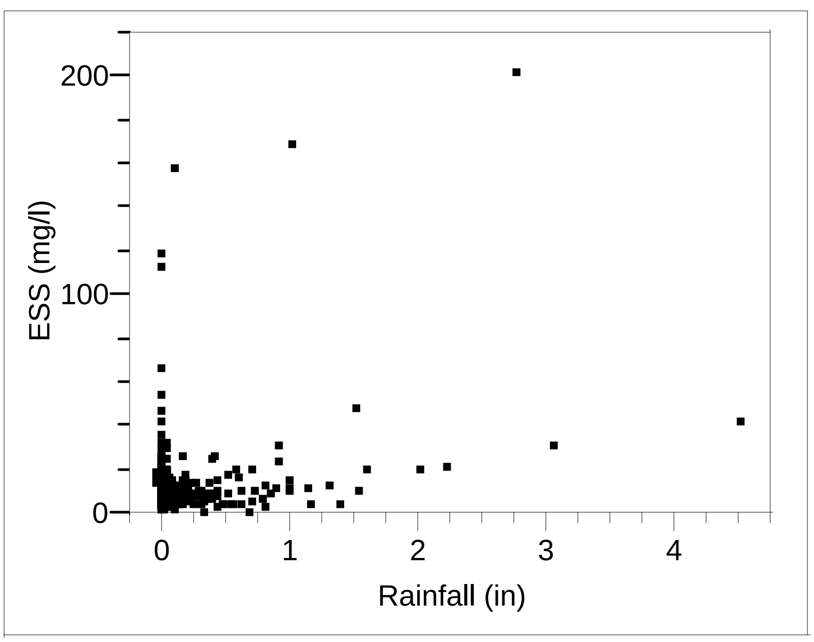

Figure 36: ESS vs. rainfall

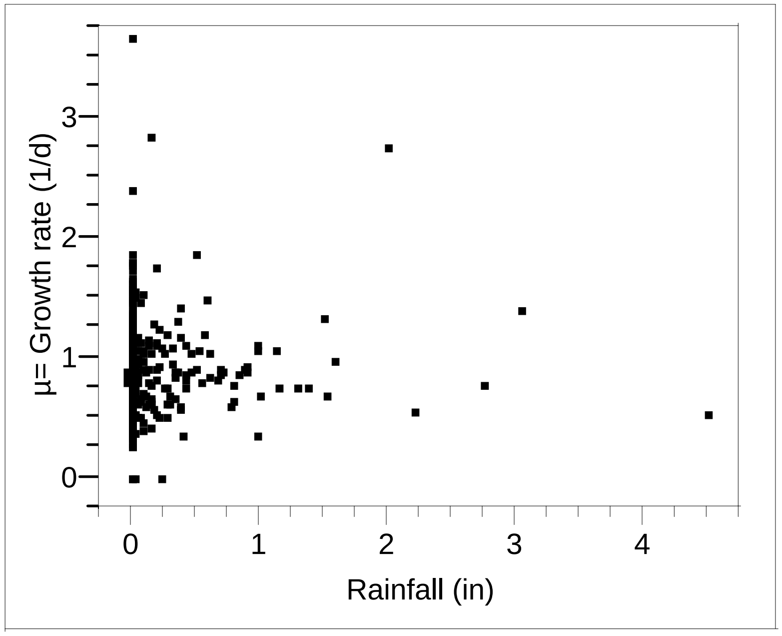

Figure 37: Growth rate vs. rainfall

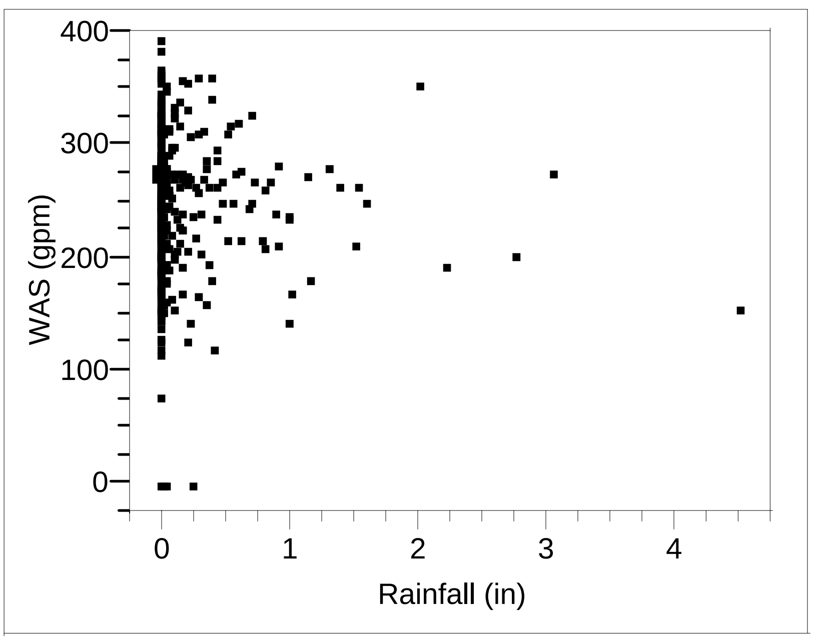

Figure 38: WAS vs. rainfall

4.2.3 Settling Parameters

Two settling parameters were considered in the data collection by Kuwahee WWTP. SVI and settleable solids were regularly sampled from the beginning of year 2001 to the end of year 2002. These two parameters can tell us the real changes on thickening and settling characteristics of the incoming activated sludge that may have occurred and affected ESS concentrations in Kuwahee WWTP.

Sludge Volume Index (SVI)

ESS as a function of SVI is shown in Figure 39. It is observed in this graph that no pattern can be established between parameters. High ESS occurred at optimal SVI (less than 100), as well as at non recommendable SVI values (over 100). Another way to look at it, is that low ESS concentrations where obtain at very low, as well, as at very high SVI values, showing no relationship between the analyzed parameters.

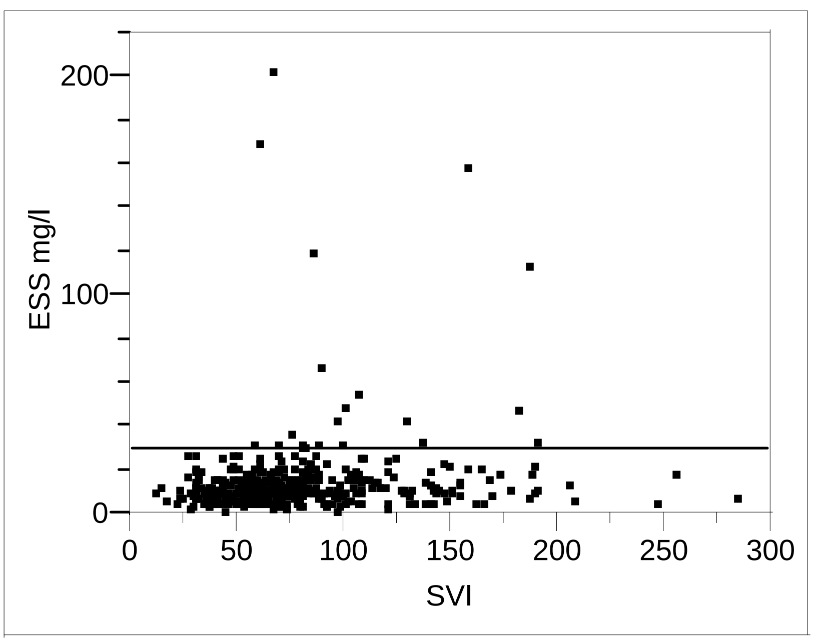

Figure 39: ESS vs. SVI

Settleable Solids

Figures 40 and 41, illustrate the effect of settleability of the activated sludge in the solids content at the final effluent, and the relation that growth rates could have in settling characteristics of the sludge generated.

When looking at the graph of ESS versus settleable solids (see Figure 40), it can be observed that settling characteristics of biomass vary widely, while ESS values were still low. In the same way it can be seen that high ESS concentrations were found either at higher and lower settleable solids values. There is no relationship of settleable solids changes with high ESS events.

Growth rates of microorganisms as a function of settleable solids are graphed in Figure 41. From the graph, bigger variations in growth rate occur when settleable solids have low values, while less of a variation occurs when the values are larger. Both parameters seem to be independent from each other.

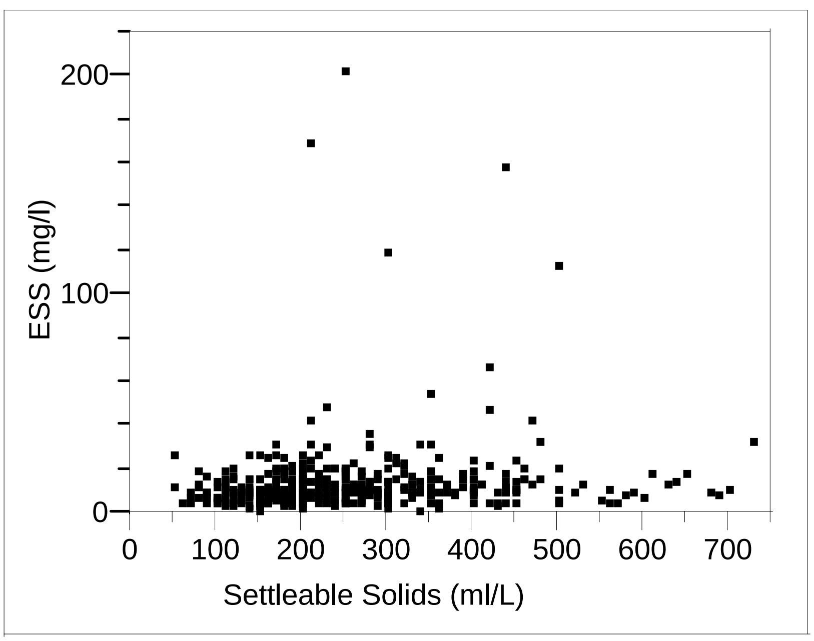

Figure 40: ESS vs. settleable solids

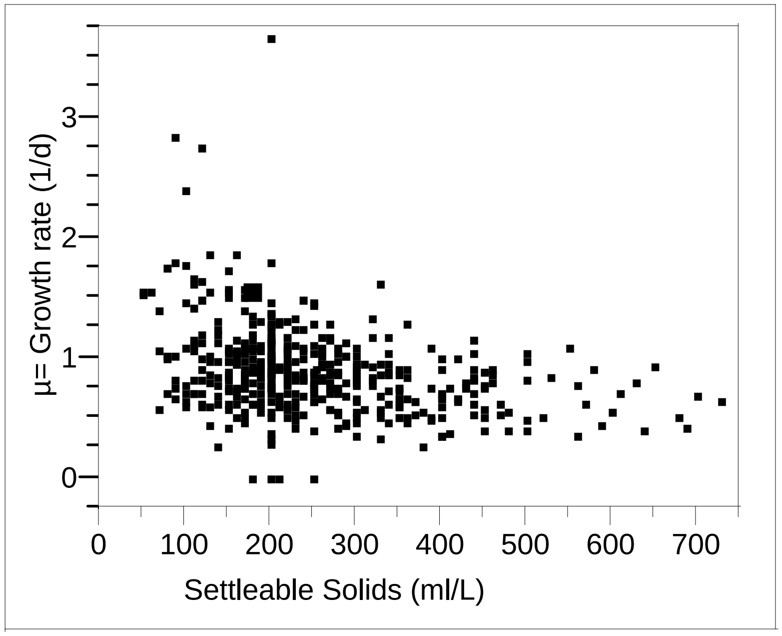

Figure 41: Growth rate vs. settleable solids

4.3 Specific Clarifier Performance Parameters

According to the literature, certain performance parameters in the clarifiers, such as inlet structure, flocculation wells, sludge collection systems, side water depth and sludge blanket levels, are mandatory in the attempt to achieve the optimal functioning of solid-liquid separation and solids thickening in the final settler.

4.3.1 Physical Parameters

From the physical parameters mentioned and described previously, only sludge blanket data are compared with ESS concentration values in this part of the analysis. Inlet structures, flocculation diameters, and sludge collection systems will be addressed later when comparing individual clarifier performance.

Sludge Blanket Height

It is important to recall that individual TSS values at the effluent weir were not taken during this sampling period. Therefore the influence of sludge blankets on the final effluent suspended solids concentration cannot be established accurately. With that in mind the daily sludge blanket height was averaged and compared with final plant ESS concentrations in Figure 42. This figure doesn't show any kind of relation between sludge blanket levels and final effluent quality relative to solid content. Upon a closer look at this graph, it can be observed that lower ESS concentrations can be reached at higher sludge blanket levels. The horizontal line sketched in Figure 42 is set at 30 mg/L as a reference ESS concentration. The vertical line represents sludge blanket heights of 3 feet, which is a good operational blanket level. Greater than that may end up causing gross solids lost at the clarifier effluent weir (Ekama et al., 1997). According to these two reference lines, the only clear thought from the figure is that there is no relationship at all between blanket heights and high ESS values. This is because of the existence of high ESS events at sludge blankets higher than 3 feet, but also during lower blanket levels.

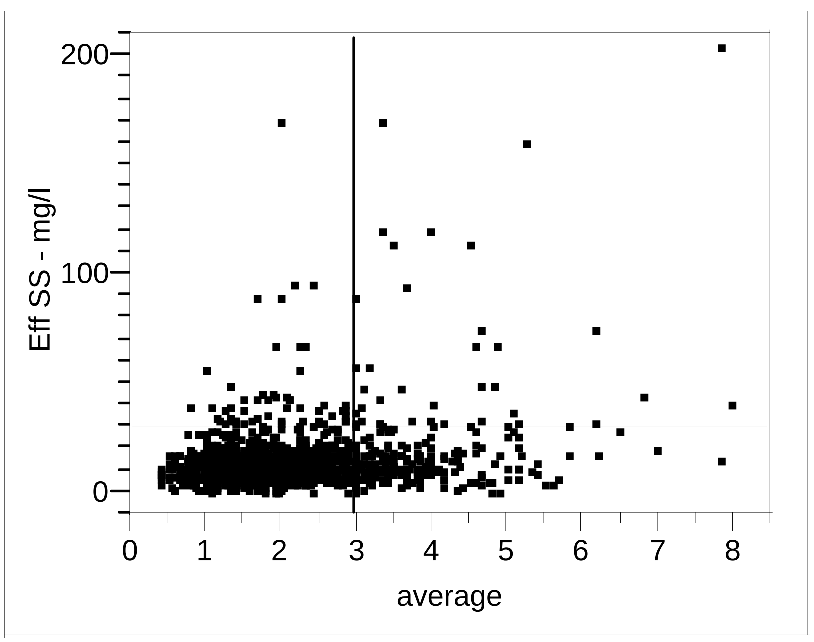

Figure 42: ESS vs. average blanket height

4.3.2 Specific Clarifier Performance Parameters

SOR and SLR were calculated using the values of contributing flows estimated from the measurements of flow levels carried out during sampling. Denitrification was checked by daily observation. All of these parameters correspond to very important performance factors that are frequently used in literature.

4.3.2.1 Surface Overflow Rate (SOR)

As commented in the previous description, SOR has been a very popular parameter in the near past. SOR represents the upward velocity in a clarifier (Wahlberg, 1995b). Theoretically, the settling velocity of floc particles in secondary clarifiers should be greater than SOR. Wahlberg et al. (1994b) and Parker et al. (1995) presented full scale operational data that shows no relationship between ESS and SOR.

Figure 43 shows ESS taken at the clarifier weir effluent as a function of SOR for all of the clarifiers used in Kuwahee WWTP, each clarifier in different color. There is not really a clear pattern between SOR and high ESS concentrations (over 45 mg/L), for clarifiers. For the same clarifier and the same overflow rate, different ESS values can be found. From this graph it is also noticeable the fact that clarifiers #2, #5 and #3 have ESS values over 30 mg/L. These clarifiers have a conventional inlet center well, while clarifiers #1, #4 and #6, don’t have any value over 30 mg/L (clarifiers #4 and #6 have flocculation wells).

The observations in the plot include flow adjustments made after daily flow gate openings were being measured, so that more accurate overflow rates could be calculated. SOR calculated values are available for the reader to see in Appendix B, Table B 7.

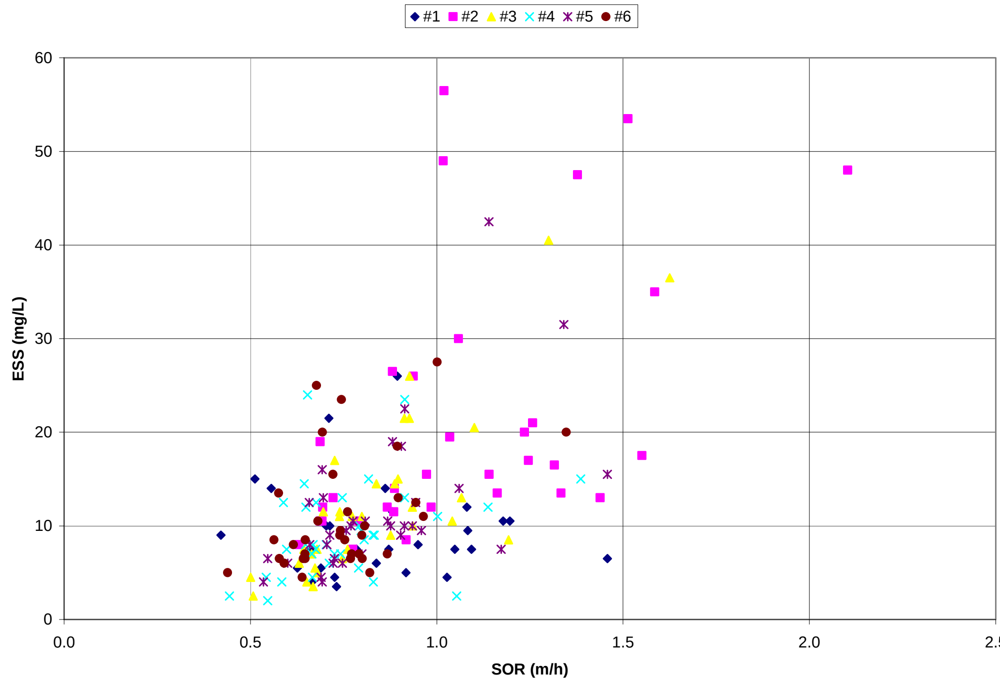

Figure 43: ESS vs. SOR for six circular clarifiers

From statistical analysis made to the mean flows between clarifiers, and knowing that the major factor influencing the overflow rate of a clarifier is the influent flow, a Tukey-Kramer analysis was performed to the calculated SOR data. This method shows in its output (see Analysis A.3, in Appendix A) that there is a statistical significant difference between the mean SOR values applied to clarifier #2 when compared the average SOR applied to the rest of the clarifiers. This finding confirms what was found before, about the different flows applied to each clarifier, where clarifier #2 receives more flow than the rest of the circular settlers. A Hsu's MCB method was applied as well to the SOR data and it showed that the mean SOR value for clarifier #2 is significantly bigger than the mean SOR applied to the rest of the clarifiers (see box plot in Figure 44).

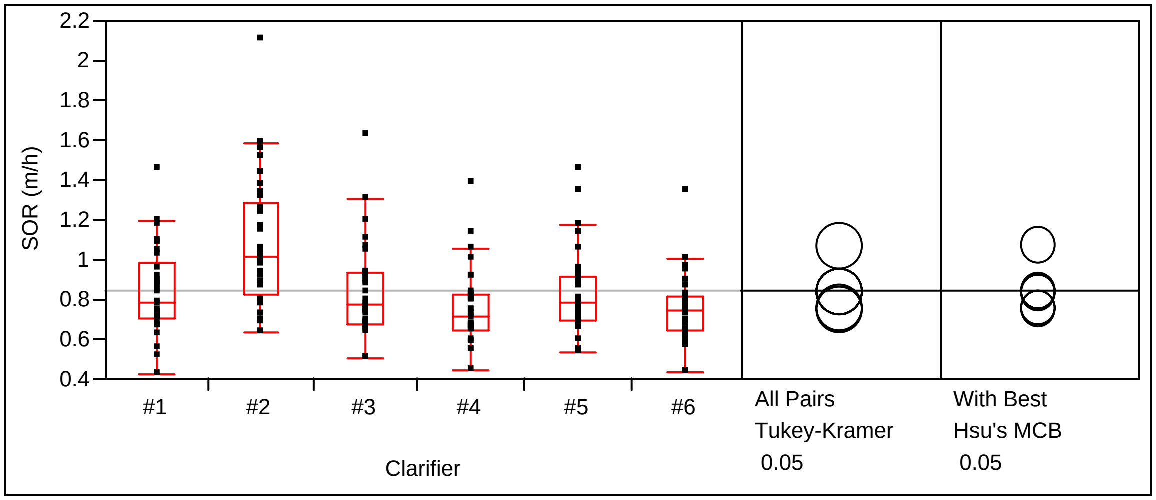

Figure 44: Side by side box plot for SOR comparison between clarifiers

4.3.2.2 Solids Loading Rate (SLR)

It has been suggested that clarifier effluent solid concentration is a function of SLR (Wahlberg et al., 1994b). In Figure 45 is plotted as function of SLR. This graph does not show a clear trend. For example, for SLR of 0.75 to 0.8 (lb/ft^2 h) there are six different ESS values that range from 8.5 to 49 mg/L. Another important observation to be made is that ESS concentrations over 30 mg/L range from SLR of 0.65 lb/ff^2 h (clarifier #2) to 1.79 lb/ft^2 h (clarifier #2). We can finalize the evaluation by saying that no relationship seems to exist between ESS and SLR, for the analyzed sampling period. The SLR data is shown in Table B 8 in Appendix B.

The Tukey-Kramer analyses used for determining differences between clarifiers SLR mean values (see Analysis A.4, in Appendix A), shows that clarifier #2 is significantly different from the rest of the clarifiers. The Hsu's MCB output (see Analysis A.4, in Appendix A) states that the mean SLR of clarifier #2 is significantly greater than the rest of the clarifiers in the secondary treatment unit. The side by side box plot used in the statistical analysis can be seen in Figure 46.

Among the parameters that need to be known to calculate the SLR, RAS is one of the most important. This is because, depending of the sludge returned to the aeration

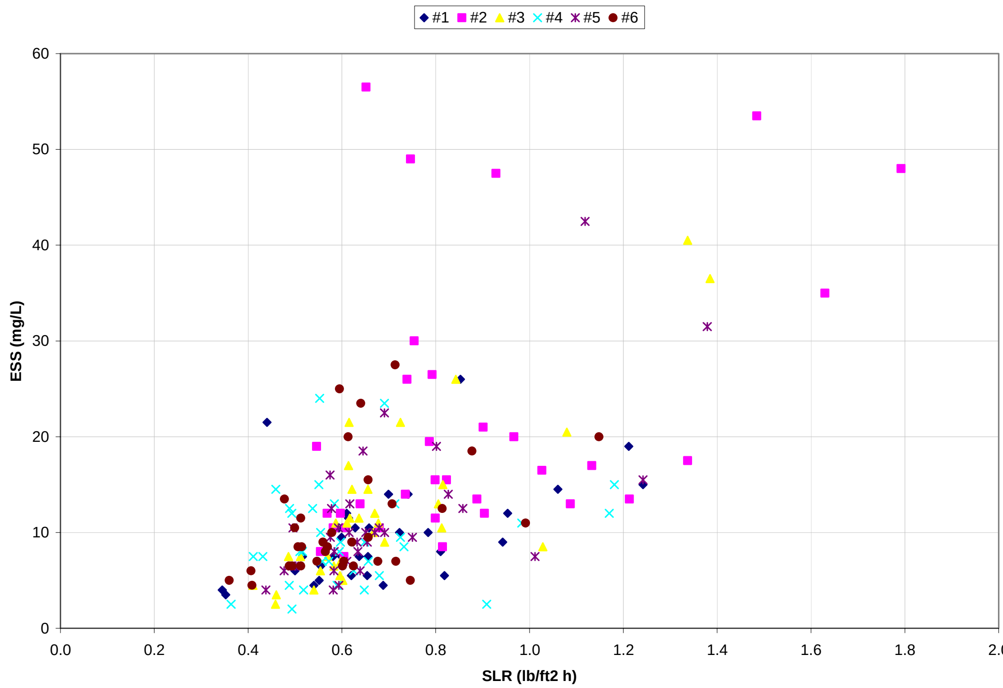

Figure 45: ESS vs. SLR for six clarifiers

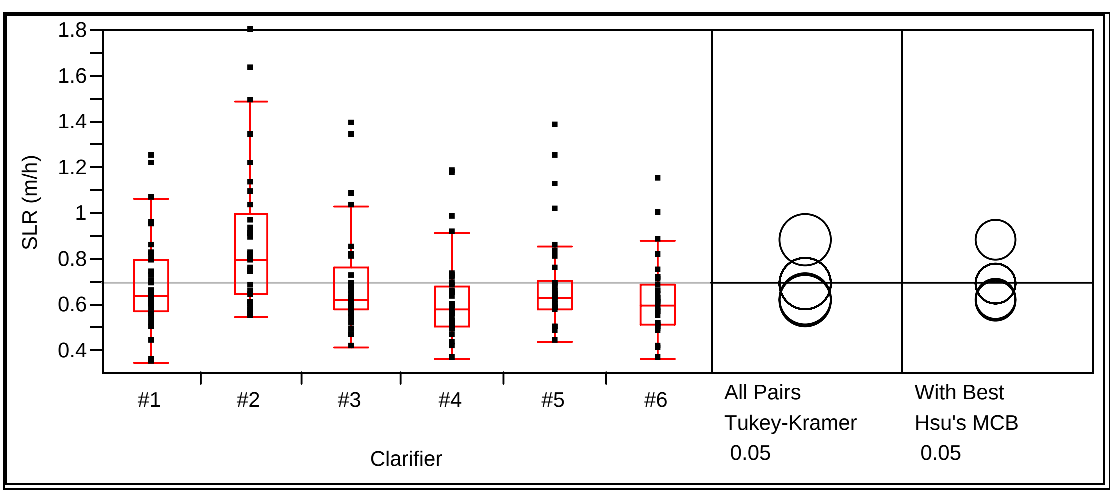

Figure 46: Side by side box plot for SLR comparison between clarifiers

basin, clarifiers will be more or less loaded with solids. Thus, the flows contributing to the SLR of the secondary clarifiers will be the aeration basin influent flow and the flow of activated sludge returned from the bottom of the final clarifiers to the biological reactor. Consequently, it would be very interesting to determine if the final clarifiers in Kuwahee WWTP are evenly contributing RAS to the aeration basin, or if there is any important difference between them.

A Tukey-Kramer analysis was applied to the sample data. The output report (see Analysis A.5 from Appendix A) states that there is a significant statistical difference between mean RAS pumped from three groups of clarifiers: clarifier #6; clarifiers #2 and 3; and clarifiers #1, 4 and 5 (as it can be seen in Figure 47). According to the Hsu's MCB analysis, from JMP 5.0, clarifier #6 has a significantly larger mean RAS value, when compared to the other 5 clarifiers. Furthermore, this analysis also tells us that clarifiers #1, 4 and 5 have significantly smaller mean RAS than the rest of the secondary clarifiers.

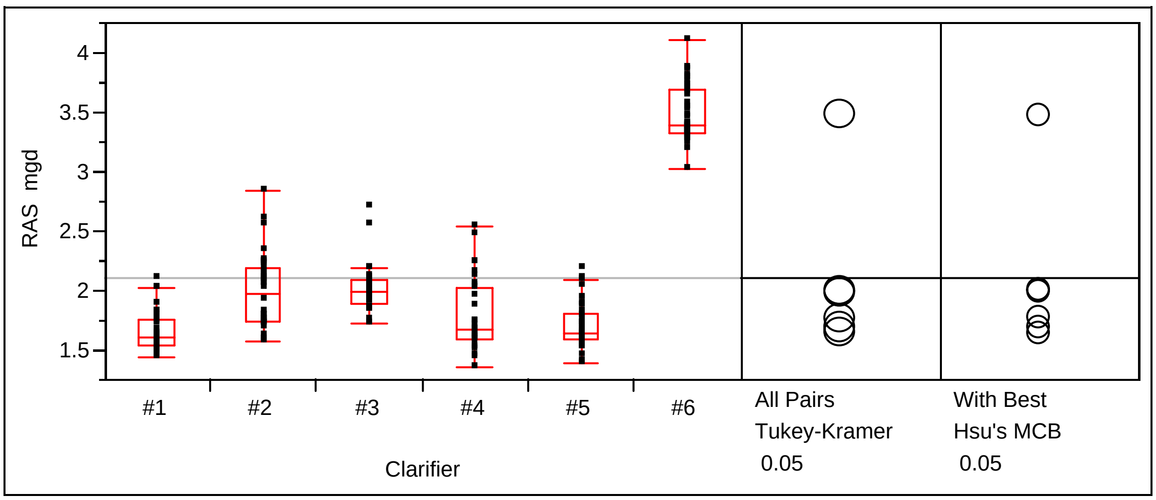

Figure 47: Side by side box plot for RAS comparison between clarifiers

4.3.2.3 Denitrification

No denitrification problems were observed during sampling period in Kuwahee WWTP. No refractile bubbles were observed to rise up to the surface of the clarifier, attached to flocculent rising particles. The observations were made every day during sampling periods, the vast majority of the time during the morning.

4.4 DSS/FSS Testing

The DSS/FSS testing is a very powerful tool, used by consultants, to find out if there is any flocculation or hydraulic problem in final clarifiers. The data analyzed were sampled from January 18th to March 31st of 2004. During this period of time, TSS samples were taken at the effluent weir of each secondary clarifier. DSS samples were taken at three locations, when possible, in each of the secondary clarifiers: at the influent center well, upstream of the center or flocculation well, and upstream of the effluent weir. FSS samples were taken at the influent to the center well. For a period of time FSS samples were taken at the beginning of the distribution channel, very close to the influent gate to clarifier #1 (see Figure 8) in parallel with the FSS sample mentioned before.

Knowing before hand that there were three different clarifier designs within the six secondary clarifiers in Kuwahee WWTP, three clarifiers were chosen for DSS/FSS testing. Clarifiers #1, 2, 3 and 5 were designed with the same characteristics (see Table 6). Clarifier #4 was designed primarily with the same characteristics of the latter group, but it was modified in the past years to obtain a better performance; sludge collection systems were changed from hydraulic suction to spiral scrapers, and the inlet well was replaced for an energy dissipation inlet well and a flocculation well. Clarifier #6 was designed and constructed as a flocculator clarifier. It was clear from the beginning that clarifiers #4 and 6 should be sampled for DSS/FSS, because they are different from the rest, and therefore they were expected to perform in a different way, so the sampling procedure should tell us up to what extent they are performing differently. On the other hand, the rest of the clarifiers were assumed to be performing equally, therefore sampling one of them should give us an idea of the performance of the others, which can be verified by the TSS measurement taken of all clarifiers during the same sampling period. Consequently clarifier #1 was chosen to be sampled for DSS/FSS testing, because of its position in the distribution channel (see Figure 8) in cases of undesired scum loads or high flows events, clarifier #1 should be the first one affected.

The sampling of DSS was performed with 3 Kemmerer samplers. At certain periods of time, during the sampling phase, one or two samplers were disabled and unavailable for sampling collections because of broken parts. In order for these parts to be replaced, new spare parts had to be ordered from the manufacturer, located in Buffalo, NY, which took a considerable amount of time. Because of this, observations in many of the sampling days were not completely taken, because one or two samplers were unavailable for sampling. For the final analysis of DSS/FSS testing, those days that had all of the data observations were taken into account. Therefore, those that had one or more of the DSS samples (influent, center well or effluent) missing were not entered in the statistical analyses. Another important comment is the use of an average value of FSS values from the three clarifiers tested daily. Data obtained during the analysis is presented in Table B 9, Appendix B.

From the data collected and selected for statistical examination two main analyses were carried out: (1) significant difference between clarifiers, using sampling observations, to find performance difference among the sampled clarifiers for comparing DSS, FSS and ESS values; (2) significant difference between test results per clarifier, will help to determine if there is any flocculation or hydraulic problem in the clarifiers.

4.4.1 Significant Difference between Clarifiers

Differences between clarifiers were examined using the Tukey-Kramer Method, for analyzing the statistical difference between clarifiers relative to each of the tests performed at the same locations. If any statistical differences were to be found, a second test was applied, in order to determine among this difference which clarifier was performing better or worst then the others. Table 10 shows a summary of the results found after the analyses mentioned before were carried out. The statistical report from JMP 5.0 for each test between clarifiers can be found in Appendix A, from Analysis A.6 to Analysis A.10.

The only clarifiers significantly different in average are clarifiers 1 and 6 when comparing ESS. These data were analyzed with JMP 5.0 using the Tukey-Kramer Method as a comparison tool. Since clarifiers 1 and 6 were found to be significantly different from each other, the Hsu Method for comparisons with the best was used from JMP 5.0. This analysis shows that Clarifier #6 is the uniquely best clarifier in effluent suspended solids (ESS) performance in comparison with clarifiers #1 and #4. This means that clarifier #6 had a mean ESS value significantly smaller than the other clarifiers tested. However, clarifier #6 may be performing better because of its high RAS rate, that pumps more than half of the influent to the clarifier. At the same time the Hsu Method output shows that clarifier #1 has the larger mean effluent TSS value when compared to clarifier #6. A box plot can be seen in Figure 48 for the comparison of ESS per clarifier. Also in Table 11 output results using the Tukey-Kramer are shown.

4.4.2 Significant Difference between Tests per Clarifier

Clarifier #1

According Table 12, in clarifier #1 DSSi, DSScw and ESS are significantly different on average than FSS. The flocculated suspended solids test (FSS) is significantly smaller on average than disperse suspended solids (DSSi and DSScw) sampled at the inlet and center well or the effluent suspended solids (ESS). However FSS is not significantly different than DSS sampled at the effluent (DSSe). The difference in the average of FSS versus ESS and DSS taken at different clarifier locations are shown in Table 12 (for JMP 5.0 output report see Analysis A.11, in Appendix A)

Table 10: Clarifier significant statistical difference

	Clarifier		
	#1	**#4**	**#6**
FSS	no	no	no
DSSi	no	no	no
DSScw	no	no	no
DSSe	no	no	no
ESS	Yes (6)	no	Yes (1)

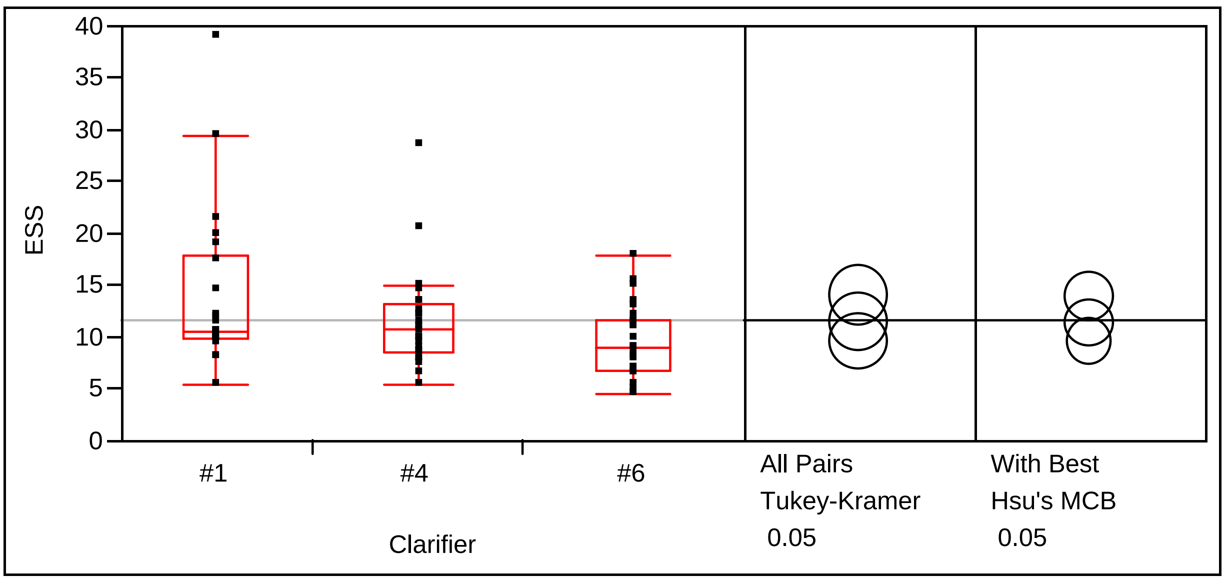

Figure 48: Side by side box plot for significant difference between clarifiers in ESS samples

Table 11: Tukey-Kramer Method for differences of ESS between clarifiers

Level			**Mean**
#1	**A**		14.06087
#4	**A**	**B**	11.541667
#6		**B**	9.7

Levels not connected by same letter are significantly different

Table 12: Tukey-Kramer Method for tests comparison in clarifier #1

Level				Mean
DSScw	A			23.977273
DSSi	A			21.727273
ESS		B		14.045455
DSSe		B	C	13.25
FSS			C	6.681818

Levels not connected by same letter are significantly different

It was expected from the DSS testing that an optimum flocculation was not occurring in the existing center well, because of its small diameter. Yet some flocculation was occurring in the sedimentation tank as the DSSe dropped from the DSSi concentration to a lower one. Therefore clarifier #1 had some hydraulic problems since DSS at the effluent weir was less than the ESS, indicating that floc was being carried over the clarifier effluent weir. This can be observed in the **Figure 49**.

Clarifier #4

In clarifier #4 DSSi and DSScw are significantly different on average than FSS. The flocculated suspended solids test (FSS) is significantly smaller on average than disperse suspended solids (DSSi and DSScw) sampled at the inlet and center well. However FSS is not significantly different than DSS sampled at the effluent (DSSe), and ESS. This suggests that average ESS values are already achieving a good performance with sampling conditions. This was expected since clarifier #4 has a flocculation well. The difference in average of FSS vs. ESS and DSS taken at different clarifier locations are shown in Table 13 (for JMP 5.0 output report see Analysis A.12, in Appendix A).

When comparing ESS values to DSSe they show no significant difference between average values for this clarifier. DSSi and DSScw mean values are greater than ESS, and mean DSSe is not significantly different than mean ESS values. This can be observed in the summary Figure 50.

Even though this clarifier does not show to have any flocculation problem,

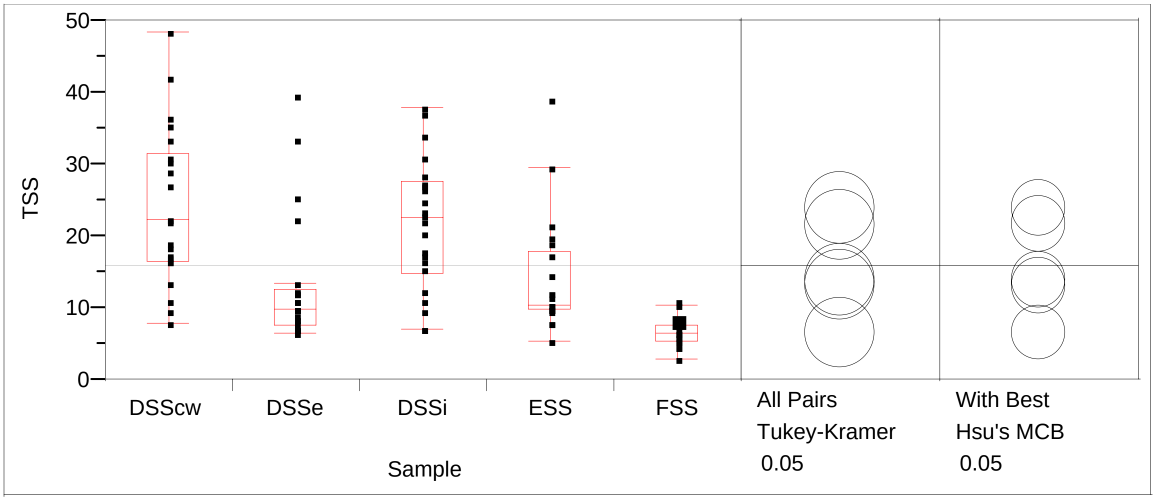

Figure 49: Side by side box plot: summary of tests applied to clarifier #1

Table 13: Tukey-Kramer Method for tests comparison in clarifier #4

Level				Mean
DSScw	**A**			29.458333
DSSi		**B**		20.370833
DSSe			**C**	12.441667
ESS			**C**	11.541667
FSS			**C**	6.3625

Levels not connected by same letter are significantly different

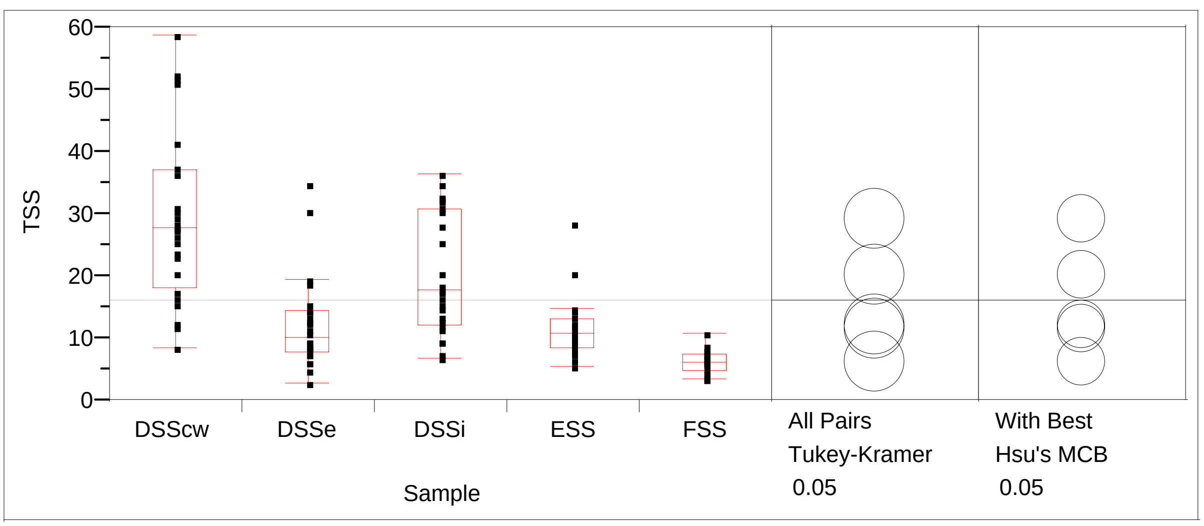

Figure 50: Side by side box plot: summary of tests applied to clarifier #4

Clarifier #6

In clarifier #6 DSSi and DSScw are significantly different on average than FSS. The flocculated suspended solids test (FSS) is significantly smaller on average than disperse suspended solids (DSSi and DSScw) sampled at the inlet and center well. However FSS is not significantly different than DSS sampled at the effluent and ESS. This shows that average ESS values are already achieving a good performance within the sampling conditions. This was expected since clarifier #6, as clarifier #4, has a flocculation well. The difference in average of FSS vs. ESS and DSS taken at different clarifier locations are shown in Table 14 (for JMP 5.0 output report see Analysis A.13, in Appendix A).

When comparing ESS values to DSSe they show no significant difference between average values for this clarifier. DSSi and DSScw means are greater than ESS, and mean DSSe is not significantly different than mean ESS values. This can be observed in Figure 51.

Table 14: Tukey-Kramer Method for tests comparison in clarifier #6

Level			Mean
DSScw	**A**		28.1
DSSi	**A**		20.6
DSSe		**B**	11.54
ESS		**B**	9.7
FSS		**B**	6.9

Levels not connected by same letter are significantly different

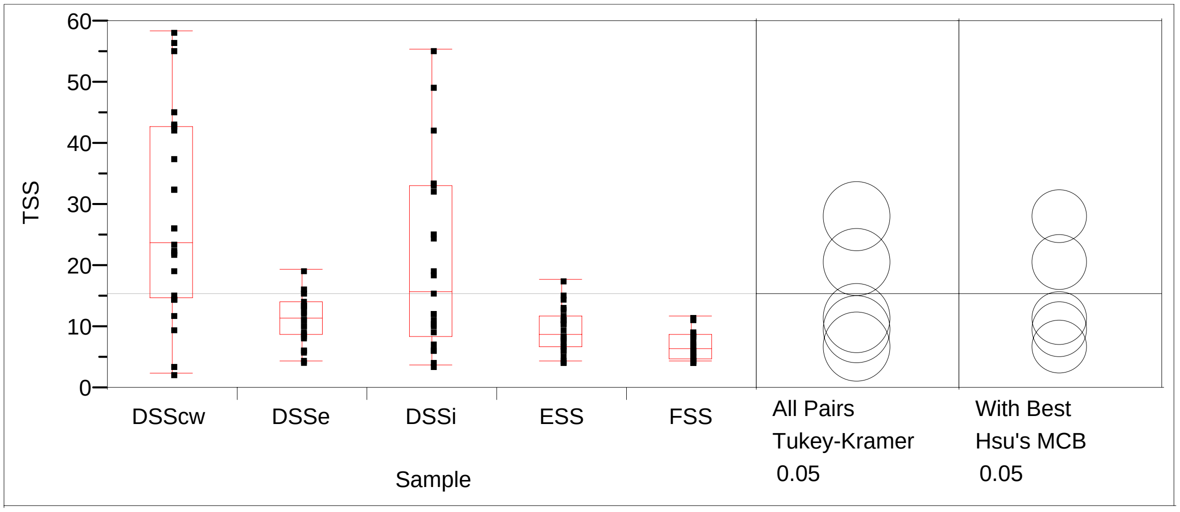

Figure 51: Side by side box plot: summary of tests applied to clarifier #6

Chapter 5: Summary

The operational data collected in the Kuwahee WWTP was grouped into three parameter categories: (1) biological parameters, which includes primary effluent BOD, RAS, MLSS, Specific Growth Rate, WAS and F/M ratio; (2) hydraulic parameters, that included primary effluent flow and rainfall, and (3) settling parameters, which included SVI and settleable solids.

The biological parameters were analyzed using excel and JMP 5.0, for any possible correlation with the overall plant ESS concentrations. None of the biological parameters showed any type of relationship with effluent suspended solids.

In the same way the hydraulic parameters were analyzed for potential correlation to high ESS events. Flow and rainfall were shown to be independent of ESS concentrations. No relationship was found when analyzing the parameters data.

SVI and settleable solids are two parameters that represent the settling characteristics of the wastewater treated in Kuwahee WWTP. All the graphs used to compare the parameters to the ESS concentration at the discharge point, showed no relationship with the solid quality at the overall plant effluent.

Sludge blanket levels observations were also collected as an operational parameter, but the analysis showed that the blanket height did not have any relationship with the ESS concentrations at the effluent discharge point.

In order to complete the data necessary for a deeper analysis of ESS concentrations at the overall discharge point, some extra data was needed to be collected. DSS and FSS were taken at different locations in three of the six clarifiers of the Kuwahee WWTP. In addition, ESS values from the weir overflow of all of the secondary clarifiers was taken as part of the sampling strategy. Either way, every time the secondary diversion was used, because of high flow events, a grab sample was taken by personnel of the facility in the secondary diversion channel. “Unfortunately” for study purposes, there were no violations to the required NPDES limits set for suspended solid discharges during the DSS/FSS testing. Even though no daily maximum, weekly average nor monthly average TSS limits were exceeded, useful information could be gathered from the existing data, so that prevention of future high TSS effluent values can be achieved.

The secondary diversion measurement of TSS values could not been use because of the inconsistencies of the data values. For this reason a TSS simulation was carried out according to the operational criteria used in Kuwahee WWTP. The simulation was generated from existing operational data. From the simulation it is important to recall the suspended solids contribution from the secondary diversion flow when blended with the effluent flow coming from the secondary clarifiers. The secondary clarifiers maintain a regular ESS concentration since when the bypass mode is activated a constant flow is run through the secondary treatment. Nevertheless the TSS value from the secondary diversion is kept constant, same as the primary effluent solids concentration, the increasing flow will make the secondary diversion flow to have an increasing influence on the final TSS value of the blended effluent discharge flow.

It was assumed at the beginning of the study that the effluent flow of the aeration basin was evenly distributed into the six secondary clarifiers. However after a period of time the ESS values from the secondary clarifiers showed important differences between clarifier #2 and the rest of the clarifiers. Recalling that clarifiers #1, 2, 3, and 5 had the same design characteristics; the final effluent was expected to be the same. Therefore the differences with clarifier #2 were analyzed from a flow perspective. That is how the flow height at the gate opening of each secondary clarifier was measured in a regular basis. The proportional flow obtained from the latter observations showed that clarifier #2 was being loaded with a larger amount of flow. Consequently, close to the end of the DSS/FSS sampling period a correction of the gate openings to each clarifier was made, setting the openings in a way that inflow to the clarifiers were distributed evenly.

RAS data was also collected by personnel of the wastewater treatment facility. This data showed that there was a tremendous difference between clarifiers relative to the returned sludge. Clarifier #6 showed to have returned rates that some cases more than doubled the other clarifiers RAS rates.

During the DSS/FSS testing an observational study was carried out as part of the research, with the intention of identify denitrification in the secondary clarifiers. After the sampling period, no denitrification was noticed in any of the settlers.

Using the DSS/FSS testing observations, a new analysis was carried out. A comparison was made between the sampled clarifiers (#1, 4 and 6). The statistical analysis showed that there was a significant difference between the suspended solids concentration coming out of clarifier #1 and clarifier #6. Clarifier #6 came out to be the one with better performance with an average ESS value of 9.7 mg/l. In the other hand, clarifier #1 showed to be the one with the worst performance (about an average of 14 mg/L). It is important to recall that clarifiers #4 and 6 are flocculator clarifiers, while clarifiers #1, 2, 3, and 4 have a conventional inlet well system.

DSSi values showed to have no difference between clarifiers. DSScw showed no significant differences between clarifiers according to the Tukey-Kramer analysis. In the same way DSSe didn't show any significant difference between the sampled clarifiers. FSS values showed to be very similar between clarifiers, with values that were very close to the 6.8 mg/L found by Wahlberg et al. (1994a).

Clarifier #1 had some hydraulic problems as the DSS at the effluent weir was less than the ESS, therefore, indicating that floc was being carried over from the sludge blanket to the effluent weirs.

Chapter 6: Conclusions

6.1 Conclusions

1. Operational parameters currently measured in the Kuwahee WWTP did not provide the sufficient information to determine the source or sources of high suspended solids concentration at the discharge effluent. Therefore new operational data should be collected to assess and solve effluent suspended solids problems in the future, such as TSS in the clarifier effluent and secondary diversion flow.
2. According to the TSS-flow simulation, the secondary diversion TSS concentration has a big impact in the overall plant ESS concentrations during high flow events. It is suggested to take TSS samples of the secondary diversion, secondary clarifiers and plant effluent with in the same period of time, so the values can be compared in future analyses.
3. During the study, the secondary clarifiers were found to be loaded unevenly because of the method used in setting the opening flow gates of each clarifier. This was causing clarifier #2 to perform poorly (SOR and SLR values were significantly higher in clarifier #2). Once the gates were leveled out, so proportional flows were being distributed in to the circular settlers, clarifier #2 started to show a performance similar to the rest of the clarifiers.
4. From those clarifiers chosen for DSS/FSS testing (clarifiers #1, #4 and #6), clarifier #1 has the highest ESS average concentration (and therefore clarifiers #2, 3, and 5), while clarifier #6 has a significantly lower ESS concentration, suggesting that it was performing better than the rest of the tested clarifiers. This might be due to the fact that more than 50% of the clarifier inflow is being returned to the aeration basin, making it difficult to determine if the flocculator well design is showing performance advantages over those clarifiers with conventional center well. The fact that mean DSS sampled at the clarifier inlet

were not significantly different between tested clarifiers shows that in average the state of flocculation of the wastewater flow entering clarifiers #1, 4 and 6 is similar. Therefore, no floc breakup is occurring in the distribution channel.

5. Clarifier #1 showed statistical differences between average DSS sampled upstream of the effluent weir and the average ESS, which indicates that there is a hydraulic problems. And since clarifiers #1, 2, 3, and 5 are identical, it is expected that for them to have the same hydraulic problems. In order to deeply study the problem, hydraulic models and dye tests can be used as a tool to understand and recommend design modifications such as baffles, for example.

6.2 Further Study

When analyzing the operational data, none of the parameters were found to be related to the high ESS events. Because of this, new data was collected. Nevertheless, no violations to the maximum daily TSS concentration occurred from January to March of 2004, and therefore no definitive answer was found. The lack of high suspended solids events could be due to mild weather during the sampling part of the study, and/or because of more careful management of treatment operation during the present year. However, from the existing data possible causes were identified and commented in the conclusions. Consequent to these findings some suggestions and recommended to Kuwahee WWTP as the following step, which will require some further study. They will be mentioned in the following paragraph.

It would be useful to have another operational strategy for high flows. Many actions can be suggested based on the actual plant operation and design, thus more studies can be made to select the optimal solution. Some suggestions are: (1) Treat the excess flows in the secondary aeration system that is not in current use and is of property of Kuwahee WWTP, instead of just running the flow through the secondary diversion. In the present the secondary aeration basin is not being used as design and the flow diverted to it is just being mixed. If treated in the secondary aeration basin, the treated flow can be redirected to the secondary clarifiers. (2) A stress test could be run in the secondary clarifiers in order to find their maximum loading capacity. If the clarifiers are shown to have an acceptable treatment performance at higher flows, some of the excess flow could be diverted from the biological reactor and run through the secondary clarifiers. (3) If more loading capacity is required, the secondary clarifiers can be upgraded by adding a flocculation well to clarifiers #1, 2, 3, and 5; and/or adding incline settlers (incline tubes or plates) to all of the six secondary clarifiers, and/or increasing the flocculator well diameter in clarifiers #4 and 6 up to the range of 32 to 35 % of the clarifier's diameter. . (4) The mix of diluted influent, during high storm events, with more solid concentrated flows (WAS) in order to enhance the flocculation properties of the wastewater, might be another way to increase performance.

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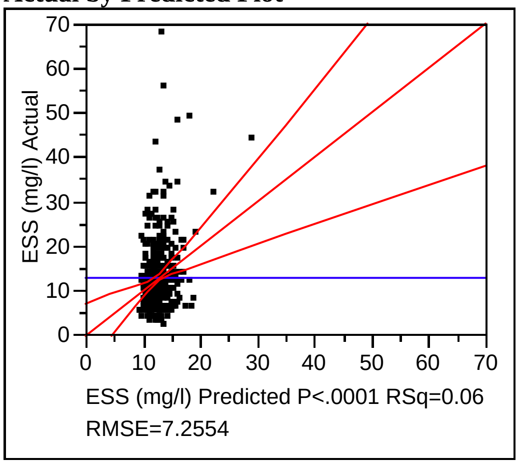
Appendices

Appendix A: Statistical Analyses

Analysis A.1: JMP 5.0 Report for Overall Plant ESS Multivariable Regression

Operational data regression

Response ESS (mg/l)
Whole Model
Actual by Predicted Plot



Summary of Fit

RSquare	0.055348
RSquare Adj	0.048833
Root Mean Square Error	7.255405
Mean of Response	12.74943
Observations (or Sum Wgts)	439

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	1341.648	447.216	8.4956
Error	435	22898.790	52.641	Prob > F
C. Total	438	24240.437		<.0001

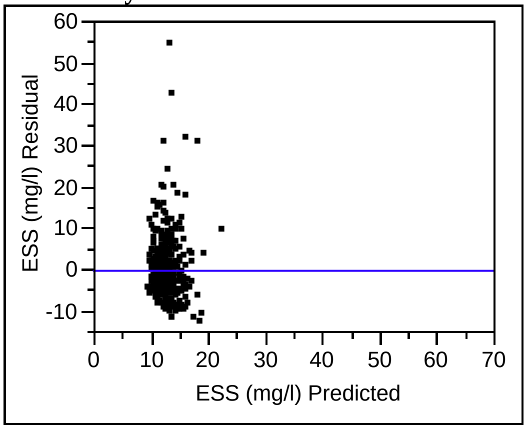
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	13.184405	1.926191	6.84	<.0001	.
WAS (gpm)	-0.011715	0.006153	-1.90	0.0576	1.0975688
SVI	0.0282346	0.009296	3.04	0.0025	1.0983697
Rainfall (in)	3.1677898	1.108833	2.86	0.0045	1.0007741

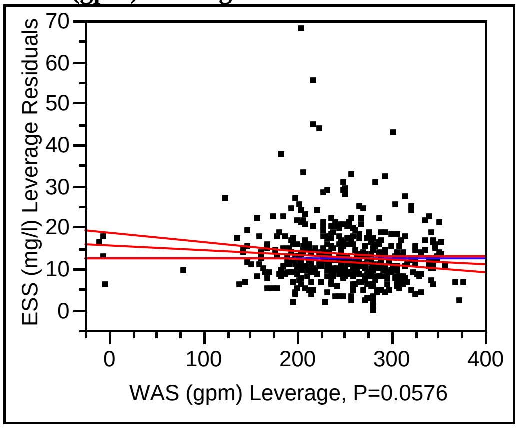
Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
WAS (gpm)	1	1	190.80837	3.6247	0.0576
SVI	1	1	485.57372	9.2243	0.0025
Rainfall (in)	1	1	429.63889	8.1617	0.0045

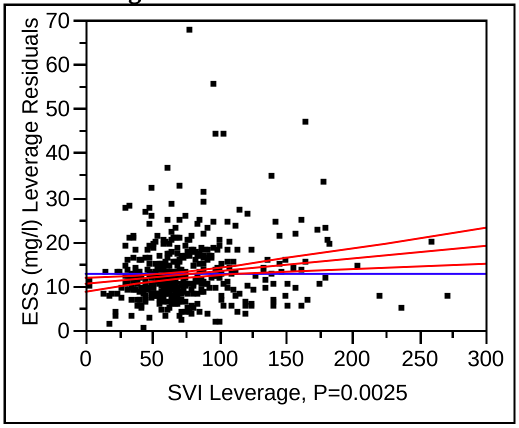
Residual by Predicted Plot



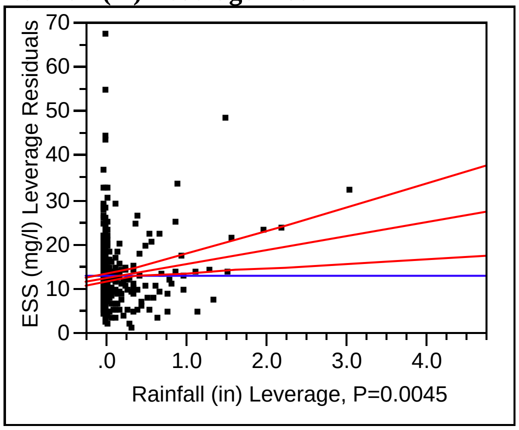
WAS (gpm)Leverage Plot



SVILeverage Plot

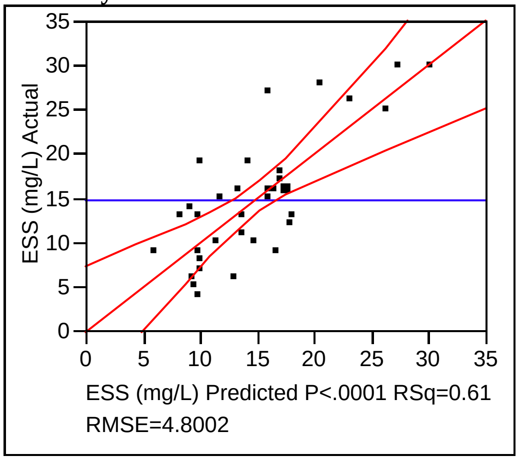


Rainfall (in) Leverage Plot



Sampling data regression

Response ESS (mg/L)
Whole Model
Actual by Predicted Plot



Summary of Fit

RSquare	0.613353
RSquare Adj	0.560023
Root Mean Square Error	4.800245
Mean of Response	14.85294
Observations (or Sum Wgts)	34

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	1060.0365	265.009	11.5010
Error	29	668.2282	23.042	Prob > F
C. Total	33	1728.2647		<.0001

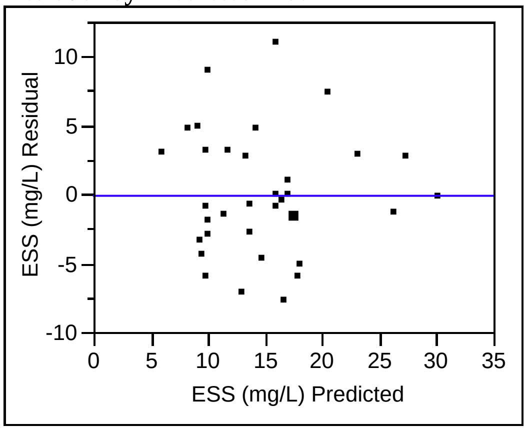
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	-15.42511	4.908357	-3.14	0.0038	.
Influent aver flow (MGD)	0.737583	0.188083	3.92	0.0005	6.0266668
Infl SS (mg/L)	0.0058395	0.003412	1.71	0.0977	1.1059862
Eff Set Solids (ml/L)	79.219024	22.57945	3.51	0.0015	1.047724
Ave SLR	-17.4287	9.805541	-1.78	0.0860	6.1342269

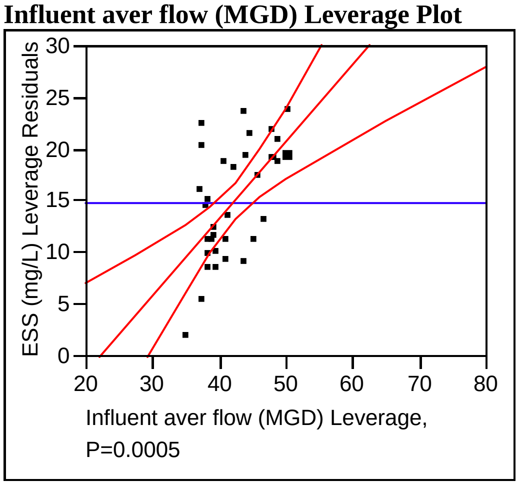
Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Influent aver flow (MGD)	1	1	354.36480	15.3788	0.0005
Infl SS (mg/L)	1	1	67.48090	2.9286	0.0977
Eff Set Solids (ml/L)	1	1	283.63449	12.3093	0.0015
Ave SLR	1	1	72.79706	3.1593	0.0860

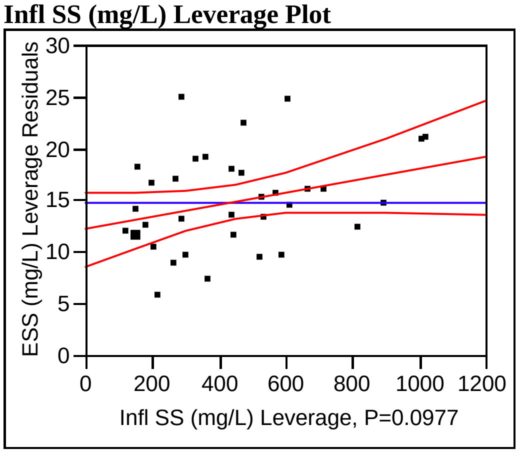
Residual by Predicted Plot



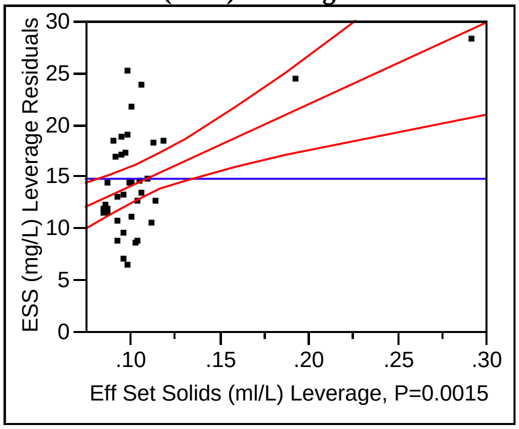
Influent aver flow (MGD) Leverage Plot



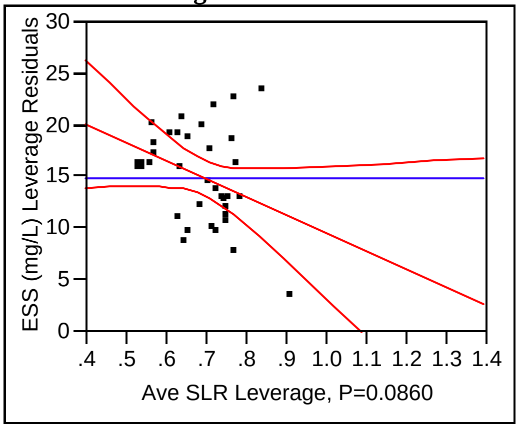
Infl SS (mg/L) Leverage Plot



Eff Set Solids (ml/L) Leverage Plot



Ave SLR Leverage Plot



Analysis A.2: JMP 5.0 Report for Flow Comparison between Clarifiers

Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
#1	3.550448	4.924014	5.919089	6.615419	8.336932	9.648618	12.29083
#2	5.318795	5.812033	6.988289	8.581311	10.84628	12.94771	17.73104
#3	4.222154	5.361713	5.698844	6.513454	7.848151	9.74565	13.70126
#4	3.742364	4.766987	5.469575	6.056748	6.991689	8.666969	11.68637
#5	4.510028	5.301673	5.858891	6.63778	7.748682	9.749741	12.29083
#6	3.701565	4.86271	5.439531	6.26427	6.830814	8.045172	11.35967

Means Comparisons
Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.87827	0.05

Abs(Dif)-LSD	#2	#3	#5	#1	#4	#6
#2	-1.3635	0.5939	0.6091	0.6111	1.2991	1.3508
#3	0.5939	-1.3635	-1.3483	-1.3463	-0.6583	-0.6066
#5	0.6091	-1.3483	-1.3433	-1.3413	-0.6533	-0.6016
#1	0.6111	-1.3463	-1.3413	-1.3635	-0.6755	-0.6239
#4	1.2991	-0.6583	-0.6533	-0.6755	-1.3433	-1.2916
#6	1.3508	-0.6066	-0.6016	-0.6239	-1.2916	-1.3433

Level			Mean
#2	A		9.0448508
#3		B	7.0874519
#5		B	7.0823083
#1		B	7.0702065
#4		B	6.3922825
#6		B	6.3406208

Levels not connected by same letter are significantly different

Comparisons with the best using Hsu's MCB

d	Alpha
2.24739	0.05
2.24739	
2.24739	
2.25044	
2.25044	
2.25044	

Mean[i]-Mean[j]-LSD	#2	#3	#5	#1	#4	#6
#2	-1.0646	0.8928	0.9043	0.9100	1.5944	1.6460
#3	-3.0220	-1.0646	-1.0531	-1.0474	-0.3630	-0.3114
#5	-3.0193	-1.0619	-1.0503	-1.0447	-0.3603	-0.3086
#1	-3.0393	-1.0819	-1.0703	-1.0646	-0.3803	-0.3286
#4	-3.7093	-1.7520	-1.7403	-1.7347	-1.0503	-0.9986
#6	-3.7610	-1.8036	-1.7920	-1.7864	-1.1020	-1.0503

If a column has any positive values, the mean is significantly less than the max.

Mean[i]-Mean[j]+LSD	#2	#3	#5	#1	#4	#6
#2	1.0646	3.0220	3.0208	3.0393	3.7108	3.7624
#3	-0.8928	1.0646	1.0634	1.0819	1.7534	1.8050
#5	-0.9058	1.0516	1.0503	1.0689	1.7403	1.7920
#1	-0.9100	1.0474	1.0461	1.0646	1.7361	1.7878
#4	-1.5958	0.3616	0.3603	0.3789	1.0503	1.1020
#6	-1.6474	0.3099	0.3086	0.3272	0.9986	1.0503

If a column has any negative values, the mean is significantly greater than the min.

Level	vs. Max p-Value	vs. Min p-Value
#2	0.833	8e-8
#3	1e-4	0.183
#5	1e-4	0.183
#1	1e-4	0.196
#4	1e-7	0.799
#6	9e-8	0.865

Analysis A.3: JMP 5.0 Report for SOR Comparison between Clarifiers

Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
#1	0.421112	0.584028	0.702052	0.784643	0.988828	1.144405	1.457793
#2	0.630852	0.689354	0.828868	1.017813	1.286458	1.535704	2.103046
#3	0.500782	0.635943	0.675929	0.772549	0.930855	1.155913	1.625081
#4	0.443875	0.565404	0.648736	0.71838	0.829271	1.027973	1.386098
#5	0.534926	0.628822	0.694912	0.787295	0.919057	1.156399	1.457793
#6	0.439036	0.576757	0.645173	0.742993	0.81019	0.954223	1.34735

Means Comparisons
Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.87827	0.05

Abs(Dif)-LSD	#2	#3	#5	#1	#4	#6
#2	-0.16172	0.07044	0.07224	0.07249	0.15409	0.16021
#3	0.07044	-0.16172	-0.15992	-0.15968	-0.07808	-0.07195
#5	0.07224	-0.15992	-0.15933	-0.15909	-0.07748	-0.07136
#1	0.07249	-0.15968	-0.15909	-0.16172	-0.08012	-0.07399
#4	0.15409	-0.07808	-0.07748	-0.08012	-0.15933	-0.15320
#6	0.16021	-0.07195	-0.07136	-0.07399	-0.15320	-0.15933

Level			Mean
#2	A		1.0727930
#3		B	0.8406295
#5		B	0.8400195
#1		B	0.8385841
#4		B	0.7581768
#6		B	0.7520493

Levels not connected by same letter are significantly different

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Comparisons with the best using Hsu's MCB

d	Alpha
2.24739	0.05
2.24739	
2.24739	
2.25044	
2.25044	
2.25044	

Mean[i]-Mean[j]-LSD	#2	#3	#5	#1	#4	#6
#2	-0.12627	0.10589	0.10726	0.10793	0.18910	0.19523
#3	-0.35844	-0.12627	-0.12490	-0.12423	-0.04306	-0.03693
#5	-0.35812	-0.12595	-0.12457	-0.12391	-0.04273	-0.03660
#1	-0.36048	-0.12832	-0.12695	-0.12627	-0.04511	-0.03898
#4	-0.43996	-0.20780	-0.20642	-0.20575	-0.12457	-0.11845
#6	-0.44609	-0.21392	-0.21254	-0.21188	-0.13070	-0.12457

If a column has any positive values, the mean is significantly less than the max.

Mean[i]-Mean[j]+LSD	#2	#3	#5	#1	#4	#6
#2	0.12627	0.35844	0.35829	0.36048	0.44013	0.44626
#3	-0.10589	0.12627	0.12612	0.12832	0.20797	0.21409
#5	-0.10743	0.12473	0.12457	0.12678	0.20642	0.21254
#1	-0.10793	0.12423	0.12408	0.12627	0.20592	0.21205
#4	-0.18927	0.04289	0.04273	0.04494	0.12457	0.13070
#6	-0.19540	0.03676	0.03660	0.03881	0.11845	0.12457

If a column has any negative values, the mean is significantly greater than the min.

Level	vs. Max p-Value	vs. Min p-Value
#2	0.833	8e-8
#3	1e-4	0.183
#5	1e-4	0.183
#1	1e-4	0.196
#4	1e-7	0.799
#6	9e-8	0.865

Analysis A.4: JMP 5.0 Report for SLR Comparison between Clarifiers

Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
#1	0.345001	0.464239	0.568014	0.63686	0.79712	1.01759	1.242087
#2	0.546116	0.573904	0.645187	0.798942	0.996562	1.425603	1.791864
#3	0.410272	0.470542	0.576401	0.61693	0.765378	1.059243	1.384622
#4	0.36365	0.445214	0.506371	0.578077	0.682466	0.945926	1.181001
#5	0.438245	0.49455	0.580659	0.633269	0.705962	1.064835	1.378711
#6	0.359686	0.44292	0.511061	0.598153	0.684454	0.84555	1.147986

Means Comparisons
Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.87827	0.05

Abs(Dif)-LSD	#2	#3	#5	#1	#4	#6
#2	-0.15768	0.03162	0.03498	0.03420	0.10137	0.10800
#3	0.03162	-0.15768	-0.15431	-0.15509	-0.08793	-0.08130
#5	0.03498	-0.15431	-0.15534	-0.15613	-0.08896	-0.08233
#1	0.03420	-0.15509	-0.15613	-0.15768	-0.09052	-0.08389
#4	0.10137	-0.08793	-0.08896	-0.09052	-0.15534	-0.14871
#6	0.10800	-0.08130	-0.08233	-0.08389	-0.14871	-0.15534

Level			Mean
#2	A		0.88213882
#3		B	0.69284278
#5		B	0.69064055
#1		B	0.69025544
#4		B	0.62425648
#6		B	0.61762580

Levels not connected by same letter are significantly different

Comparisons with the best using Hsu's MCB

d	Alpha
2.24739	0.05
2.24739	
2.24739	
2.25044	
2.25044	
2.25044	

Mean[i]-Mean[j]-LSD	#2	#3	#5	#1	#4	#6
#2	-0.12312	0.06618	0.06912	0.06876	0.13551	0.14214
#3	-0.31241	-0.12312	-0.12017	-0.12053	-0.05379	-0.04716
#5	-0.31371	-0.12441	-0.12146	-0.12182	-0.05508	-0.04844
#1	-0.31500	-0.12571	-0.12276	-0.12312	-0.05638	-0.04975
#4	-0.38009	-0.19080	-0.18784	-0.18821	-0.12146	-0.11483
#6	-0.38672	-0.19743	-0.19447	-0.19484	-0.12809	-0.12146

If a column has any positive values, the mean is significantly less than the max.

Mean[i]-Mean[j]+LSD	#2	#3	#5	#1	#4	#6
#2	0.12312	0.31241	0.31387	0.31500	0.38026	0.38689
#3	-0.06618	0.12312	0.12458	0.12571	0.19096	0.19759
#5	-0.06929	0.12001	0.12146	0.12259	0.18784	0.19447
#1	-0.06876	0.12053	0.12199	0.12312	0.18838	0.19501
#4	-0.13567	0.05362	0.05508	0.05621	0.12146	0.12809
#6	-0.14230	0.04699	0.04844	0.04958	0.11483	0.12146

If a column has any negative values, the mean is significantly greater than the min.

Level	vs. Max p-Value	vs. Min p-Value
#2	0.833	6e-6
#3	0.002	0.252
#5	0.001	0.264
#1	0.001	0.272
#4	1e-5	0.795
#6	6e-6	0.868

Analysis A.5: JMP 5.0 Report for RAS Comparison between Clarifiers

Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
#1	1.4375	1.4975	1.547938	1.61125	1.7535	1.961	2.115
#2	1.58125	1.6535	1.74	1.96875	2.194313	2.4445	2.8455
#3	1.725	1.79625	1.894	1.99	2.087438	2.197903	2.71
#4	1.355	1.450875	1.585563	1.6765	2.028188	2.244	2.5415
#5	1.386	1.489375	1.596875	1.6345	1.80225	2.068625	2.19
#6	3.024	3.259375	3.332687	3.3975	3.688167	3.832625	4.11125

Means Comparisons
Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.87784	0.05

Abs(Dif)-LSD	#6	#3	#2	#4	#5	#1
#6	-0.1690	1.3046	1.3235	1.5405	1.6157	1.6608
#3	1.3046	-0.1690	-0.1501	0.0670	0.1421	0.1872
#2	1.3235	-0.1501	-0.1690	0.0481	0.1232	0.1684
#4	1.5405	0.0670	0.0481	-0.1690	-0.0939	-0.0487
#5	1.6157	0.1421	0.1232	-0.0939	-0.1690	-0.1239
#1	1.6608	0.1872	0.1684	-0.0487	-0.1239	-0.1690

Level				Mean
#6	A			3.4862982
#3		B		2.0127075
#2		B		1.9938317
#4			C	1.7767402
#5			C	1.7016111
#1			C	1.6564485

Levels not connected by same letter are significantly different

Comparisons with the best using Hsu's MCB

d	Alpha
2.24869	0.05
2.24869	
2.24869	
2.24869	
2.24869	
2.24869	

Mean[i]-Mean[j]-LSD	#6	#3	#2	#4	#5	#1
#6	-0.1321	1.3415	1.3604	1.5775	1.6526	1.6978
#3	-1.6057	-0.1321	-0.1132	0.1039	0.1790	0.2242
#2	-1.6245	-0.1509	-0.1321	0.0850	0.1602	0.2053
#4	-1.8416	-0.3680	-0.3492	-0.1321	-0.0569	-0.0118
#5	-1.9168	-0.4432	-0.4243	-0.2072	-0.1321	-0.0869
#1	-1.9619	-0.4883	-0.4694	-0.2524	-0.1772	-0.1321

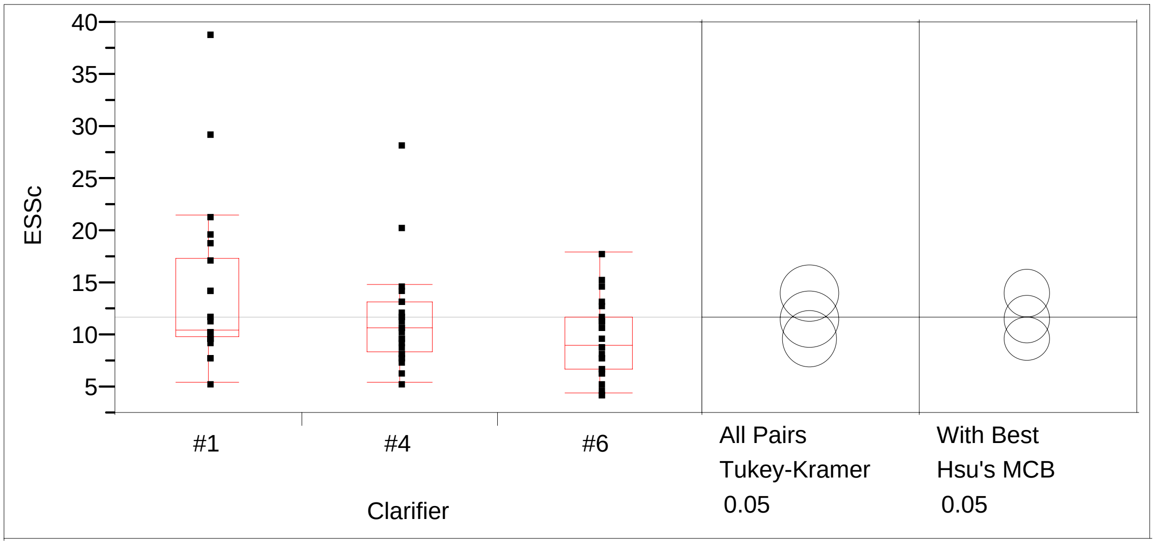
If a column has any positive values, the mean is significantly less than the max.

Mean[i]-Mean[j]+LSD	#6	#3	#2	#4	#5	#1
#6	0.1321	1.6057	1.6245	1.8416	1.9168	1.9619
#3	-1.3415	0.1321	0.1509	0.3680	0.4432	0.4883
#2	-1.3604	0.1132	0.1321	0.3492	0.4243	0.4694
#4	-1.5775	-0.1039	-0.0850	0.1321	0.2072	0.2524
#5	-1.6526	-0.1790	-0.1602	0.0569	0.1321	0.1772
#1	-1.6978	-0.2242	-0.2053	0.0118	0.0869	0.1321

If a column has any negative values, the mean is significantly greater than the min.

Level	vs. Max p-Value	vs. Min p-Value
#6	0.833	0
#3	0	1e-8
#2	0	8e-8
#4	0	0.078
#5	0	0.522
#1	0	0.971

Analysis A.6: JMP 5.0 Report of Significant Difference between Clarifiers for TSS Analysis for each clarifier effluent (ESS)



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
#1	5.5	8	10	10.5	17.5	26.3	39
#4	5.5	7	8.5	10.75	13.25	17.75	28.5
#6	4.5	4.8	6.75	9	11.75	15.2	18

Means Comparisons

Dif=Mean[i]-Mean[j]	#1	#4	#6
#1	0.0000	2.5192	4.3609
#4	-2.5192	0.0000	1.8417
#6	-4.3609	-1.8417	0.0000

Alpha=0.05

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.39532	0.05

Abs(Dif)-LSD	#1	#4	#6
#1	-3.9323	-1.3719	0.5080
#4	-1.3719	-3.8495	-1.9692
#6	0.5080	-1.9692	-3.7717

Positive values show pairs of means that are significantly different.

Level			Mean
#1	A		14.060870
#4	A	B	11.541667
#6		B	9.700000

Levels not connected by same letter are significantly different

Comparisons with the best using Hsu's MCB

d	Alpha
1.94488	0.05
1.94737	
1.94963	

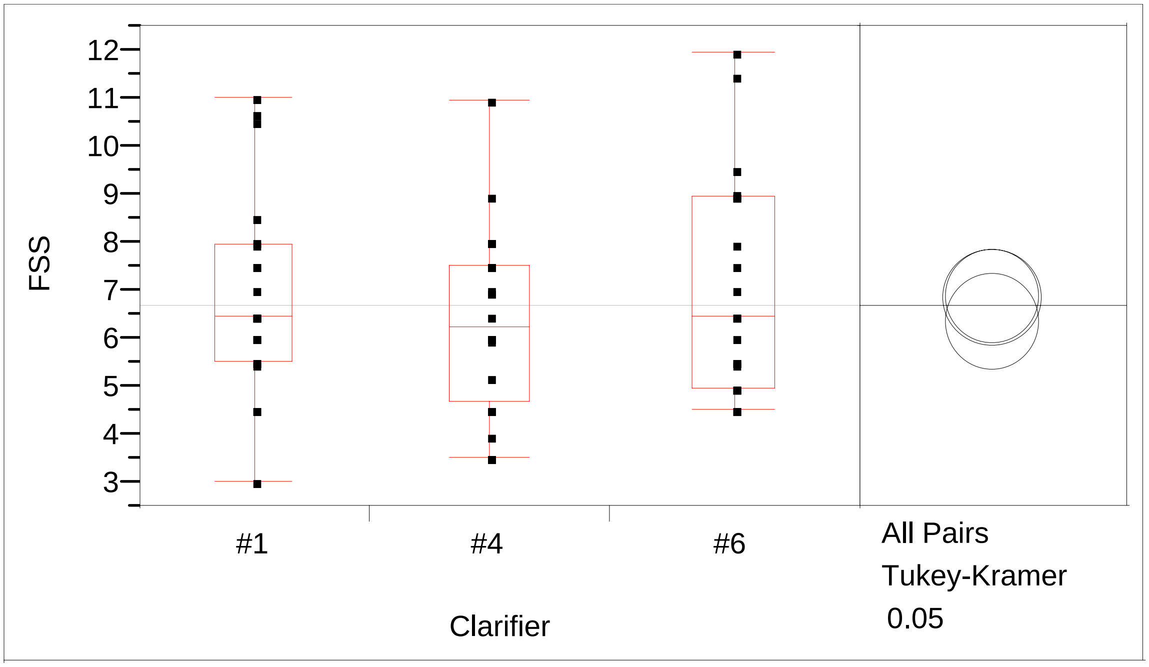
Mean[i]-Mean[j]-LSD	#1	#4	#6
#1	-3.1928	-0.6442	1.2249
#4	-5.6786	-3.1296	-1.2601
#6	-7.4892	-4.9398	-3.0699

If a column has any positive values, the mean is significantly less than the max.

Mean[i]-Mean[j]+LSD	#1	#4	#6
#1	3.1928	5.6827	7.4968
#4	0.6402	3.1296	4.9434
#6	-1.2325	1.2565	3.0699

If a column has any negative values, the mean is significantly greater than the min.

Analysis A.7: JMP 5.0 Report of Significant Difference between Clarifiers for FSS Analysis for each clarifier



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
#1	3	4.5	5.5	6.5	8	10.6	11
#4	3.5	3.5	4.675	6.25	7.5	8.5	11
#6	4.5	4.5	5	6.5	9	10.3	12

Means Comparisons

Dif=Mean[i]-Mean[j]	#6	#1	#4
#6	0.00000	0.04493	0.53750
#1	-0.04493	0.00000	0.49257
#4	-0.53750	-0.49257	0.00000

Alpha=0.05

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.39532	0.05

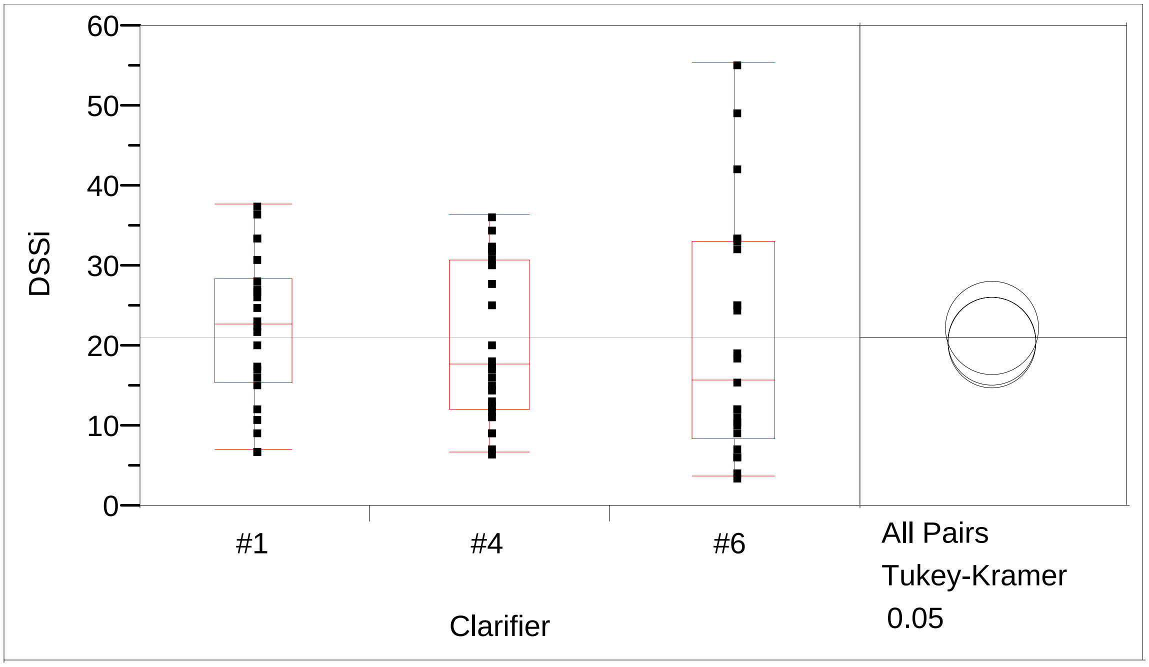
Abs(Dif)-LSD	#6	#1	#4
#6	-1.3653	-1.3497	-0.8419
#1	-1.3497	-1.4234	-0.9159
#4	-0.8419	-0.9159	-1.3934

Positive values show pairs of means that are significantly different.

Level		Mean
#6	A	6.9000000
#1	A	6.8550725
#4	A	6.3625000

Levels not connected by same letter are significantly different

Analysis A.8: JMP 5.0 Report of Significant Difference between Clarifiers for DSS Analysis for each Clarifier at the Influent of the Center Well (DSSi)



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
#1	7	8	15.5	23	28.5	35.8	38
#4	7	8.5	12.25	17.75	30.875	34	36.5
#6	4	5.7	8.5	16	33	45.3	55.5

Means Comparisons

Dif=Mean[i]-Mean[j]	#1	#6	#4
#1	0.0000	1.6609	1.8900
#6	-1.6609	0.0000	0.2292
#4	-1.8900	-0.2292	0.0000

Alpha=0.05

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.39532	0.05

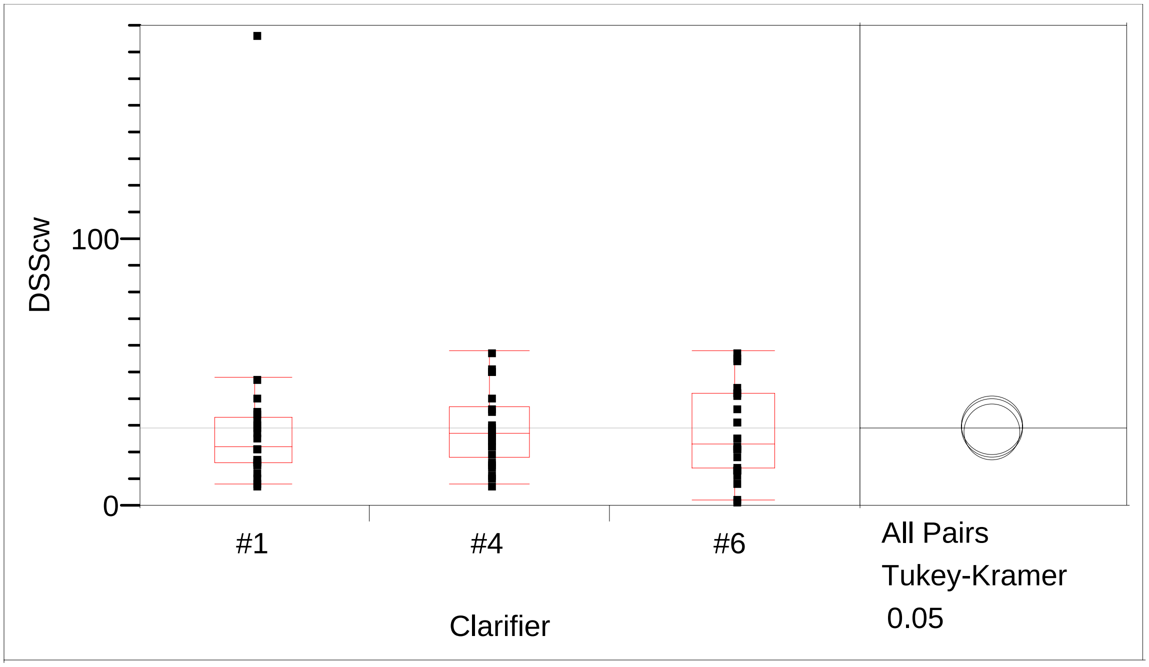
Abs(Dif)-LSD	#1	#6	#4
#1	-8.1398	-6.3145	-6.1645
#6	-6.3145	-7.8074	-7.6591
#4	-6.1645	-7.6591	-7.9684

Positive values show pairs of means that are significantly different.

Level		Mean
#1	A	22.260870
#6	A	20.600000
#4	A	20.370833

Levels not connected by same letter are significantly different

Analysis A.9: JMP 5.0 Report of Significant Difference between Clarifiers for DSS Analysis for each Clarifier at the upstream of the Center Well (DSScw)



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
#1	8	10.1	16.5	22.5	33.5	45.9	177.3333
#4	8.5	12.25	18.25	27.75	37.25	52.25	59
#6	2.5	7.6	15	24	42.75	56.1	58.5

Means Comparisons

Dif=Mean[i]-Mean[j]	#1	#4	#6
#1	0.0000	1.1866	2.5449
#4	-1.1866	0.0000	1.3583
#6	-2.5449	-1.3583	0.0000

Alpha=0.05

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.39532	0.05

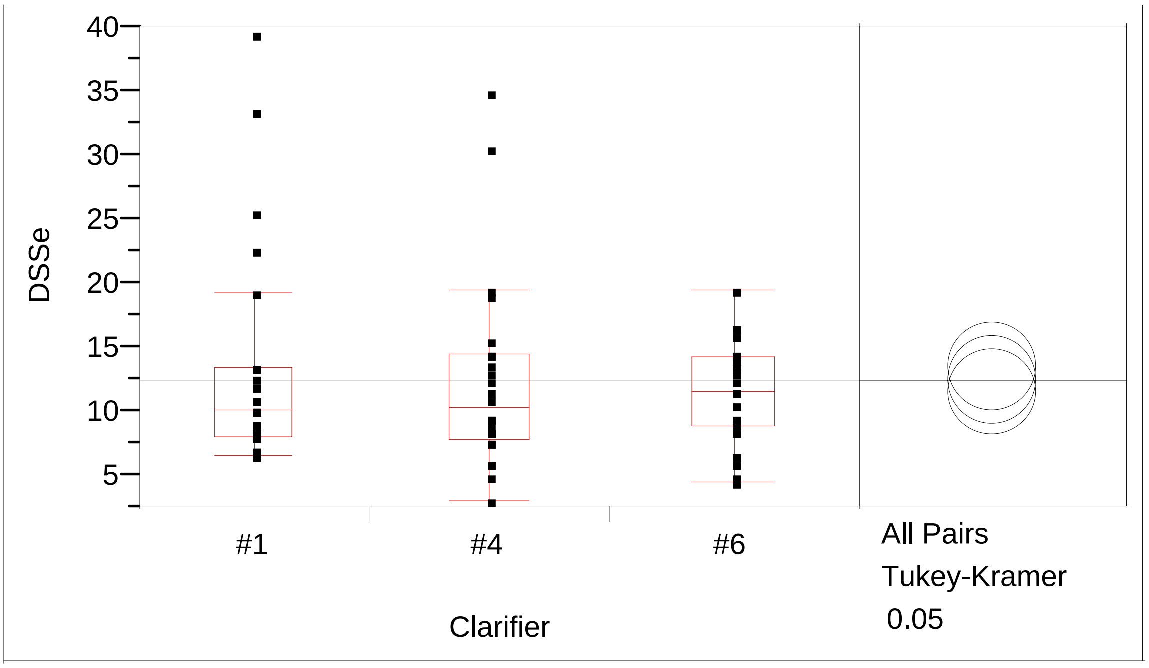
Abs(Dif)-LSD	#1	#4	#6
#1	-16.046	-14.691	-13.177
#4	-14.691	-15.708	-14.192
#6	-13.177	-14.192	-15.391

Positive values show pairs of means that are significantly different.

Level		Mean
#1	A	30.644928
#4	A	29.458333
#6	A	28.100000

Levels not connected by same letter are significantly different

Analysis A.10: JMP 5.0 Report of Significant Difference between Clarifiers for DSS Analysis for each Clarifier at the upstream of the Effluent Weir (DSSe)



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
#1	6.5	7	8	10	13.5	30.3	39.5
#4	3	5.5	7.75	10.25	14.5	25	35
#6	4.5	5.6	8.75	11.5	14.25	16.5	19.5

Means Comparisons

Dif=Mean[i]-Mean[j]	#1	#4	#6
#1	0.0000	1.0728	1.9745
#4	-1.0728	0.0000	0.9017
#6	-1.9745	-0.9017	0.0000

Alpha=0.05

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.39532	0.05

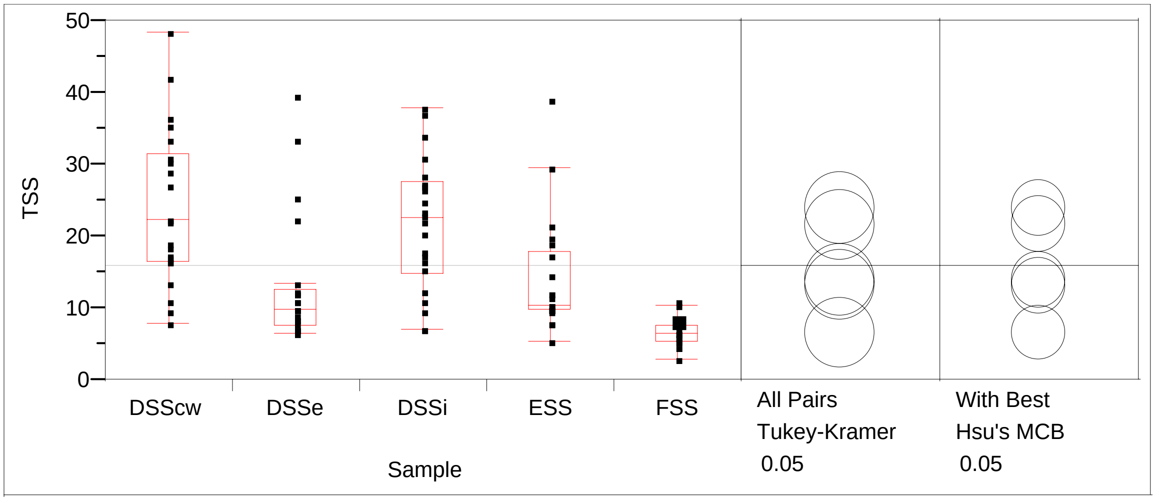
Abs(Dif)-LSD	#1	#4	#6
#1	-4.9576	-3.8329	-2.8830
#4	-3.8329	-4.8532	-3.9028
#6	-2.8830	-3.9028	-4.7552

Positive values show pairs of means that are significantly different.

Level		Mean
#1	A	13.514493
#4	A	12.441667
#6	A	11.540000

Levels not connected by same letter are significantly different

Analysis A.11: JMP 5.0 Report of Significant Difference between Tests Applied to Clarifier #1



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
DSScw	8	9.95	16.5	22.25	31.625	40.35	48.5
DSSe	6.5	7	7.75	10	12.75	31.1	39.5
DSSi	7	7.75	14.75	22.5	27.75	36.1	38
ESS	5.5	8	10	10.5	17.875	27.1	39
FSS	3	4.5	5.5	6.5	7.625	9.9	11

Means Comparisons

Dif=Mean[i]-Mean[j]	DSScw	DSSi	ESS	DSSe	FSS
DSScw	0.000	2.250	9.932	10.727	17.295
DSSi	-2.250	0.000	7.682	8.477	15.045
ESS	-9.932	-7.682	0.000	0.795	7.364
DSSe	-10.727	-8.477	-0.795	0.000	6.568
FSS	-17.295	-15.045	-7.364	-6.568	0.000

Alpha=0.05

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.77575	0.05

Abs(Dif)-LSD	DSScw	DSSi	ESS	DSSe	FSS
DSScw	-6.948	-4.698	2.983	3.779	10.347
DSSi	-4.698	-6.948	0.733	1.529	8.097
ESS	2.983	0.733	-6.948	-6.153	0.415
DSSe	3.779	1.529	-6.153	-6.948	-0.380
FSS	10.347	8.097	0.415	-0.380	-6.948

Positive values show pairs of means that are significantly different.

Level				Mean
DSScw	A			23.977273
DSSi	A			21.727273
ESS		B		14.045455
DSSe		B	C	13.250000
FSS			C	6.681818

Levels not connected by same letter are significantly different

Comparisons with the best using Hsu's MCB

d	Alpha
2.18656	0.05
2.18656	
2.18656	
2.18656	
2.18656	

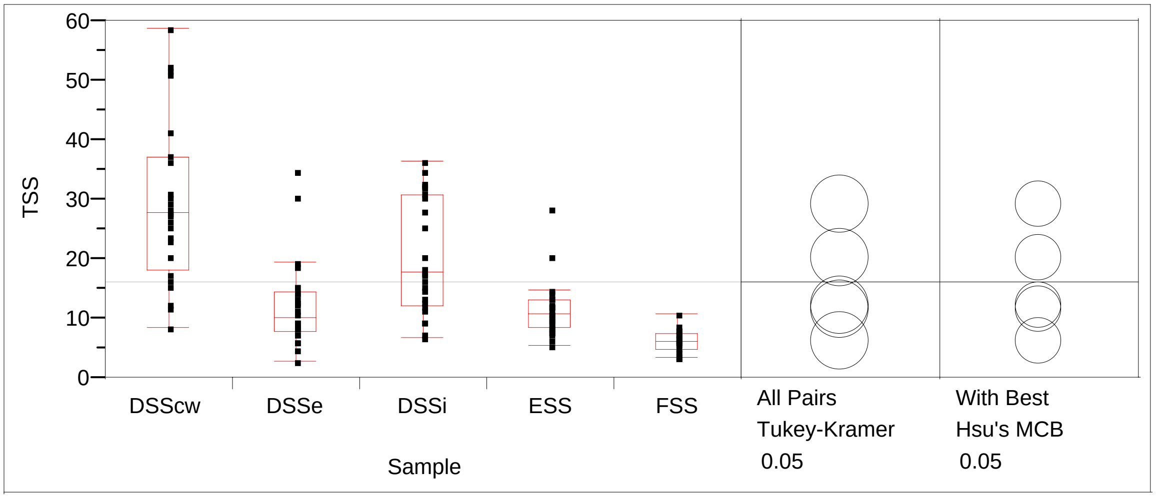
Mean[i]-Mean[j]-LSD	DSScw	DSSi	ESS	DSSe	FSS
DSScw	-5.474	-3.224	4.458	5.254	11.822
DSSi	-7.724	-5.474	2.208	3.004	9.572
ESS	-15.405	-13.155	-5.474	-4.678	1.890
DSSe	-16.201	-13.951	-6.269	-5.474	1.095
FSS	-22.769	-20.519	-12.837	-12.042	-5.474

If a column has any positive values, the mean is significantly less than the max.

Mean[i]-Mean[j]+LSD	DSScw	DSSi	ESS	DSSe	FSS
DSScw	5.474	7.724	15.405	16.201	22.769
DSSi	3.224	5.474	13.155	13.951	20.519
ESS	-4.458	-2.208	5.474	6.269	12.837
DSSe	-5.254	-3.004	4.678	5.474	12.042
FSS	-11.822	-9.572	-1.890	-1.095	5.474

If a column has any negative values, the mean is significantly greater than the min.

Analysis A.12: JMP 5.0 Report of Significant Difference between Tests Applied to Clarifier #4



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
DSScw	8.5	12.25	18.25	27.75	37.25	52.25	59
DSSe	3	5.5	7.75	10.25	14.5	25	35
DSSi	7	8.5	12.25	17.75	30.875	34	36.5
ESS	5.5	7	8.5	10.75	13.25	17.75	28.5
FSS	3.5	3.5	4.675	6.25	7.5	8.5	11

Means Comparisons

Dif=Mean[i]-Mean[j]	DSScw	DSSi	DSSe	ESS	FSS
DSScw	0.000	9.088	17.017	17.917	23.096
DSSi	-9.088	0.000	7.929	8.829	14.008
DSSe	-17.017	-7.929	0.000	0.900	6.079
ESS	-17.917	-8.829	-0.900	0.000	5.179
FSS	-23.096	-14.008	-6.079	-5.179	0.000

Alpha=0.05

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.77154	0.05

Abs(Dif)-LSD	DSScw	DSSi	DSSe	ESS	FSS
DSScw	-6.841	2.246	10.175	11.075	16.255
DSSi	2.246	-6.841	1.088	1.988	7.167
DSSe	10.175	1.088	-6.841	-5.941	-0.762
ESS	11.075	1.988	-5.941	-6.841	-1.662
FSS	16.255	7.167	-0.762	-1.662	-6.841

Positive values show pairs of means that are significantly different.

Level				Mean
DSScw	A			29.458333
DSSi		B		20.370833
DSSe			C	12.441667
ESS			C	11.541667
FSS			C	6.362500

Levels not connected by same letter are significantly different

Comparisons with the best using Hsu's MCB

d	Alpha
2.18426	0.05
2.18426	
2.18426	
2.18426	
2.18426	

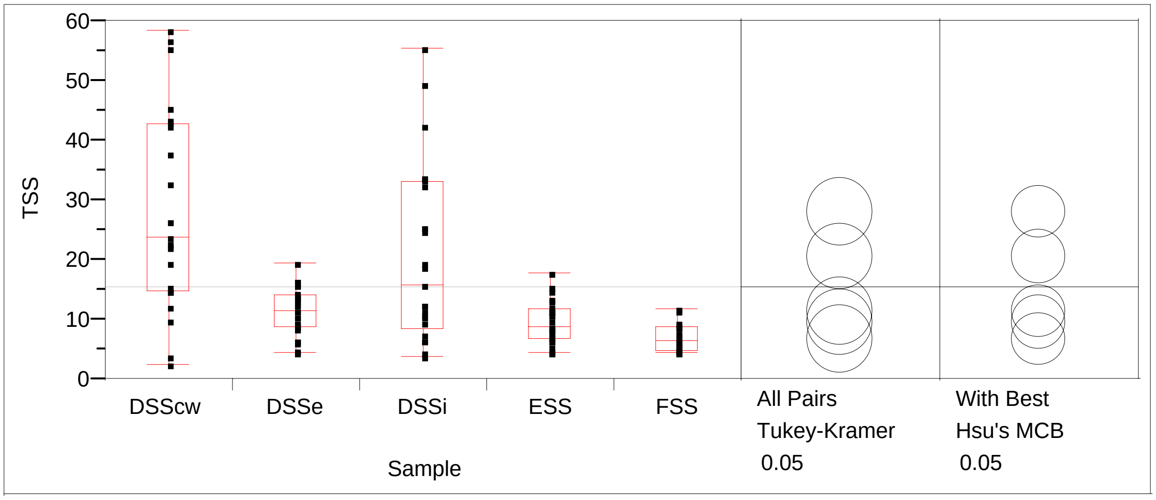
Mean[i]-Mean[j]-LSD	DSScw	DSSi	DSSe	ESS	FSS
DSScw	-5.392	3.696	11.625	12.525	17.704
DSSi	-14.479	-5.392	2.538	3.438	8.617
DSSe	-22.408	-13.321	-5.392	-4.492	0.688
ESS	-23.308	-14.221	-6.292	-5.392	-0.212
FSS	-28.487	-19.400	-11.471	-10.571	-5.392

If a column has any positive values, the mean is significantly less than the max.

Mean[i]-Mean[j]+LSD	DSScw	DSSi	DSSe	ESS	FSS
DSScw	5.392	14.479	22.408	23.308	28.487
DSSi	-3.696	5.392	13.321	14.221	19.400
DSSe	-11.625	-2.538	5.392	6.292	11.471
ESS	-12.525	-3.438	4.492	5.392	10.571
FSS	-17.704	-8.617	-0.688	0.212	5.392

If a column has any negative values, the mean is significantly greater than the min.

Analysis A.13: JMP 5.0 Report of Significant Difference between Tests Applied to Clarifier #6



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
DSScw	2.5	7.6	15	24	42.75	56.1	58.5
DSSe	4.5	5.6	8.75	11.5	14.25	16.5	19.5
DSSi	4	5.7	8.5	16	33	45.3	55.5
ESS	4.5	4.8	6.75	9	11.75	15.2	18
FSS	4.5	4.5	5	6.5	9	10.3	12

Means Comparisons

Dif=Mean[i]-Mean[j]	DSScw	DSSi	DSSe	ESS	FSS
DSScw	0.000	7.500	16.560	18.400	21.200
DSSi	-7.500	0.000	9.060	10.900	13.700
DSSe	-16.560	-9.060	0.000	1.840	4.640
ESS	-18.400	-10.900	-1.840	0.000	2.800
FSS	-21.200	-13.700	-4.640	-2.800	0.000

Alpha=0.05

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.76969	0.05

Abs(Dif)-LSD	DSScw	DSSi	DSSe	ESS	FSS
DSScw	-7.916	-0.416	8.644	10.484	13.284
DSSi	-0.416	-7.916	1.144	2.984	5.784
DSSe	8.644	1.144	-7.916	-6.076	-3.276
ESS	10.484	2.984	-6.076	-7.916	-5.116
FSS	13.284	5.784	-3.276	-5.116	-7.916

Positive values show pairs of means that are significantly different.

Level			Mean
DSScw	A		28.100000
DSSi	A		20.600000
DSSe		B	11.540000
ESS		B	9.700000
FSS		B	6.900000

Levels not connected by same letter are significantly different

Comparisons with the best using Hsu's MCB

d	Alpha
2.18325	0.05
2.18325	
2.18325	
2.18325	
2.18325	

Mean[i]-Mean[j]-LSD	DSScw	DSSi	DSSe	ESS	FSS
DSScw	-6.240	1.260	10.320	12.160	14.960
DSSi	-13.740	-6.240	2.820	4.660	7.460
DSSe	-22.800	-15.300	-6.240	-4.400	-1.600
ESS	-24.640	-17.140	-8.080	-6.240	-3.440
FSS	-27.440	-19.940	-10.880	-9.040	-6.240

If a column has any positive values, the mean is significantly less than the max.

Mean[i]-Mean[j]+LSD	DSScw	DSSi	DSSe	ESS	FSS
DSScw	6.240	13.740	22.800	24.640	27.440
DSSi	-1.260	6.240	15.300	17.140	19.940
DSSe	-10.320	-2.820	6.240	8.080	10.880
ESS	-12.160	-4.660	4.400	6.240	9.040
FSS	-14.960	-7.460	1.600	3.440	6.240

If a column has any negative values, the mean is significantly greater than the min.

Appendix B: Data Tables and Figures

Table B 1: Correlation matrix for operational data

	Prim Inf BOD	ESS (mg/l)	WAS (gpm)	SVI	Settleable Solids	MLSS (mg/l)	μ (1/d)	Rainfall (in)	Prim Eff Avg Flow	F/M ratio	RAS (mgd)
Prim Inf BOD (mg/l)	1	0.0137	0.0089	-0.0173	0.1312	0.2878	-0.094	-0.0253	-0.2734	0.4116	0.0327
ESS (mg/l)	0.0137	1	-0.1363	0.1723	0.1498	-0.0466	-0.041	0.1285	-0.0445	0.0119	-0.0012
WAS (gpm)	0.0089	-0.1363	1	-0.2981	-0.2948	0.0197	0.6025	0.0063	-0.1396	-0.0391	-0.0018
SVI	-0.0173	0.1723	-0.2981	1	0.8326	-0.2819	-0.126	-0.0277	0.0692	0.2359	-0.0103
Settleable Solids (ml/L)	0.1312	0.1498	-0.2948	0.8326	1	0.2043	-0.3507	-0.0825	-0.0326	-0.0614	-0.0046
MLSS (mg/l)	0.2878	-0.0466	0.0197	-0.2819	0.2043	1	-0.4139	-0.0913	-0.2087	-0.5308	0.1512
μ (1/d)	-0.094	-0.041	0.6025	-0.126	-0.3507	-0.4139	1	0.0969	0.0054	0.277	-0.1807
Rainfall (in)	-0.0253	0.1285	0.0063	-0.0277	-0.0825	-0.0913	0.0969	1	0.081	0.1156	-0.0262
Prim Eff Avg Flow (mgd)	-0.2734	-0.0445	-0.1396	0.0692	-0.0326	-0.2087	0.0054	0.081	1	0.4436	0.0304
F/M ratio	0.4116	0.0119	-0.0391	0.2359	-0.0614	-0.5308	0.277	0.1156	0.4436	1	-0.0481
RAS (mgd)	0.0327	-0.0012	-0.0018	-0.0103	-0.0046	0.1512	-0.1807	-0.0262	0.0304	-0.0481	1

Table B 2: Correlation matrix for sampling data

	Rainfall (in)	Influent aver flow (MGD)	Infl Temp (°C)	Inf BOD (mg/L)	Eff BOD (mg/L)	Infl SS (mg/L)	ESS (mg/L)	Eff Set Solids (ml/L)	Inf pH	Eff pH	MLSS (mg/L)	RAS MGD	Ave SOR	Ave SLR	SVI
Rainfall (in)	1	-0.2174	0.4038	0.4258	0.0234	0.3159	-0.0916	-0.1212	0.2223	-0.3441	0.158	-0.137	-0.16	-0.086	0.1865
Influent aver flow (MGD)	-0.2174	1	-0.4254	-0.4661	0.4238	-0.2062	0.6072	0.0058	-0.151	-0.0701	0.1682	0.1454	0.9811	0.913	-0.472
Infl Temp (°C)	0.4038	-0.4254	1	0.4934	-0.1527	0.4786	-0.4158	-0.343	0.1863	-0.1311	0.0008	0.3248	-0.405	-0.362	0.748
Inf BOD (mg/L)	0.4258	-0.4661	0.4934	1	-0.0381	0.5718	-0.2767	-0.0842	0.1955	0.0655	-0.0069	-0.077	-0.451	-0.402	0.3431
Eff BOD (mg/L)	0.0234	0.4238	-0.1527	-0.0381	1	-0.0806	0.4038	0.1649	0.0368	-0.1213	0.0273	-0.198	0.4111	0.376	-0.169
Infl SS (mg/L)	0.3159	-0.2062	0.4786	0.5718	-0.0806	1	0.0194	-0.1915	-0.075	-0.1585	-0.0646	0.1932	-0.225	-0.237	0.5101
ESS (mg/L)	-0.0916	0.6072	-0.4158	-0.2767	0.4038	0.0194	1	0.3918	-0.145	-0.0952	-0.0679	-0.048	0.5629	0.449	-0.338
Eff Settle. Solids (ml/L)	-0.1212	0.0058	-0.343	-0.0842	0.1649	-0.1915	0.3918	1	0.1868	0.1517	-0.0084	-0.199	-0.011	-0.021	-0.231
Inf pH	0.2223	-0.1513	0.1863	0.1955	0.0368	-0.0748	-0.1448	0.1868	1	0.3989	0.0977	-0.111	-0.182	-0.135	0.0095
Eff pH	-0.3441	-0.0701	-0.1311	0.0655	-0.1213	-0.1585	-0.0952	0.1517	0.3989	1	0.0117	-0.011	-0.142	-0.131	-0.071
MLSS (mg/L)	0.158	0.1682	0.0008	-0.0069	0.0273	-0.0646	-0.0679	-0.0084	0.0977	0.0117	1	0.0808	0.1375	0.507	-0.186
RAS MGD	-0.1371	0.1454	0.3248	-0.0766	-0.1975	0.1932	-0.048	-0.1986	-0.111	-0.0109	0.0808	1	0.1248	0.105	0.4045
Ave SOR	-0.1602	0.9811	-0.4049	-0.4507	0.4111	-0.225	0.5629	-0.0108	-0.182	-0.1418	0.1375	0.1248	1	0.92	-0.48
Ave SLR	-0.0861	0.9128	-0.3615	-0.4022	0.3764	-0.2366	0.4487	-0.0207	-0.135	-0.1313	0.5071	0.1047	0.9204	1	-0.496
SVI	0.1865	-0.4723	0.748	0.3431	-0.1685	0.5101	-0.3379	-0.2306	0.0095	-0.0709	-0.1861	0.4045	-0.48	-0.496	1

Table B 3: Effluent suspended solids values measured at the claifier effluent weir

	Clarifier effluent TSS (mg/L)						
	#1	#2	#3	#4	#5	#6	Date
ESSc	14.4	37.8	26.0	9.3	18.6	13.2	1/18
ESSc	9.5	15.0	15.5	14.5	3.0	7.0	1/19
ESSc	-	15.5	17.0	8.0	16.5	6.5	1/20
ESSc	5.5	19.5	2.5	10.0	10.5	11.5	1/21
ESSc	10.0	18.0	17.5	10.0	13.5	8.0	1/22
ESSc	12.0	21.1	14.0	11.5	10.0	8.5	1/24
ESSc	11.5	14.0	18.5	13.5	13.5	9.0	1/25
ESSc	10.0	23.5	21.0	13.5	18.5	13.0	1/26
ESSc	39.0	27.0	13.5	12.5	23.5	15.0	1/27
ESSc	10.0	23.0	28.0	10.0	17.5	10.0	1/28
ESSc	10.5	15.0	21.5	12.0	11.0	5.5	1/29
ESSc	8.0	22.5	14.5	11.5	12.0	7.5	2/1
ESSc	29.5	23.5	11.5	8.5	11.5	8.5	2/2
ESSc	17.5	34.5	15.5	20.5	15.0	13.5	2/3
ESSc	10.0	19.0	10.0	28.5	13.5	9.0	2/4
ESSc	20.0	17.5	23.0	11.0	13.5	12.0	2/5
ESSc	19.0	35.0	40.5	12.0	31.5	11.0	2/7
ESSc	14.5	53.5	20.5	11.0	42.5	18.5	2/8
ESSc	5.5	13.0	13.0	23.5	22.5	8.5	2/9
ESSc	10.5	47.5	21.5	15.0	10.0	11.5	2/10
ESSc	12.0	17.0	15.0	8.5	19.0	15.5	2/12
ESSc	8.0	15.0	8.5	5.5	8.0	6.5	2/14
ESSc	8.0	21.0	9.0	6.5	10.0	11.0	2/15
ESSc	10.5	21.0	12.0	9.0	10.0	10.0	2/16
ESSc	12.0	15.5	14.5	10.0	9.0	9.0	2/17
ESSc	9.5	13.5	11.0	8.0	7.0	6.5	2/18
ESSc	11.5	15.5	17.0	24.0	10.0	7.0	2/19
ESSc	9.5	18.0	17.0	13.5	16.0	9.0	2/21
ESSc	7.5	19.0	7.5	12.5	6.0	8.5	2/22
ESSc	5.0	14.0	4.0	12.5	16.0	13.5	2/23
ESSc	7.5	0.0	14.5	13.0	10.5	6.5	2/24
ESSc	7.5	49.0	0.0	8.0	10.5	10.5	2/25
ESSc	4.5	19.5	11.0	12.0	9.5	6.5	2/26
ESSc	3.5	12.0	3.5	7.5	6.5	6.0	2/28
ESSc	4.0	12.0	4.5	2.5	4.0	5.0	2/29
ESSc	6.0	26.5	7.0	4.5	8.0	8.5	3/1
ESSc	10.0	13.5	26.0	9.5	12.5	5.0	3/2
ESSc	21.5	56.5	7.5	7.5	10.5	4.5	3/3
ESSc	6.5	9.5	35.0	9.5	2.5	5.5	3/4

Table B 3: Continued

ESSc	15.0	48.0	36.5	15.0	15.5	20.0	3/6
ESSc	9.0	17.5	8.5	2.5	7.5	12.5	3/7
ESSc	14.0	16.5	10.5	13.0	14.0	7.0	3/8
ESSc	14.0	20.0	21.5	9.0	9.5	7.0	3/9
ESSc	10.0	12.0	15.5	9.5	10.5	12.5	3/10
ESSc	14.0	21.0	13.0	10.5	20.5	11.5	3/11
ESSc	5.5	12.0	11.0	8.0	9.0	8.0	3/12
ESSc	6.5	8.5	11.5	4.0	13.0	6.5	3/13
ESSc	7.5	11.5	2.5	2.0	6.5	7.0	3/14
ESSc	18.5	17.0	15.0	0.0	12.5	4.5	3/15
ESSc	8.0	26.0	9.0	7.0	10.0	13.0	3/16
ESSc	9.5	13.5	10.5	7.5	0.0	18.0	3/17
ESSc	26.0	30.0	10.0	14.5	18.5	27.5	3/18
ESSc	26.0	30.0	10.0	14.5	18.5	27.5	3/19
ESSc	10.0	10.5	10.5	7.0	10.5	34.0	3/20
ESSc	9.0	14.0	8.5	14.0	7.0	39.5	3/21
ESSc	10.0	10.5	11.5	5.5	4.5	23.5	3/22
ESSc	5.5	10.5	5.5	7.0	8.0	20.0	3/24
ESSc	7.5	8.0	6.0	6.0	12.5	25.0	3/25
ESSc	13.0	12.5	12.5	9.5	13.5	18.5	3/27
ESSc	9.5	7.0	9.0	5.5	7.0	8.5	3/28
ESSc	0.0	7.5	6.5	4.0	6.0	6.5	3/29
ESSc	4.5	13.0	5.0	4.5	6.0	9.5	3/30
ESSc	10.5	10.5	7.5	7.0	4.0	9.0	3/31

Table B 4: Flow level values measured at each clarifier opening gate

	Clarifier Flow Level (inches)					
Date	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**
2/7	9.67	13.00	10.67	9.33	11.00	7.91
2/8	9.17	12.83	9.33	8.50	9.67	7.58
2/9	10.67	14.17	10.50	9.00	9.00	7.42
2/10	9.17	14.33	9.50	8.50	9.50	7.91
2/12	11.50	13.67	9.83	8.83	9.67	7.91
2/14	scum	10.83	8.33	7.00	8.00	6.92
2/15	scum	11.17	8.00	7.00	8.50	6.92
2/16	9.00	12.33	9.17	8.17	9.17	7.91
2/17	9.17	12.00	9.33	8.33	9.50	8.41
2/18	9.00	13.33	9.17	7.67	9.17	7.42
2/19	8.33	11.17	8.33	7.50	8.83	7.42
2/21	scum	scum	8.67	7.50	8.67	6.92
2/22	11.17	10.50	9.83	10.33	9.17	9.89
2/23	8.00	10.67	7.83	7.08	8.33	6.92
2/24	9.17	cleaning	9.17	8.17	9.50	8.41
2/25	7.83	11.33	cleaning	7.83	9.00	7.58
2/26	7.67	11.17	8.33	7.00	8.17	6.92
2/28	6.00	10.17	7.83	7.00	8.50	6.92
2/29	6.17	10.17	7.33	6.50	7.83	6.43
3/1	6.83	10.83	8.17	6.67	8.67	6.92
3/2	8.83	13.67	9.50	8.17	9.67	8.41
3/3	8.00	11.83	8.83	7.83	9.00	7.42
3/4	scum	10.83	8.50	7.00	8.50	6.92
3/6	10.17	14.67	11.33	9.67	10.17	9.40
3/7	9.17	13.00	10.00	8.83	9.83	7.91
3/8	8.67	12.00	9.50	8.33	9.67	7.91
3/9	9.17	12.67	9.50	8.50	9.83	7.91
3/10	scum	scum	9.83	8.67	9.33	8.41
3/11	scum	scum	9.83	8.67	9.83	8.41
3/12	9.17	12.67	9.50	8.33	9.17	7.91
3/13	7.50	11.00	8.33	7.00	8.33	6.92
3/14	8.50	11.33	6.50	7.00	7.00	10.14
3/14	10.17	13.00	7.00	7.83	7.00	11.13
3/14	10.33	12.00	7.17	8.00	7.50	11.87
3/15	10.33	10.67	8.67	cleaning	9.00	7.42
3/16	11.33	10.33	9.67	8.00	9.67	9.89
3/17	9.00	9.50	8.00	6.00	cleaning	8.90
3/18	13.00	11.50	10.17	7.00	9.83	10.88
3/20	scum	9.67	8.17	8.83	7.67	8.90
3/21	scum	9.00	7.33	8.00	8.67	9.89

Table B 4: Continued

3/22	11.17	10.50	9.83	10.50	9.17	9.89
3/24	8.50	8.33	8.17	9.00	8.00	8.41
3/25	9.00	7.83	7.83	8.83	8.17	8.41
3/27	scum	scum	7.67	8.33	7.83	8.41
3/28	scum	8.00	7.83	8.33	7.50	8.41
3/29	cleaning	9.33	9.00	10.00	9.00	9.64
3/30	9.33	8.67	8.17	8.00	8.67	8.90
3/31	9.00	8.33	8.17	8.00	8.33	8.90

Table B 5: Proportional flow levels according to measured flow

		Clarifier Proportional Flows (MGD)					
Date	**Total Flow**	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**
2/7	61.58	15.7	21.1	17.3	15.2	17.9	12.8
2/8	57.08	16.1	22.5	16.4	14.9	16.9	13.3
2/9	60.75	17.6	23.3	17.3	14.8	14.8	12.2
2/10	58.91	15.6	24.3	16.1	14.4	16.1	13.4
2/12	61.41	18.7	22.3	16.0	14.4	15.7	12.9
2/14	Scum	Scum	Scum	Scum	Scum	Scum	Scum
2/15	Scum	Scum	Scum	Scum	Scum	Scum	Scum
2/16	55.75	16.1	22.1	16.4	14.6	16.4	14.2
2/17	56.74	16.2	21.1	16.4	14.7	16.7	14.8
2/18	55.75	16.1	23.9	16.4	13.8	16.4	13.3
2/19	51.58	16.2	21.6	16.2	14.5	17.1	14.4
2/21	Scum	Scum	Scum	Scum	Scum	Scum	Scum
2/22	60.89	18.3	17.2	16.1	17.0	15.1	16.2
2/23	48.84	16.4	21.8	16.0	14.5	17.1	14.2
2/24	44.41	20.6	cleaning	20.6	18.4	21.4	18.9
2/25	43.58	18.0	26.0	cleaning	18.0	20.7	17.4
2/26	49.26	15.6	22.7	16.9	14.2	16.6	14.1
2/28	46.42	12.9	21.9	16.9	15.1	18.3	14.9
2/29	44.43	13.9	22.9	16.5	14.6	17.6	14.5
3/1	48.09	14.2	22.5	17.0	13.9	18.0	14.4
3/2	58.24	15.2	23.5	16.3	14.0	16.6	14.4
3/3	52.92	15.1	22.4	16.7	14.8	17.0	14.0
3/4	Scum	Scum	Scum	Scum	Scum	Scum	Scum
3/6	65.40	15.5	22.4	17.3	14.8	15.5	14.4
3/7	58.75	15.6	22.1	17.0	15.0	16.7	13.5
3/8	56.08	15.5	21.4	16.9	14.9	17.2	14.1
3/9	57.58	15.9	22.0	16.5	14.8	17.1	13.7
3/10	Scum	Scum	Scum	Scum	Scum	Scum	Scum
3/11	Scum	Scum	Scum	Scum	Scum	Scum	Scum
3/12	56.75	16.2	22.3	16.7	14.7	16.2	13.9
3/13	49.09	15.3	22.4	17.0	14.3	17.0	14.1
3/14	50.47	16.8	22.5	12.9	13.9	13.9	20.1
3/14	56.13	18.1	23.2	12.5	14.0	12.5	19.8
3/14	56.87	18.2	21.1	12.6	14.1	13.2	20.9
3/15	cleaning	cleaning	cleaning	cleaning	cleaning	cleaning	cleaning
3/16	58.89	19.2	17.5	16.4	13.6	16.4	16.8
3/17	cleaning	cleaning	cleaning	cleaning	cleaning	cleaning	cleaning
3/18	62.38	20.8	18.4	16.3	11.2	15.8	17.4
3/20	Scum	Scum	Scum	Scum	Scum	Scum	Scum

Table B 5: Continued

3/21	Scum	Scum	Scum	Scum	Scum	Scum	Scum
3/22	61.06	18.3	17.2	16.1	17.2	15.0	16.2
3/24	50.41	16.9	16.5	16.2	17.9	15.9	16.7
3/25	50.07	18.0	15.6	15.6	17.6	16.3	16.8
3/27	Scum	Scum	Scum	Scum	Scum	Scum	Scum
3/28	Scum	Scum	Scum	Scum	Scum	Scum	Scum
3/29	46.98	cleaning	19.9	19.2	21.3	19.2	20.5
3/30	51.74	18.0	16.8	15.8	15.5	16.8	17.2
3/31	50.74	17.7	16.4	16.1	15.8	16.4	17.5

Table B 6: Secondary diversion suspended solids concentration

Plant Influent		Primary effluent		Secondary Diversion		Secondary Treatment		Load Plant Effluent		Curve Plant Effluent		
Flow (MGD)	TSS (mg/L)	Flow (MGD)	TSS (mg/L)	Flow (MGD)	TSS (mg/L)	Flow (MGD)	TSS (mg/L)	Flow (MGD)	TSS (mg/L)	Flow (MGD)	TSS (mg/L)	% error
25	535	25	97	0	0	25	12	25	12	25	11	7.80
30	515	30	101	0	0	30	13	30	13	30	14	6.28
35	495	35	105	0	0	35	14	35	14	35	16	18.72
40	475	40	109	0	0	40	14	40	14	40	19	29.79
45	455	45	113	0	0	45	15	45	15	45	21	39.71
50	435	50	116	0	0	50	16	50	16	50	24	48.64
55	415	55	120	0	0	55	17	55	17	55	26	56.73
60	396	55	120	5	120	55	18	60	27	60	29	6.99
65	376	55	120	10	120	55	18	65	34	65	31	8.16
70	356	55	120	15	120	55	18	70	40	70	34	15.95
75	336	55	120	20	120	55	18	75	46	75	36	20.25
80	316	55	120	25	120	55	18	80	50	80	39	22.63
85	296	55	120	30	120	55	18	85	54	85	41	23.85
90	276	55	120	35	120	55	18	90	58	90	44	24.30
95	256	55	120	40	120	55	18	95	61	95	46	24.22
100	236	55	120	45	120	55	18	100	64	100	49	23.77
105	217	55	120	50	120	55	18	105	67	105	51	23.03
110	197	55	120	55	120	55	18	110	69	110	54	22.08
115	177	55	120	60	120	55	18	115	72	115	57	20.96
120	157	55	120	65	120	55	18	120	74	120	59	19.70

Table B 7: Secondary clarifiers SOR data

Clarifier Area (m2)	1329.80	1329.80	1329.80	1329.80	1329.80	1329.80
Date	**SOR (m/h) #1**	**SOR (m/h) #2**	**SOR (m/h) #3**	**SOR (m/h) #4**	**SOR (m/h) #5**	**SOR (m/h) #6**
2/7	1.18	1.58	1.30	1.14	1.34	0.96
2/8	1.08	1.51	1.10	1.00	1.14	0.89
2/9	1.08	1.44	1.07	0.91	0.91	0.75
2/10	0.88	1.38	0.91	0.82	0.91	0.76
2/12	1.05	1.25	0.90	0.81	0.88	0.72
2/16	0.92	1.26	0.93	0.83	0.93	0.81
2/17	0.87	1.14	0.89	0.79	0.90	0.80
2/18	0.78	1.16	0.80	0.67	0.80	0.65
2/19	0.73	0.97	0.73	0.65	0.77	0.65
2/22	0.73	0.69	0.64	0.68	0.60	0.65
2/23	0.67	0.89	0.65	0.59	0.69	0.58
2/24	0.84	-	0.84	0.75	0.87	0.77
2/25	0.70	1.02	-	0.70	0.81	0.68
2/26	0.71	1.04	0.77	0.65	0.76	0.64
2/28	0.51	0.87	0.67	0.60	0.73	0.59
2/29	0.42	0.69	0.50	0.44	0.53	0.44
3/1	0.56	0.88	0.66	0.54	0.71	0.56
3/2	0.86	1.33	0.93	0.80	0.94	0.82
3/3	0.69	1.02	0.76	0.67	0.78	0.64
3/6	1.46	2.10	1.63	1.39	1.46	1.35
3/7	1.09	1.55	1.19	1.05	1.17	0.94
3/8	0.95	1.32	1.04	0.91	1.06	0.87
3/9	0.89	1.24	0.93	0.83	0.96	0.77
3/12	0.71	0.99	0.74	0.65	0.71	0.62
3/13	0.63	0.92	0.70	0.58	0.70	0.58
3/14	0.66	0.88	0.51	0.55	0.55	0.79
3/16	1.03	0.94	0.88	0.73	0.88	0.90
3/18	1.20	1.06	0.94	0.64	0.90	1.00
3/22	0.84	0.79	0.74	0.79	0.69	0.74
3/24	0.70	0.69	0.67	0.74	0.66	0.69
3/25	0.72	0.63	0.63	0.71	0.66	0.68
3/29	-	0.77	0.75	0.83	0.75	0.80
3/30	0.78	0.72	0.68	0.67	0.72	0.74
3/31	0.75	0.69	0.68	0.66	0.69	0.74

Table B 8: Secondary clarifiers SLR data

Clar. Area (ft2)	14313.88	14313.88	14313.88	14313.88	14313.88	14313.88
Date	**SLR (lb/ft2 h) #1**	**SLR (lb/ft2 h) #2**	**SLR (lb/ft2 h) #3**	**SLR (lb/ft2 h) #4**	**SLR (lb/ft2 h) #5**	**SLR (lb/ft2 h) #6**
2/7	1.21	1.63	1.34	1.17	1.38	0.99
2/8	1.06	1.48	1.08	0.98	1.12	0.88
2/9	0.82	1.09	0.81	0.69	0.69	0.57
2/10	0.59	0.93	0.62	0.55	0.62	0.51
2/12	0.95	1.13	0.82	0.73	0.80	0.66
2/16	0.66	0.90	0.67	0.60	0.67	0.58
2/17	0.61	0.80	0.62	0.55	0.63	0.56
2/18	0.60	0.89	0.61	0.51	0.61	0.49
2/19	0.61	0.82	0.61	0.55	0.65	0.55
2/22	0.58	0.55	0.51	0.54	0.48	0.51
2/23	0.55	0.74	0.54	0.49	0.57	0.48
2/24	0.66	-	0.66	0.58	0.68	0.60
2/25	0.52	0.75	-	0.52	0.59	0.50
2/26	0.54	0.79	0.59	0.49	0.58	0.49
2/28	0.35	0.60	0.46	0.41	0.50	0.41
2/29	0.35	0.57	0.41	0.36	0.44	0.36
3/1	0.50	0.79	0.60	0.49	0.63	0.51
3/2	0.78	1.21	0.84	0.72	0.86	0.75
3/3	0.44	0.65	0.49	0.43	0.50	0.41
3/6	1.24	1.79	1.38	1.18	1.24	1.15
3/7	0.94	1.34	1.03	0.91	1.01	0.81
3/8	0.74	1.03	0.81	0.71	0.83	0.68
3/9	0.70	0.97	0.72	0.65	0.75	0.60
3/12	0.65	0.90	0.68	0.59	0.65	0.56
3/13	0.56	0.81	0.62	0.52	0.62	0.51
3/14	0.60	0.80	0.46	0.49	0.49	0.71
3/16	0.81	0.74	0.69	0.57	0.69	0.71
3/18	0.85	0.75	0.67	0.46	0.64	0.71
3/22	0.72	0.68	0.64	0.68	0.59	0.64
3/24	0.62	0.61	0.60	0.66	0.58	0.61
3/25	0.64	0.55	0.55	0.63	0.58	0.59
3/29	-	0.60	0.58	0.65	0.58	0.62
3/30	0.69	0.64	0.60	0.59	0.64	0.66
3/31	0.63	0.58	0.57	0.56	0.58	0.62

Table B 9: FSS, DSSi, DSScw, DSSe, and ESS data per clarifier

	TSS analysis (mg/L)				
Clarifier #	**FSS**	**DSSi**	**DSScw**	**DSSe**	**ESSc**
#1	10.7	34.0	177.3	19.3	14.4
#1	8.5	18.0	13.5	39.5	9.5
#1	6.0	9.5	29.0	7.0	5.5
#1	6.0	38.0	19.0	12.0	10.0
#1	4.5	28.5	27.0	8.5	12.0
#1	6.5	23.5	16.5	10.0	11.5
#1	7.5	20.5	22.5	9.0	10.0
#1	5.5	23.0	17.0	7.0	39.0
#1	7.0	25.0	11.0	13.5	10.0
#1	7.5	31.0	30.5	33.5	10.5
#1	5.5	11.0	35.5	6.5	29.5
#1	11.0	12.5	18.5	25.5	17.5
#1	5.5	7.0	9.5	22.5	10.0
#1	8.0	26.5	31.0	10.0	20.0
#1	10.5	22.0	22.5	8.5	19.0
#1	6.0	16.5	22.0	11.0	14.5
#1	4.5	7.0	48.5	8.0	10.5
#1	6.5	27.0	17.5	12.0	12.0
#1	3.0	15.5	36.5	7.0	8.0
#1	6.5	34.0	33.5	12.5	8.0
#1	8.0	27.5	42.0	7.0	10.5
#1	6.5	37.0	8.0	10.0	10.0
#1	6.5	17.5	16.5	11.0	21.5
#4	4.5	12	27.5	35	14.5
#4	5.2	32.4	12	13.6	8
#4	3.5	30.5	59	9.5	10
#4	4	25.5	51	14.5	10
#4	6	33	30.5	14.5	11.5
#4	11	31	17.5	15.5	13.5
#4	8	18	12.5	13	13.5
#4	6	13	36.5	8.5	12.5
#4	7	15	28.5	19	12
#4	6	16.5	24	8.5	8.5
#4	8	35	28	11.5	20.5
#4	8	32	16.5	12.5	28.5
#4	9	28	37.5	11	11
#4	7	20.5	52.5	8.5	12
#4	7.5	9.5	8.5	3	11
#4	4.5	7.5	15.5	19.5	15
#4	6.5	13.5	31	5	8.5

Table B 9: Continued

#4	3.5	11.5	29.5	7.5	5.5
#4	3.5	36.5	25.5	7.5	6.5
#4	6	18.5	52	6	9
#4	7.5	15.5	23	9	9.5
#4	7	9.5	26.5	30.5	10.5
#4	6	7	20.5	6	8
#4	7.5	17.5	41.5	9.5	7.5
#6	11.5	7.5	15	11.5	7
#6	9	49.5	33	8.5	6.5
#6	6	6.5	4	5	11.5
#6	7	55.5	45.5	14	8
#6	9.5	25	22.5	14.5	9
#6	5.5	32.5	19.5	10.5	13
#6	4.5	11	33	14	15
#6	7.5	33.5	58.5	16	5.5
#6	5	25.5	43.5	16.5	8.5
#6	5	25.5	57	16.5	13.5
#6	9	19.5	15	13.5	9
#6	9	19	2.5	9	12
#6	6.5	34	38	19.5	11
#6	4.5	42.5	15	9	11.5
#6	5.5	11.5	55.5	6.5	15.5
#6	5	6.5	43	6.5	6.5
#6	6.5	10.5	10	16	11
#6	4.5	34	42.5	12.5	10
#6	8	9.5	22	14	5
#6	9	12.5	26.5	10.5	4.5
#6	12	16	24	11.5	11.5
#6	5.5	6.5	12	9.5	8
#6	6.5	4	23	4.5	7
#6	5.5	4.5	26.5	6	4.5
#6	5	12.5	15.5	13	18

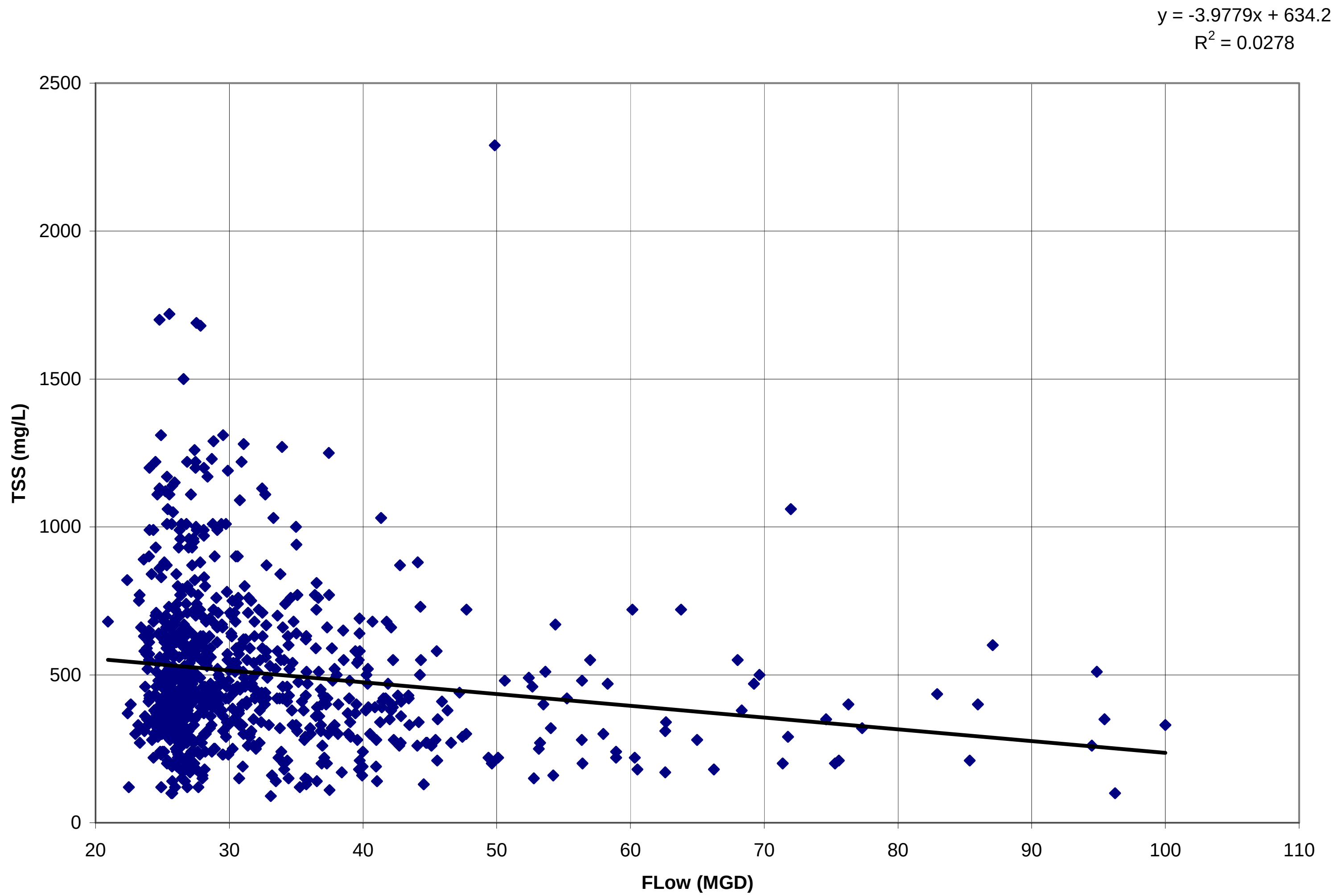


Figure B 1: Plant influent TSS vs. total plant inflow

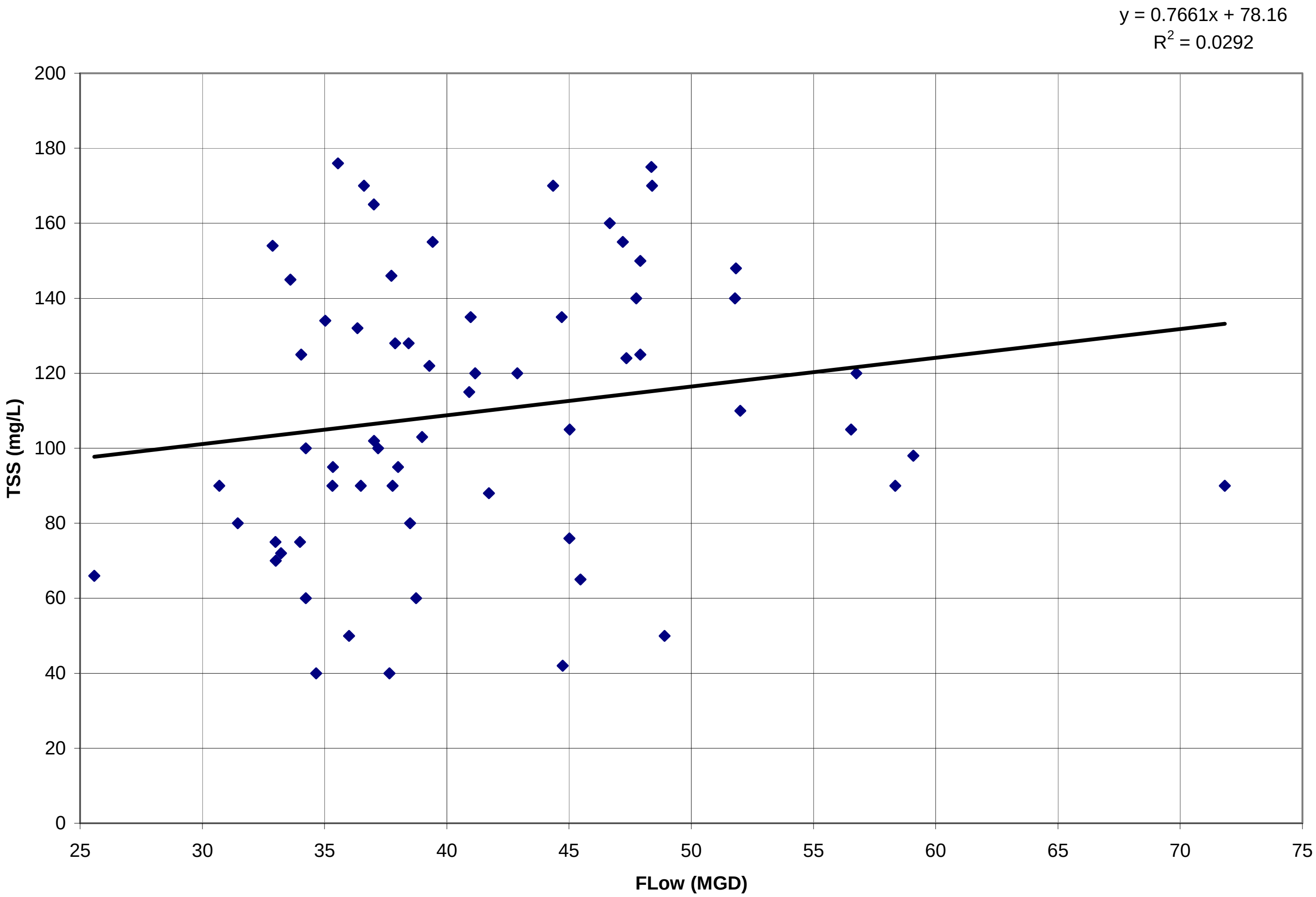


Figure B 2: Primary effluent TSS vs. total plant influent

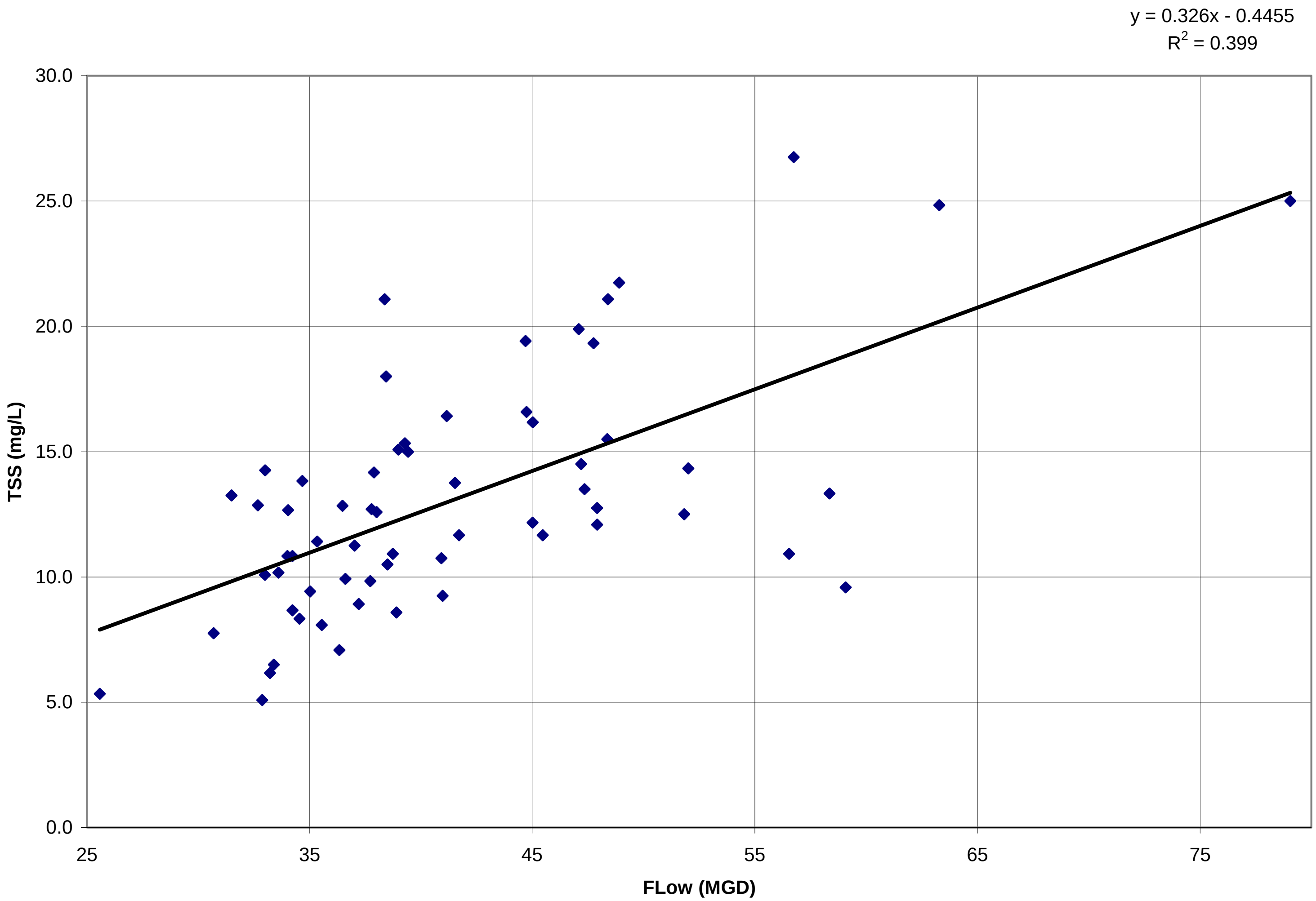


Figure B 3: Secondary clarifiers effluent TSS vs. total plant inflow

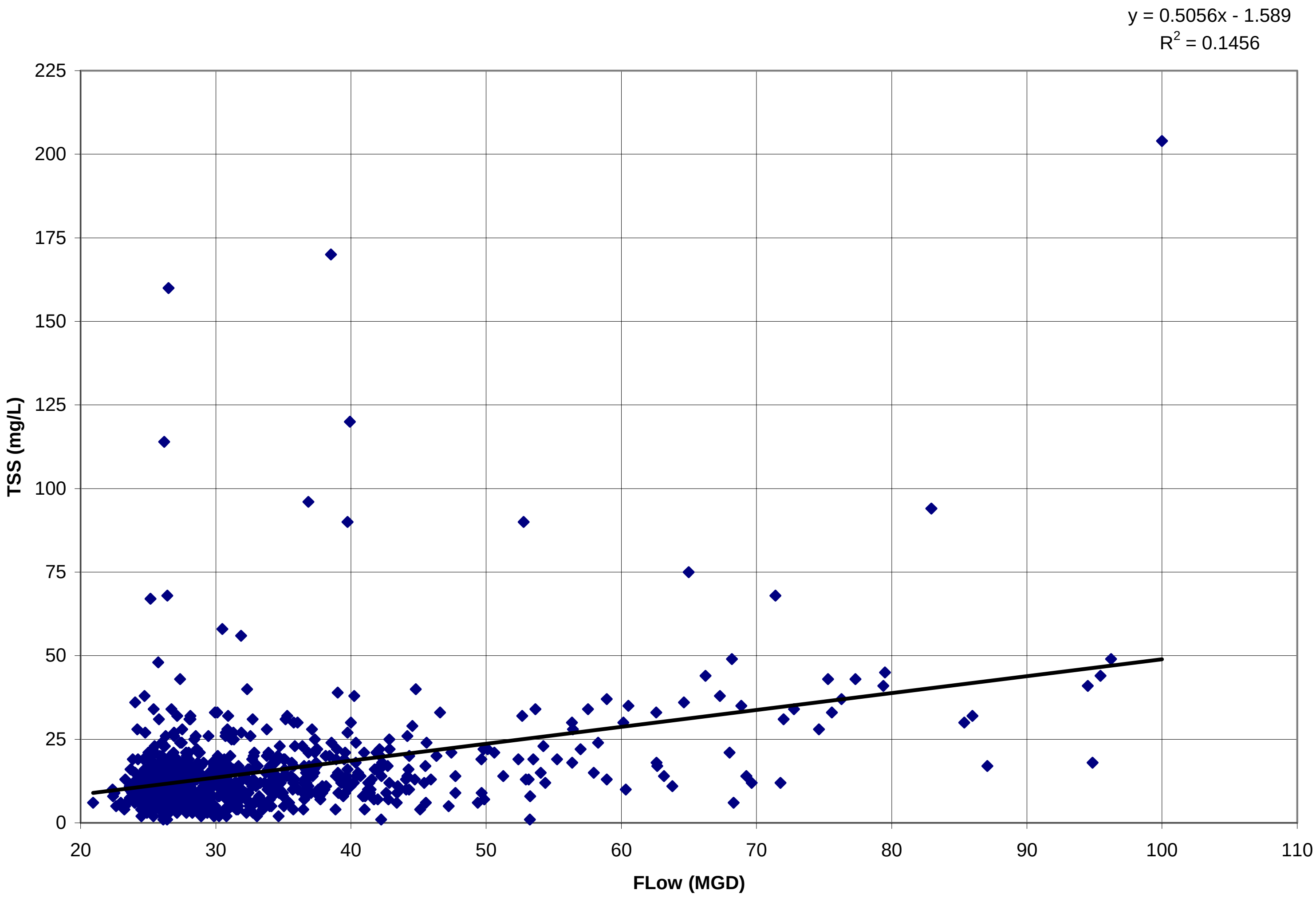


Figure B 4: Overall plant ESS vs. total plant inflow

Vita

Patricio Alejandro Moreno was born in Santiago, Chile on January 13, 1977. He attended the public system of schools in Antofagasta, Chile, and Union County, New Jersey, where he graduated from Summit High School in May 1995. He entered the Universidad de Santiago de Chile in March of 1996, receiving a Bachelor of Civil Engineering in December 2002. Mr. Moreno entered the Master's program in Environmental Engineering as a full time student in January of 2003. Working as a graduate research assistant, he officially received his Master of Science Degree in Environmental Engineering in August of 2004.