Graz University of Technology

# Settling of solids in raw wastewater – primary settling tanks and storm water tanks

**Doctoral Thesis**


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Graz, June 2012

Graz University of Technology

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Dissertation zum Erwerb des
akademischen Titels Doktor der technischen Wissenschaften
(Dr. techn.) der Studienrichtung Bauingenieurswissenschaften

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Verfasst am Institut für Siedlungswasserwirtschaft und
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............................................
(Muhammad Tahseen ASLAM)

*Dedicated to my loving mom, father (Late) and family.*
*Their support, insight, guidance, patience and kind wishes always,*
*craft the success for me!*

# ACKNOWLEDGEMENT

First of all, I would like to thank the Almighty Allah, for His divine guidance and providence. His support, blessings, goodness, and kindness were always with me. He blessed me with motivation, passion, and hard work. It was His blessings which made me able to plan, visualize, and execute my dreams into the reality. I would like to dedicate this achievement to Him.

Every PhD student wishes to conduct research under a visionary and inspirational supervisor, as well as with a researcher who is intelligent and motivating. I am very lucky to find this ideal supervisor in form of Prof. Dr. Harald Kainz. I am really thankful to him for giving me the exceptional opportunity of doing a PhD with him. His constant encouragement, help, and invaluable supervision helped me to groom my educational, research and writing capabilities which further excelled me to broaden my vision and brought best out of me for this research work.

I owe my deepest gratitude to Prof. Dr. Wolfgang Guenthert and Prof. Dr. Raimund Haberl for being part of my dissertation evaluation committee and accepting the role of Examiner despite his busy schedule.

I am very obliged to Dr. Guenter Gruber who supported me throughout my stay here in Graz. He was always there for any type of guidance and help.

A big thank to the laboratory and technical staff (Harald Gerhold, Bernd Stojanovic, Lisa Weißensteiner, Melanie Zeiler, Arthur Fischer-Colbrie and Roland Fuchs) of Institute of Urban Water Management and Landscape Water Engineering. They helped me a lot during the experimentation stage of my work.

I would like to thank Mrs. Roswitha Pauritsch, Mrs. Sabine Dallago for their extended support in the official matters and library matters.

In addition I would like to thank all my working colleagues who became friends here at the Institute.

I would like to thank my inspirational father Muhammad Aslam (Late) and my loving mother Mst. Hafeez Akhtar, whose prayers, motivations and belief in me got me that far. They are always a source of inspiration and driving force behind my studies. I would also like to share my achievements and joy with my brother named Muhammad Nadeem Aslam, my sisters (Mrs. Shaheen Kausar, Mrs. Mamoona Mussarat) and their families. I will never forget the contribution of my wife ‘Mrs. Munazza Tahseen’ during my research and stay in Austria. I find no more words to thank them for their continuous support.

I was lucky enough to find myself among very loving and caring family of Pakistani scholars in Graz. They always fill in the gap of a family and made me happy while I was sad.

I am thankful to my employer Pakistan Council of Scientific and Industrial Research (PCSIR) for granting me a study leave to complete my PhD studies.

At the end my heartiest tribute to my country Pakistan and Higher Education Commission (HEC), Government of Pakistan, for funding my research as without their assistance I would not have a chance to pursue my PhD and full fill my dreams. In the same spirit my tribute goes to the Austrian Agency for International Cooperation in Education and Research (OeAD-GmbH) for their services in managing stay in Graz.

# ABSTRACT

Wastewater contains a variety of solid materials varying from rags to colloidal matters. The most important physical characteristic of wastewater is its total solid content, which is composed of floating matter, settleable matter, colloidal matter and matter in solution. Sedimentation is best method to remove readily settleable solids and floating material and thus reduce the suspended solid content.

Settling of solids in raw urban wastewater has been described in this thesis. The study also includes the settling of wastewater in primary settling tanks and storm water tanks. Literature studies show that there are many apparatuses used for settling of urban wastewater but mostly used for sludge in secondary settling tanks. The characteristics of raw wastewater are much different from the activated sludge at wastewater treatment plant. In raw wastewater, the particles/solids are not homogenized and have a lot of variation regarding settling point of view as compared to secondary sludge. These instruments / apparatuses have been used by considering one or two settling parameters. Each instrument had their advantages and disadvantages.

A new apparatus was developed and described in this Thesis to perform efficient settling of raw wastewater and wastewater in primary settling tanks / storm water tanks. I had tried to include maximum settling parameters so that comprehensive settling studies can be performed with this new apparatus. This instrument is economical and very easy to use. It can be transported easily from one place to another. A lot of experiments were performed with this apparatus in the laboratory of Institute of Urban Water Management and Landscape Water Engineering at Graz University of Technology as well as on site at Graz Wastewater Treatment Plant (WWTP). Three additional same apparatuses were constructed to do the parallel experiments and to speed up the research work. The experiments were performed in both weathers (Dry and wet weather) to find out the difference in settling behaviour of solids in raw wastewater. It helps in the estimation of primary sludge and effectiveness of primary settling tank / storm water tanks.

The results show that in raw wastewater, solids split in three fractions i.e. fast settling solids, suspended solids and floating solids. The settling time used for this apparatus is in the range of 3 minutes to 2 hours. It was concluded that most of the solids settle within the first 10 minutes, with a general settling velocity of more than 10m/h. The other settling parameters include Particle size, Settling Velocity, types of solids e.g. Organic/Inorganic solids, shape of solids etc. Chemical Oxygen Demand (COD) is also measured to estimate the pollution associated with these solids. The settling of solids in the settling apparatus is also monitored by the self-made Videos. It is find out from the Video Analyses that the particle size with a cross-section ranges from 0.1 to 350 $mm^2$ and the settling velocity lies in the range of 0.5 – 3.5 cm/sec (18 – 126 m/h). These experiments were performed in dry as well as wet weather. The results will be used for future modelling work for storm water tanks and primary clarifier tanks at WWTPs.

**KURZFASSUNG**

Abwasser enthält von Grobstoffen bis hin zu kolloiden Substanzen ein breites Spektrum an Feststoffen. Einer der wichtigsten physikalischen Parameter im Abwasser ist der Anteil der gesamten Feststoffe. Dieser setzt sich aus flotierbaren, absetzbaren, kolloiden und gelösten Anteilen zusammen.

Diese Arbeit beschreibt das Absetzverhalten von Feststoffen in Rohabwasser im Allgemeinen sowie das Absetzverhalten von Abwasser in Vorklärbecken einer Kläranlage und in einem Mischwasserüberlaufbecken im Speziellen. In der Literatur werden einige Messvorrichtungen zur Bestimmung des Absetzverhaltens in Rohabwasser beschrieben, die meisten davon sind allerdings auf das Absetzverhalten von Belebtschlamm im Nachklärbecken ausgelegt. Die Charakteristik von Rohabwasser unterscheidet sich jedoch maßgeblich von der des Belebtschlamms, da die Partikel nicht homogenisiert sind und eine deutlich größere Streuung im Absetzverhalten aufweisen.

In dieser Arbeit wird eine neue Messvorrichtung entwickelt. Dabei wurde versucht, ein Maximum an Absetzparametern zu berücksichtigen, so dass umfassende Studien mit der Messeinrichtung möglich sind. Die Einrichtung ist einfach zu benutzen und günstig herzustellen. Eine Vielzahl von Experimenten wurde im Labor des Instituts sowie direkt vor Ort auf der Kläranlage Graz Gössendorf durchgeführt. Es wurden drei identische Messeinrichtungen hergestellt, um Versuche parallel durchführen zu können und um die Forschungsarbeit zu beschleunigen. Die Versuche wurden bei Trockenwetter- und Mischwasserabflussbedingungen durchgeführt, um die Unterschiede im Absetzverhalten bei diesen Systemzuständen beschreiben zu können. Die Untersuchungen unterstützen die Auslegung von Vorklär- und Mischwasserüberlaufbecken.

Die Ergebnisse zeigen, dass im Rohabwasser drei Fraktionen identifiziert werden können, nämlich schnell absetzbare Stoffe, Schwebstoffe und Schwimmstoffe. Absetzzeiten in der Messeinrichtung lagen zwischen 3 Minuten und 2 Stunden. Absetzparameter wie Partikelgröße, Absetzgeschwindigkeit, Feststofftyp (z.B. organisch/anorganisch), Form der Partikel etc. wurden bestimmt. Es wurde festgestellt, dass sich der Großteil der Feststoffe innerhalb der ersten 10 Minuten mit einer Absetzgeschwindigkeit von über 10 m/h absetzt. Zur Abschätzung der organischen Verschmutzung an den Festsoffen wurde der chemische Sauerstoffbedarf ebenfalls bestimmt. Die Absetzversuche wurden mitgefilmet und die Videos ausgewertet. Die Videoanalysen zeigen Partikelgrößen zwischen 0.1 und 350 $mm^2$ und Absetzgeschwindigkeiten im Bereich von 0.5 bis 3.5 cm/s (18 bis 126 m/h).

Die durchgeführten Untersuchungen geben wichtige Anhaltspunkte für die Dimensionierung von Mischwasserüberlauf- und Vorklärbecken und werden zukünftig für die Modellierung dieser Becken zum Einsatz kommen.

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# 1 Chapter – 1 Introduction

## 1.1 Introduction

An essential part of water pollution is carried by the solids present in wastewater. In particular, certain kinds of micro pollutants like heavy metals or polycyclic aromatic hydrocarbons (PAHs) (Haritopoulou, 1996) are strongly associated with total suspended solids (TSS). These solids enter the sewerage system from many sources. Mr. Ashley (Ashley et al., 2004) has reported five principal sources: the atmosphere, the catchment surfaces, domestic sewage, the environment and processes inside the drainage/sewerage system, industrial and commercial effluents and solids from construction sites. Gasperia (Gasperia et al., 2008) reported many priority pollutants including metals, PAHs, pesticides, organotins, volatile organic compounds, chlorobenzenes, phthalates and alkylphenols attached with solids in wastewater during dry as well as wet weather periods.

Sedimentation or settling by gravity is the most common method of solids liquid separation in both water and wastewater treatment plants (Imam et al., 1983).The settling characteristics of the solids and hydraulic characteristics are perhaps the two most important among many other factors which affect the performance of the settling tanks (Tay, 1982). The sedimentation of solids particles in fluids is a part of different natural and industrial phenomenon (Hazzab et al., 2008). The understanding about the shape and size of particles is very necessary for settling studies.

## 1.2 Problem Identification

The solids present in wastewater take pollution with them and can be dangerous for the aquatic life if discharged without a proper treatment. The need of the day is to keep these solids in the sewerage system, to prevent it from spilling out to receiving waters and to restrict as much of it as possible to wastewater treatment plants (WWTPs) or other retention facilities within the catchment area. Different kinds of facilities are used for this purpose and all of them try to remove the TSS fraction by providing storage volumes and settling processes in the volumes. Presently there is limited information available about the TSS retention efficiency in these facilities. One crucial aspect is to acquire a better understanding of the different TSS fractions involved, in order to develop proper strategies to remove them.

The normal practice of disposing of the combined sewage during wet weather conditions is just the sedimentation in storm water tanks or Combine Sewer Overflow (CSO) tanks. Michelbach (Michelbach, 1995) describes that in combined sewer system there are three sources of solids i.e. sewage, sediment and slime. Dry and wet weather flows are a mixture of solubles, settleable solids, suspended solids and floatables. Storm water tanks reduce the pollution caused by CSO which is harmful for receiving water bodies. The settling processes in the CSO tanks are not easy to describe as it depends on settling behavior of the settleable solids and current in the tanks. Many scientists have worked in early 1990s on settling behaviour of setteleable solids (Brombach et al., 1992); (Pisano, 1996); (Tyack et al., 1992). Kutzner (Kutzner et al., 2007) has established a framework-proposal for the validation of mathematical models with zero or one dimensional spatial resolution for particle separation processes for storm water and combined sewer overflow treatment. He reported that there is an urgent need for future research in sewer solids sedimentation and remobilization.

## 1.3 Aims of Project

The objectives of the Thesis are based on the problems mentioned above and given below:

- To determine the fractions of solids in raw wastewater, with different behaviour
- To determine the settling behavior of every fraction of solids
- To determine pollution load due to these solids
- To acquire a better understanding of the different TSS fractions involved, in order to develop proper strategies to remove them

## 1.4 Methodology

A comprehensive methodology was developed in compliance with the aims and objectives described in the previous section.

The first part of work covers a literature review regarding settling of solids in wastewater, settling instruments and settling practices.

In the second part, a settling apparatus was developed on the basis of literature review and experiments for settling processes were performed on this apparatus at laboratory level as well as On-Site at Graz wastewater treatment plant. Quality parameters were also tested. All this experimentation was based on the standardized procedures and methods.

The results from the experiments were discussed in the next portion of the work. Settling fractions were estimated and optimized with respect to settling time. Settling velocities and particle size were estimated and their correlation is discussed in detail with statistical graph and tables.

## 1.5 Structure

The structure of Thesis is according to the methodology.

The first chapter highlights the background information, problem identification and objectives of the Thesis.

The chapters (2 – 3) include the literature review on settling of solids in raw wastewater, settling methods / instruments, settling practices and mathematical modeling for settling of solids in raw wastewater.

The fourth chapter describes the materials and methods used for the sampling, experimentation and field study of this work.

The chapters (5 – 7) comprises of results and discussion. The chapter 5 discusses the results of experiments performed at laboratory level and On-Site with the help of statistical tools. The chapter 6 mainly focuses on the video analyses. The chapter 7 discusses the prediction model developed for the estimation of effluent concentration of settling tanks.

The last chapter (8) summarizes the work and proposes a brief outlook for further research.

# 2 Chapter – 2 Solids in raw wastewater - Literature Review

This chapter discusses the brief theoretical description of the different topics came under the umbrella of settling of solids in raw wastewater. In the first part of the chapter, the solids and their types in raw wastewater will be discussed. The second part describes the processes used to reduce solids in dry and wet weather. The physical principles regarding settling of solids in urban raw wastewater are described in the last section of the chapter.

## 2.1 Solids in wastewater

The total solid content in wastewater is most important physical characteristic of wastewater, which comprises of floating matter, settleable matter, colloidal matter and suspended matter (Metcalf & Eddy, 2003). The urban wastewater has a variety of solid materials varying from rags to colloidal material. The classification of solids is described in Table 2.1.

**Table 2.1: Solids found in urban wastewater and their definition (Metcalf & Eddy, 2003)**

| Solids | Description |
| --- | --- |
| Total solids (TS) | The residue remaining after a wastewater sample has been evaporated and dried at a specified temperature (103 to 105 °C) |
| Total volatile solids (TVS) | Those solids that can be volatilized and burned off when the TS are ignited (500 ± 50 °C) |
| Total fixed solids (TFS) | The residue that remains after TS are ignited (500 ± 50 °C) |
| Total suspended solids (TSS) | Portion of the TS retained on a filter with a specified pore size, measured after being dried at a specified temperature (105 °C). The filter used most commonly for the determination of TSS is the Whatman glass fiber filter, which has a nominal pore size of about 1.58 µm. |
| Volatile suspended solids (VSS) | Those solids that can be volatilized and burned off when the TSS are ignited (500 ± 50 °C) |
| Fixed suspended solids (FSS) | The residue that remains after TSS are ignited (500 ± 50 °C) |
| Total dissolved solids (TDS) (TS – TSS) | Those solids that pass through the filter, and are then evaporated and dried at specified temperature. It should be noted that what is measured as TDS is comprised of colloidal and dissolved solids. Colloids comprised of colloidal and dissolved solids. Colloids are typically in the size range from 0.001 to 1 µm. |
| Total volatile dissolved solids (VDS) | Those solids that can be volatilized and burned off when the TDS are ignited (500 ± 50 °C) |
| Settleable solids | Suspended solids, expressed as milliliters per liter, that will settle out of suspension within a specified period of time. |

The solids which are mentioned in above table have a strong co-relation with each other, which can be comprehensively highlighted in Figure 2.1.

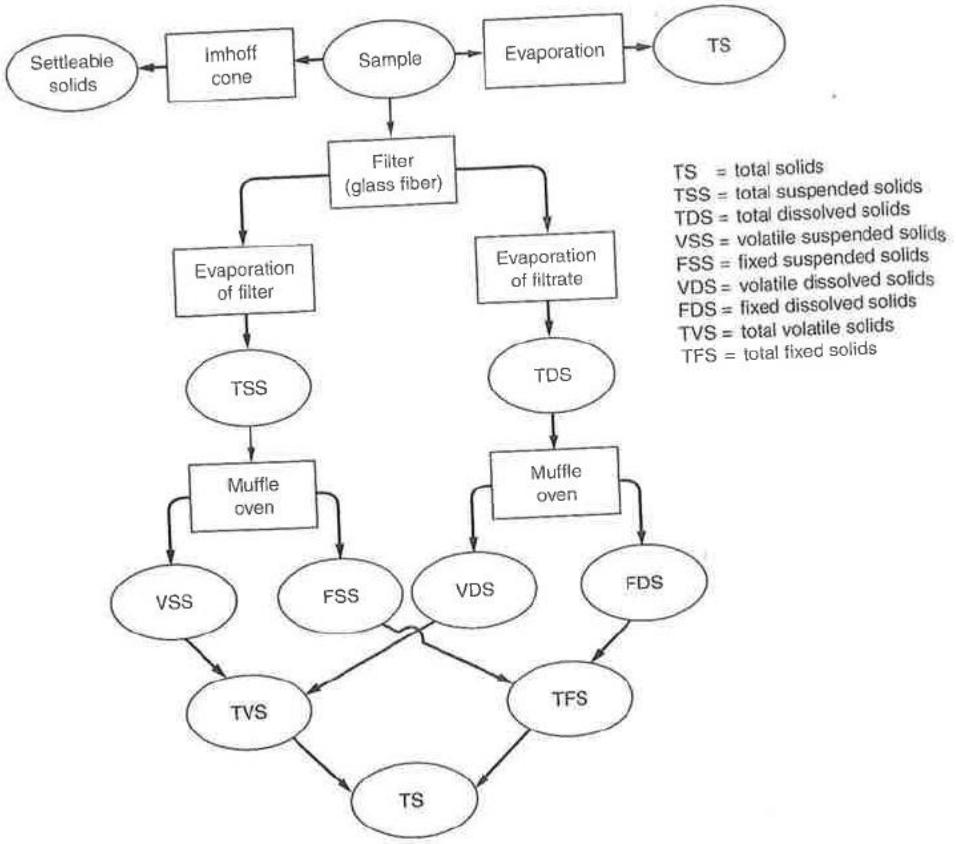



**Figure 2.1: Interrelationships of solids found in water and wastewater. (Metcalf & Eddy, 2003).**

### 2.1.1 Origin of solids

The solids in urban wastewater originate from a variety of sources. The major sources are broadly categorized as follows (Ashley et al., 2004):

- The atmosphere, which contains dust and aerosols
- The surfaces of catchment, where solids deposit/accumulate during dry weather periods and are washed off during storm events: roofs, streets, parking areas and highways etc.
- Domestic sewage that constitutes the largest proportion of organic solids
- The effluent from Industrial and commercial activities and solids from construction sites, which typically may contribute very significantly to the solids loads entering sewers.

The above sources are discussed briefly in the following headings (Ashley et al., 2004).

#### *2.1.1.1 The atmosphere*

The atmosphere contains dust particles and aerosols that contribute to raindrop formation. These particles are originated from different sources which few times can be remote from the catchment where they will precipitate: heating, automobile traffic, waste incineration, industry, construction sites, erosion of natural soils etc. These particles are transported within raindrops during storm events. The contribution of these particles to the total mass of solids during storm water events is usually < 10% and the suspended solids concentration in rainfall water ranges from 1 – 10 mg/L, with mean values of about 3 – 4 mg/L (Goettle, 1978; Novotny et al., 1985; Uchimura et al., 1996).

#### *2.1.1.2 Catchment surfaces*

The solids which are washed off from the different surfaces of a catchment are responsible for main contribution to the pollutant load of runoff water. For practical reasons, three primary sources of 'surface solids' are described as below (Ashley et al., 2004):

- Roofs
- Streets, highways and car parks
- Gullies

In addition to the above three sources, permeable and other natural surfaces also contribute especially during heavy rainfall events.

#### *2.1.1.3 Solids from domestic wastewater*

The sources of domestic wastewater can be categorized in a number of ways, depending of the objectives of their study. These sources are mentioned as below (Ashley et al., 2004):

- Fine faecal and other organic particles (sanitary solids)
- Large faecal and other organic matter (gross solids)
- Paper, rags and miscellaneous sewage litter (sanitary refuse, also generally included as gross solids)
- Kitchen sink organics (fine and large)

#### *2.1.1.4 Commercial, industrial and construction activities*

The solids from these sources can be of different types depending upon the type of an activity or industry and these should be measured for each specific area/location. These differences include all parameters: size, density, organic fraction, associated pollutants, concentrations etc. The construction activities can significantly influence the solids loads entered into sewer systems. The nature of these solids is dependent on both the materials used for the construction and nature of the ground (silt, clay, gravel etc). The solids are usually predominantly mineral, with low or reduced associated pollutant loads. However, they can contribute locally to the solids load entering into sewer systems and to the sewer sediment build-up (Ashley et al., 2004).

## 2.2 Settling of solids in wastewater

The gravity separation is one of the most popular and effective unit operations in wastewater treatment, for the removal of suspended and colloidal materials from wastewater. The gravitational phenomena used for wastewater treatment is described in Table 2.2. The term 'Sedimentation' applies to the separation of suspended particles that are heavier than water, by gravitational settling. The two terms *sedimentation* and *settling* are mostly used interchangeably. The sedimentation basin may also be referred to as a sedimentation tank, clarifier, settling basin, or settling tank (Metcalf & Eddy, 2003).

**Table 2.2: Different gravitational phenomena used in wastewater treatment (Metcalf & Eddy, 2003)**

| Type of separation phenomenon | Description | Application/ occurrence |
|---|---|---|
| Discrete particle settling | Refers to the settling of particles in a suspension of low solids concentration by gravity in a constant acceleration field. Particles settle as individual entities, and there is no significant interaction with neighboring particles | Removal of grit and sand particles from wastewater |
| Flocculent Settling | Refers to a rather dilute suspension of particles that coalesce, or flocculate, during the settling operation. By coalescing, the particles increase in mass and settle at a faster rate | Removal of a portion of the TSS in untreated wastewater in primary settling facilities. Also removes chemical floc in settling tanks |
| Ballasted flocculent settling | Refers to the addition of an inert ballasting agent and a polymer to a partially flocculated suspension to promote rapid settling and improved solids reduction. A portion of the recovered ballasting agent is recycled to the process. | Removal of the portion of the TSS in untreated wastewater, wastewater from combined systems and industrial wastewater. Also reduces BOD and phosphorous. |
| Hindered settling (zone settling) | Refers to suspensions of intermediate concentration, in which interparticle forces are sufficient to hinder the settling of the neighboring particles. The particles tend to remain in fixed positions with respect to each other and the mass of particles settles as a unit. A solids-liquid interface develop at the top of the settling mass | Occurs in secondary settling facilities used in conjunction with biological treatment facilities |
| Compression | Refers to settling in which the particles are of | Usually occurs in the lower layers |

| | | |
|---|---|---|
| settling | such concentration that a structure is formed and further settling can occur only by compression of the structure. Compression takes place from the weight of the particles which are constantly being added to the structure by sedimentation from the supernatant liquid. | of a deep solids or biosolids mass, such as in the bottom of deep secondary settling facilities and in solids-thickening facilities |
| Accelerated gravity settling | Removal of particles in suspension by gravity settling in an acceleration field | Removal of grit and sand particles from wastewater |
| Flotation | Removal of particles in suspension that are lighter than water by air or gas flotation | Removal of greases and oils, light material that floats, thickening of solids suspensions |

Sedimentation is used to remove grit and TSS in primary settling basins, biological floc removal in the activated sludge settling basin and chemical floc removal when the chemical coagulation is used. Sedimentation is also used to concentrate the solids in the sludge thickeners. The prime objective of the sedimentation is to produce a clarified effluent, but it is also necessary to produce sludge with the solids concentration that can be handled and treated easily.

The gravitational settling can be categorized in four types depending upon the concentration and tendency of particles to interact, which are given below (Metcalf & Eddy, 2003):

- Discrete particle
- Flocculent
- Hindered settling
- Compression

### 2.2.1 Particle settling theory

The settling of discrete, non flocculating particles can be analyzed by means of classic laws of sedimentation which are formed by Newton and Stokes. Newton law gives the terminal particle velocity by equating the gravitational force of particle to the frictional resistance or drag. The gravitational force is explained by following equation:

$F_G = (\rho_p - \rho_w) g V_p$ [kg.m/s$^2$] …………………………………………...Eq. 2.1

Where $F_G$ = gravitational force, MLT$^{-2}$ [kg.m/s$^2$]

$\rho_p$ = density of particles, ML-3 [kg/m$^3$]

$\rho_w$ = density of water, ML$^{-3}$ [kg/m$^3$]

$g$ = acceleration due to gravity, $LT^{-2}$ (9.81 [$m/s^2$])

$Vp$ = volume of particle, $L^3$ [$m^3$]

The frictional drag force is dependent on the particle velocity, fluid density, fluid viscosity, particle diameter and drag coefficient $C_d$ (dimensionless), and is described by the following equation 2.2.

$F_d = \frac{C_d A_p \rho_w v_p^2}{2}$ [$kg.m/s^2$] ……………………………………...Eq. 2.2

Where $F_d$ = frictional drag force, $MLT^{-2}$ [$kg.m/s^2$]

$C_d$ = drag coefficient (unitless)

$A_p$ = cross-sectional or projected area of particles in direction of flow, $L^2$ [$m^2$]

$v_p$ = particle settling velocity, $LT^{-1}$ [m/s]

Equating the gravitational force to the frictional drag force for the spherical particle produces Newton's law:

$v_{p(t)} = \sqrt{\frac{4g}{3C_d}\left(\frac{\rho_p - \rho_w}{\rho_w}\right) d_p} \approx \sqrt{\frac{4g}{3C_d}\left(sg_p - 1\right) d_p}$ [m/s]…………………………...Eq. 2.3

Where $v_{p(t)}$ = terminal velocity of particle, $LT^{-1}$ [m/s]

$d_p$ = diameter of particle, L [m]

$sg_p$ = specific gravity of the particle

The coefficient of drag force $C_d$ takes on different values depending on whether the flow regime surrounding the particle is laminar or turbulent. The drag coefficient for various particles is elaborated in Figure 2.2, as a function of the Reynolds number. The Figure 2.2 describes that there are three more or less distinct regions, depending on the Reynolds number ($N_R$): laminar ($N_R$ < 1), transitional ($N_R$ = 1 to 2000), and turbulent ($N_R$ > 2000).

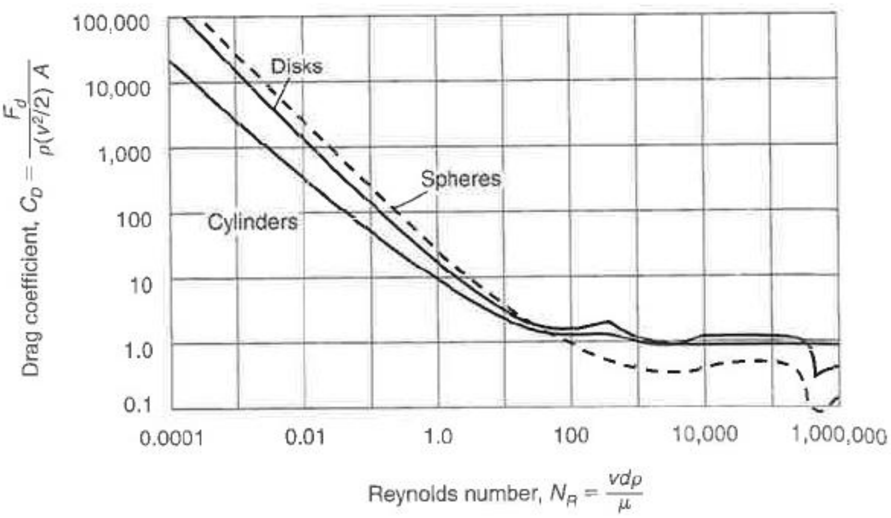



**Figure 2.2: Coefficient of drag as a function of Reynolds number (Metcalf & Eddy, 2003)**

Although particle shape affects the value of the drag coefficient, for particles that are approximately spherical, the curve mentioned in Figure 2.2 is calculated by the following equation (upper limit of $N_R = 10^4$):

$$C_d = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34 \qquad [\text{-}] \qquad \text{……………………………………...Eq. 2.4}$$

The Reynolds number $N_R$ for settling particles is defined as

$$N_R = \frac{v_p d_p \rho_w}{\mu} = \frac{v_p d_p}{v} \qquad [\text{-}] \qquad \text{……………………………………...Eq. 2.5}$$

Where $\mu$ = dynamic viscosity, $MTL^{-2}$ [N.s/m$^2$]

$v$ = kinetic viscosity, $L^2T^{-1}$ [m$^2$/s]

Other terms are defined as above.

The equation 2.3 should be modified for non spherical particles. Gregory reported an application that has been proposed is to rewrite Eq. 2.3 given as below (Gregory et al., 1999):

$$v_{p(t)} = \sqrt{\frac{4g}{3C_d\varphi}\left(\frac{\rho_p - \rho_w}{\rho_w}\right)d_p} \approx \sqrt{\frac{4g}{3C_d\varphi}\left(sg_p - 1\right)d_p} \quad \text{[m/s]…………………………...Eq. 2.6}$$

Where $\varphi$is a shape factor and the other terms are as defined in previous equations. The value of shape factor for spheres is 1.0, while for sand grain it is 2.0 and for fractal floc the shape factor value is up to and greater than 20 (≥ 20). The shape factor is must also be accounted for in computing Reynold Number ($N_R$). The application of Eq. 2.6 will be considered in subsequent discussion of flocculent and ballasted flocculent settling (Metcalf & Eddy, 2003).

#### *2.2.1.1 Settling in laminar region*

For Reynolds numbers less than about 1.0, viscosity is the predominant force governing the settling processes, and the first term in Eq. 2.4 predominates. Assuming spherical particles, substitution of the first term of the drag coefficient equation (Eq. 2.4 into Eq. 2.3) produces stokes law:

$$v_p = \frac{g(\rho_p - \rho_w)d_p^2}{18\mu} \approx \frac{g(sg_p - 1)d_p^2}{18v} \quad \text{[m/s]} \quad \text{...Eq. 2.7}$$

The terms in the above equation are defined previously.

For laminar flow conditions, Stokes found the drag force to be as under:

$$F_D = 3\pi\mu v_p d_p \quad [\text{Kg.m/s}^2] \quad \text{...Eq. 2.8}$$

Stokes law (Eq. 2.7) can also be derived by equating the drag force found by stokes to the effective weight of the particle (Eq. 2.1) (Metcalf & Eddy, 2003).

#### *2.2.1.2 Settling in the transition region*

In the transition region, the complete form of the drag equation (Eq. 2.1) is used to determine the settling velocity. Because of the nature of drag equation, finding the settling velocity is an interactive process. As an aid in visualizing settling in the transition region, Figure 2.3 has been prepared, which covers the laminar and the transition region for particle sizes of interest in wastewater engineering.

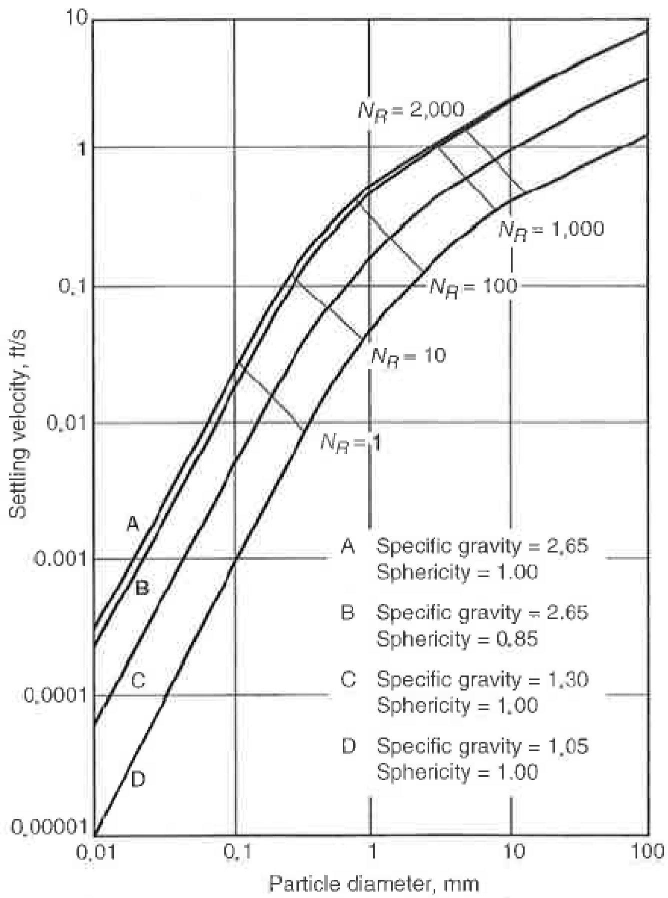



**Figure 2.3: Settling velocities for various particle sizes under varying conditions at 20 °C, settling velocity in ft/s versus particle size in mm (Metcalf & Eddy, 2003)**

#### *2.2.1.3 Settling in the turbulent region*

In the turbulent region, inertial forces are predominant and the effect of the first two terms in the drag coefficient equation (Eq. 2.4) is reduced. For settling in the turbulent region, a value of 0.4 is used for the coefficient of drag. If a value of 0.4 is substituted into Eq. 2.6 for $C_d$, the resulting equation is

$$v_p = \sqrt{3.33g\left(\frac{\rho_p-\rho_w}{\rho_w}\right)d_p} \approx \sqrt{3.33g\left(sg_p-1\right)d_p} \text{ [m/s]} \quad \text{...Eq. 2.9}$$

### 2.2.2 Discrete Particle Settling

In the design of sedimentation tank, the usual procedure is to select a particle with the terminal velocity $v_c$ and to design the basin so that all particles that have terminal velocity equal to or greater than $v_c$ will be removed. The rate at which clarified water is produced is equal to

$$Q = Av_c \quad \text{[m}^3\text{/s]} \quad \text{...Eq. 2.10}$$

Where $Q$ = flowrate, $L3T^{-1}$ [$m^3$/s]

$A$ = surface of sedimentation basin, $L^2$ [$m^2$]

$v_c$ = particle settling velocity, $LT^{-1}$ [m/s]

By rearranging above equation, the results are given as under:

$v_c = \frac{Q}{A}$ = overflow rate, $LT^{-1}$ [$m^3/m^2$ d]

It can be said from the above equation that the critical velocity is equivalent to the overflow rate or surface loading rate. A common basis for design for discrete particle settling recognizes that the flow capacity depends on the depth.

For continuous flow sedimentation, the length of the basin and the time a unit volume of water in the basin (detention time) should be such that all particles with the design velocity $v_c$ will settle to the bottom of the tank. The design velocity, detention time and basin depth are related as mentioned in the following equation 2.11:

$$v_c = \frac{depth}{detention\ time} \quad \text{[m/s]} \qquad \text{.................................Eq. 2.11}$$

Practically, the design factors must be adjusted to allow for the effects of the inlet and outlet turbulence, short circuiting, sludge storage and velocity gradients due to operation of sludge-removal equipment (Metcalf & Eddy, 2003).

### 2.2.3 Flocculent particle settling

Particles in relatively dilute solutions / wastewater do not act as discrete particles but will coalesce during sedimentation. As coalesce or flocculation occurs, the mass of the particle in wastewater increases and it settle faster. The extent to which flocculation occurs, depend on the opportunity for contact, which varies with different parameters like overflow rate, depth of the basin, velocity gradients in the system, concentration of the particles and range of particle sizes. The effect of these variables can only be estimated by sedimentation tests.

The settling characteristics of a suspension of the flocculent particles can be determined by using a settling column test. Such a settling column can be of any diameter but should be equal in height to the depth of the proposed settling tank. In case of activated sludge hindered settling occurs if diameter is less than 0.3 meter. The wastewater which contains the suspended matter, should be introduced into the column in such a way that a uniform distribution of particle sizes occur from top to bottom. A proper care should be taken to ensure that a uniform temperature is maintained throughout the test to eliminate the possibility of convection currents.

Settling should take place under the quiescent conditions. The duration of the test should be equivalent to the settling time in the proposed settling tank. At the conclusion of the settling time, the settled matter that has deposited at the bottom of the column is drawn off, the remaining liquid is mixed, and the TSS of the liquid is measured. The TSS of the liquid is then compared to the sample TSS before settling to get the percent removal (Metcalf & Eddy, 2003).

### 2.2.4 Hindered (Zone) Settling

In wastewater that contain a high concentration of suspended solids, both hindered or zone settling and compression settling usually occur in addition to discrete (free) and flocculent settling. The settling phenomenon that occurs when a concentrated suspension of solids, initially of uniform concentration throughout, is placed in a graduated cylinder is shown in Figure 2.4. Due to the high concentration of particles, the liquid tends to move up through the interstices of the contacting particles. In result, the contacting particles tend to settle as a zone or 'blanket', maintaining the same relative position respect to each other. The phenomenon is called as hindered settling (Metcalf & Eddy, 2003).

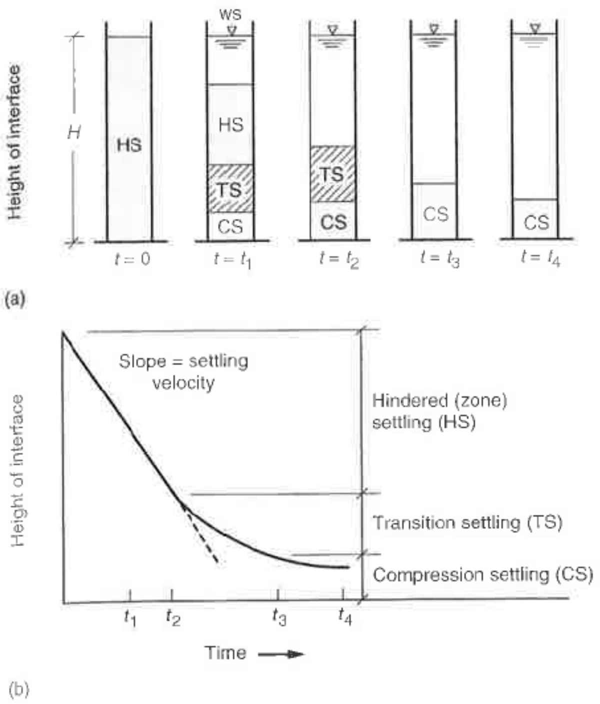



**Figure 2.4: Definition sketch for hindered (zone) settling: (a) settling column in which the suspension is transitioning through various phases of settling and (b) the corresponding interface settling curve (Metcalf & Eddy, 2003)**

As the particles settle, a relatively clear layer of water is produced above the particles in a settling portion. The scattered, relatively light particles usually settle as discrete or flocculent particles. In most of the cases, an identifiable interface develops between the upper region and the hindered settling region, as illustrated in Figure 2.4. The range of settling in the hindered settling region is described as a function of the concentration of solids and their characteristics.
As settling process continues, a compressed layer of particles begin to form on the bottom of the cylinder in the compression settling region. The particles apparently form such structure in which there is close physical contact between the particles (Metcalf & Eddy, 2003).

### 2.2.5 Compression Settling

The volume required for the sludge in the compression region can also be estimated by settling tests. The rate of consolidation has been estimated to be proportional to the difference in the depth at time t and the depth to which sludge will settle after a long and specific period of time. The long term consolidation can be modeled as a first order decay function, as described in the equation 2.12 given as under (Metcalf & Eddy, 2003).

$$H_t - H_\infty = (H_2 - H_\infty)e^{-i(t-t_2)} \quad \text{[m]} \qquad \text{……………………Eq. 2.12}$$

Where $H_t$ = sludge height at time t, L

$H_\infty$ = sludge depthafter long settling period, on the order of 24 h, L

$H_2$ = sludge height at time $t_2$, L

$i$ = constant for a given suspension

The process of stirring during settling, serves to compact solids in the compression region by breaking up the floc and permitting water to escape. Rakes are often used on sedimentation equipment to manipulate the solids and thus obtain better compaction.

# 3 Chapter – 3 Settling Practices and methods – Literature Review

The settling practices performed for raw wastewater will be discussed in this chapter. The prime focus of this chapter will be to study and evaluate the existing practices for settling in wastewater in both weather conditions i.e. dry weather and wet weather. In the first part of the chapter, the settling studies in primary sedimentation tanks and CSO tanks / storm water tanks are discussed. In the second part of the chapter the few important and efficient existing settling methods were discussed in detail. The last part of the chapter discusses the approach towards mathematical modeling in settling of solids in raw wastewater.

## 3.1 Primary Sedimentation

The purpose of the treatment by sedimentation is to remove readily settleable solids and floating material and ultimately reduce the suspended solids content. Primary sedimentation is used as a preliminary step in the further processing of the wastewater. Efficiently designed and operated primary sedimentation tanks should remove from 50 to 70% of the suspended solids and from 25 to 40 percent of the BOD. In (Kainz & Kauch, 2010) the requirements for the design of primary settling tank are summarized in a comprehensive way.

Sedimentation tanks have also been used as storm water retention tanks, which are designed to provide a moderate detention period (10 to 30 minutes) for overflows from either combined sewers or storm sewers. The purpose of sedimentation removes is to remove a substantial portion of the organic solids that otherwise would be discharged directly to the receiving waters. Sedimentation tanks have also been used to provide detention periods sufficient for effective removal of inorganic solids for such overflows. These inorganic solids will cause turbidity in the receiving water and ultimately pollute water body (Metcalf & Eddy, 2003).

## 3.2 Settling of solids in raw wastewater - Dry Weather

The solids in raw wastewater are much different from the secondary or activated sludge. These solids are very complex in nature, varying in shape and size. The settling is not so homogenous in raw wastewater. It is not easy to understand the behaviour of solids in raw wastewater. In dry weather, the settling practices for raw wastewater can be studied by describing the settling processes in existing primary sedimentation tanks of wastewater treatment plants. The primary sedimentation tanks are also situated in many treatment plants after initial physical treatment steps i.e. grit chamber, screening, sand trap etc. But in many developing countries the primary settling tank is used for the primary sedimentation of raw wastewater prior to any or minimal physical treatment. So the settling studies of primary sedimentation tanks can best be used as settling studies for raw wastewater in dry weather conditions.

A lot of research has been done in the decades of 1980s, 1970s or before, for settling studies in primary sedimentation tanks. The study of settling operations has been performed on the basis of two broad guidelines. The first of these was concerned with determination of sedimentation rate of particles whose geometric and physical characteristic are known, together with those of suspension. The second guideline is dealt with modeling continuous settling tanks based on the knowledge of the sedimentation properties of the suspension and of the basin's hydraulic profile. A number of scientists have done a major work in settling of solids in primary sedimentation tank in that era (Veits, 1977) (Annesini et al., 1979) (Tay, 1982) (Imam et al., 1983).

In the developing countries like Pakistan, the research work for the settling of solids in raw wastewater is reported in (Akhtar et al., 1997). Mr. Akhtar has carried out his study on the tannery effluent. He designed a special settling column to investigate the characteristics of effluent arising from Karachi tanneries. He used coagulants like Potash Alum and Ferric Chloride and performed the Jar test to determine the optimum dosage of the coagulants. The design curves in terms of percent removal of solids vs loading rate and detention time were plotted using data obtained from the settling column. These curves can be used in designing the settling tanks of tannery waste treatment plant.

Some scientists also worked in later decades also on the raw wastewater, discussing various aspects of the settling in raw wastewater or domestic institutional wastewater (Lindeborg et al., 1996) (Andoh & Smisson, 1996) (Oke et al., 2006) (Razmi et al., 2009).

In the decade of 1990s and 2000s, the research focus was turned towards settling studies in secondary settling tanks especially on settling of activated sludge. The research in this area has been ignored. The characteristics of the solids in raw wastewater are very much changed from last two decades, due to change in the lifestyle, industrial activities and urbanization. So the settling practices in primary sedimentation tanks have to be modified according to new pattern, considering the current type of solids present in raw wastewater.

## 3.3 Settling of solids in raw wastewater - Wet Weather

The wastewater is stored in combined sewer over flow tanks or storm water tanks in wet weather conditions. A special care is needed in the designing of these retention tanks, as the effluent of these tanks goes directly in the water bodies. Some cities have combined sewer system and some have separate sewer system for both dry weather and wet weather flows. The need was to develop a protocol under which these CSO tanks or storm water tanks should be designed in this manner that maximum solids settle in these tanks in less time. Many scientists have started to think over it and developed many apparatuses in 1990s for measuring the settling velocities and other settling parameters (Michelbach & Weiß, 1996) (Marsalek & Marsalek, 1997) (Brombach & Pisano, 1997) (Chancelier et al., 1998) (Harwood & Saul, 2000) (Laplace et al., 2003) (Mourad et al., 2006) (de Graaf et al., 2008) (Abda et al., 2008) (Brombach et al., 2008) (Gromaire et al., 2008) (Welker, 2008) (Klepiszewski, 2008) (Dufresne et al., 2009). These scientists developed different protocols, modeling approaches to describe the settling of solids in raw wastewater in wet weather conditions.

### 3.3.1 Combined Sewer Overflows

The removal of suspended solids by gravity separation is applied in the treatment of combined sewer overflows (CSOs). Gravitational settling is achieved in settling tanks, the effectiveness of which depends on the characteristics of the treated wastewater and the design parameters of the settling tank. The important tank design characteristics include surface loading rate (SLR = flow rate / tank surface area), flow distribution and turbulence level in the tank (Metcalf & Eddy, 2003). The good design of tank ensures flow mixing and spreading in the inlet zone, calm and efficient settling in the settling zone and smooth flow exit at the outlets. The theoretical and historical practices describes the tanks hydraulics as a consideration of surface loading rate and general recommendations about tank layout, but the modern approaches introduces computational fluid dynamics (CFD) models which entails the flow distributions in settling tanks and effective corrections of inadequate designs (He et al., 2004). Characteristics of the settling processes for wastewater from CSOs were studied and analyzed by different research groups (Piro et al., 2011; Wong & Piedrahita, 2000) and prepare different techniques for producing efficient settling in CSO Tanks.

Settleability of wastewater in CSOs can be determined with the help of two devices:

a) Quiescent Settling devices

b) Dynamic settling devices

#### *3.3.1.1 Quiescent Settling Devices*

These devices includes the traditional settling columns (Metcalf & Eddy, 2003) in addition to more recent designs, such as Auston Column (Tyack et al., 1993; Tyack et al., 1996); Umwelt und Fluid Technik apparatus (Michelbach & Woehrle, 1992; Michelbach & Woehrle, 1993), or multiple columns used in such protocols as VICTOR, VIPCOL or VICAS (Chebbo et al., 2003a; Gromaire et al., 2003).

There are normally three problems or errors occurred during experiment in quiescent settling

1) problems in obtaining initial uniform distribution of particles in the column
2) inability to measure precisely fast settling particles at the beginning of the test
3) questionable reproduction of settling conditions in full scale settling tanks (Aiguier et al., 1996; Aiguier et al., 1998; O'Connor et al., 2002).

MetCalf and Eddy (Metcalf & Eddy, 2003) report that the design settling velocities or overflow rates obtained from column experiments are often multiplied by a factor ranging 0.65 – 0.85 while the corresponding detention times are multiplied by a factor of 1.25 to 1.5.

#### *3.3.1.2 Dynamic Settling Device*

There are three apparatuses found in literature came under the category of dynamic settling i.e. (Dobbins, 1944), (Rasmussen & Larsen, 1996) and (Walling & Woodward, 1993). The first two scientists / research teams used the traditional settling column with modification of adding oscillating grids for mechanical generation of turbulence. Such a modification avoids the limitation of “quiescent” settling columns, but the resulting design is relatively complex, generated turbulence needs to be related to that observed in settling basins (this point was raised by H.A. Einstein in the discussion of the Dobbins' paper), and the difficulties with initial test conditions or chemical additions. In (Walling & Woodward, 1993) apparatus, the tested medium flows through the apparatus, which better mimics the dynamic settling in actual settling tanks. The original Walling and Woodward's apparatus was used e.g., by (Lau & Krishnappen, 1997) to measure size distribution of settling stormwater flocs and further modified by (Krishnappan et al., 2004) to adapt it for testing CSO settleability.

### 3.3.2 CSO Elutriation apparatus

Marsalek (Marsalek et al., 2006) had developed a CSO elutriation apparatus by taking into consideration of the apparatuses (Krishnappan et al., 2004) and (Walling & Woodward, 1993). He developed this apparatus basically for measuring size distribution of suspended solids in rivers.

The CSO elutriation apparatus consists of a train of eight settling chambers connected in such a way that the CSO sample enters the most upstream settling chamber near the bottom, flows upward to exit near the top and enters the next downstream chamber near the bottom, and so on. Sediment flocs with settling velocities greater than the upward suspension velocity settle in the individual settling chambers. The eighth chamber is configured to have a downward flow designed to trap floatables. The diameters of the chambers increase progressively in the downstream direction, with corresponding decreases in flow velocities allowing finer and finer particles to settle in successive chambers. The internal diameters of settling columns 1 through 8 are 25, 34, 49, 70, 105, 143, 197 and 197 mm. The pump drawing the water-suspended solids mixture at a rate of 0.5 L/min. is located on the downstream side of the apparatus so that flocs are not disrupted before passing through the settling chambers. For this flow rate, the flow velocities in individual chambers are 17, 9.2, 4.4, 2.2, 0.96, 0.52 and 0.25 mm/s, respectively. Such velocities correspond to a range from 1 to 61.2 m/h, which covers not only the range of overflow rates used in practice for design of primary clarifiers (2.5 – 4.2 m/h; (Metcalf & Eddy, 2003)), but also some higher velocities, which would be achievable with chemical addition. The sediment fraction with a settling velocity smaller than the flow velocity in the last chamber (0.25 mm/s) leaves the apparatus, and is collected and included in the calculation of the particle settling velocity distributions and in checking the mass balance of experiments.

#### *3.3.2.1 Operating procedure*

CSO samples collected in the field were brought to the laboratory and used to fill two 25 L cans. During the elutriation test, the contents of cans were kept well mixed by impellers. Tests with various types of impellers and their speeds did not show significant variation in elutriation results. At the start of experiments, chambers 1 to 8 were filled with distilled water, and the pump drawing water through the apparatus was activated at a rate of 0.5 L/min. The CSO sample would displace the distilled water and move through the system. The entire test took about 1.5 h and during this period, about 45 L of a CSO sample would pass through the apparatus. Particles with settling velocities greater than 0.25 mm/s settled in one of the settling chambers, those with smaller velocities passed through the apparatus and the pump, and were captured in an effluent container. At the end of the test, solids were removed from individual settling chambers and their masses determined using a standard TSS (total suspended solids) analysis (APHA, 1998). A mass balance check was conducted, by comparing the solids mass in the initial sample to the sum of masses recovered from the settling chambers (including wall wash off) and in the effluent container. Because of high volumes of the initial and final effluent samples, the corresponding solids masses were estimated by sub-sampling these sources and performing TSS analysis on the collected samples. Mass balance errors for individual tests ($(M_{out}–M_{in})/M_{in}$) ranged from -16.1 to +16.4%, with a standard deviation of 10.3% (n = 12), and were deemed acceptable (Marsalek et al., 2006).

## 3.4 Settling methods

The settling behaviour of solids in wastewater is studied and analyzed by various protocols developed and used by several research teams since the beginning of the 1990s, (Benoist & Lijklema, 1990; Tyack et al., 1996; Michelbach & Woehrle, 1993; Aiguier et al., 1996; Pisano, 1996; Gromaire-Mertz et al., 1998; Maus et al., 2008; Chebbo & Gromaire, 2009).

The objective of all protocols is to determine the different settling parameters with special emphasis on the estimation of settling velocity curves. Every protocol has its own benefits and drawbacks. Some discuss only one parameter and some have excellent results in settling velocity curves. Some requires more manpower and long duration of time. Few important settling methods/apparatuses are discussed as under:

### 3.4.1 Brombach Method

The method was developed at the Umwelt- and Fluid- Technik, UFT, Dr. H. Brombach GmbH, D-6990 Bad Mergentheim, Germany (Michelbach & Woehrle, 1993). First, the solids from a sample of ~1g settle for two hours in an Imhoff cone as shown in Figure 3.1.

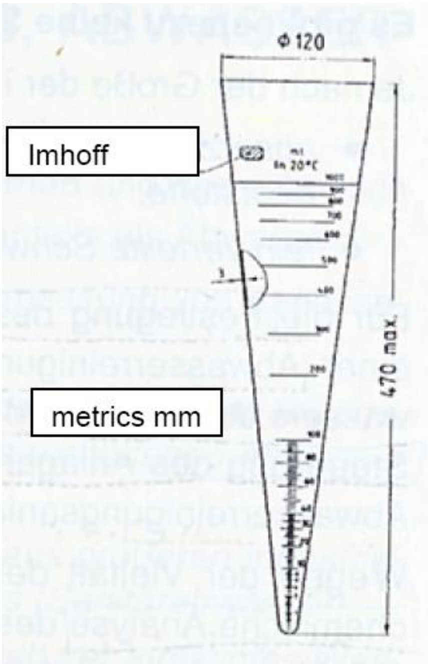



**Figure 3.1: Imhoff cone**

Next, the settled solids are placed in a vertical Perspex cylinder having a feeding mechanism at the top and a cone at the bottom, as can be seen from Figure 3.2. This apparatus was specially developed for this project to determine the settling velocity of settleable solids between 23.3 and 0.01 cm/s.

The feeding mechanism was now pushed quickly over the Perspex cylinder. The time started and the particles began to sink down to the cone at the bottom. Samples were taken at logarithmically spaced time intervals from the bottom of the Perspex tube. Each sample was analyzed for settleable solids (in mL/L), total solids (in mg/L) and loss on ignition (in %).

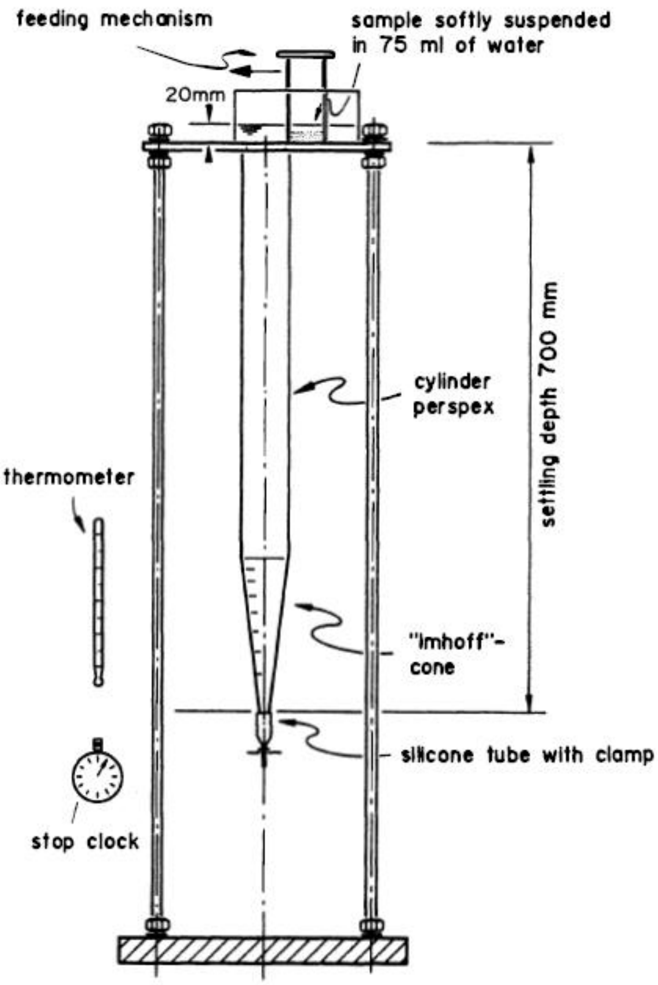



**Figure 3.2: Settling Apparatus (Michelbach & Woehrle, 1993)**

From these fractioned samples, the median of the settling velocity for settleable solids and dry mass were determined. The median characterizes the frequency distribution by a single characteristic parameter.

The procedure is easy to handle and it is possible to carry out the experience quite fast. Otherwise, the residue in the Imhoff cone varies between 25% and 40% of the initial mass. Therefore the distribution curves of the German UFT method do not represent the full interval of settling velocity. Only the distribution of particles which settled 2 hours in an Imhoff cone and with a settling velocity greater than 0,01cm/s is represented.

### 3.4.2 Water Elutriation system Method – Maus/Uhl

The water elutriation apparatus is developed by the research team of Prof. Uhl at Muenster, Germany. The authors (Maus et al., 2008) adapted the water elutriation system from (Krishnappan et al., 2004) for an automatic handling to examine the treatment efficiency of settling tanks under real operating conditions on site. The system consists of sedimentation columns arranged interconnected in series with increasing sizes in flow direction. A peristaltic pump at the end of the last column feeds continuously water through the series of sedimentation columns. The columns are connected in such a way that the sample enters the most upstream settling column near the bottom, flows upward to exit near the top and enters the next downstream column near the bottom, and so on. Particles with settling velocities greater than the upward flow velocity can settle in the column.

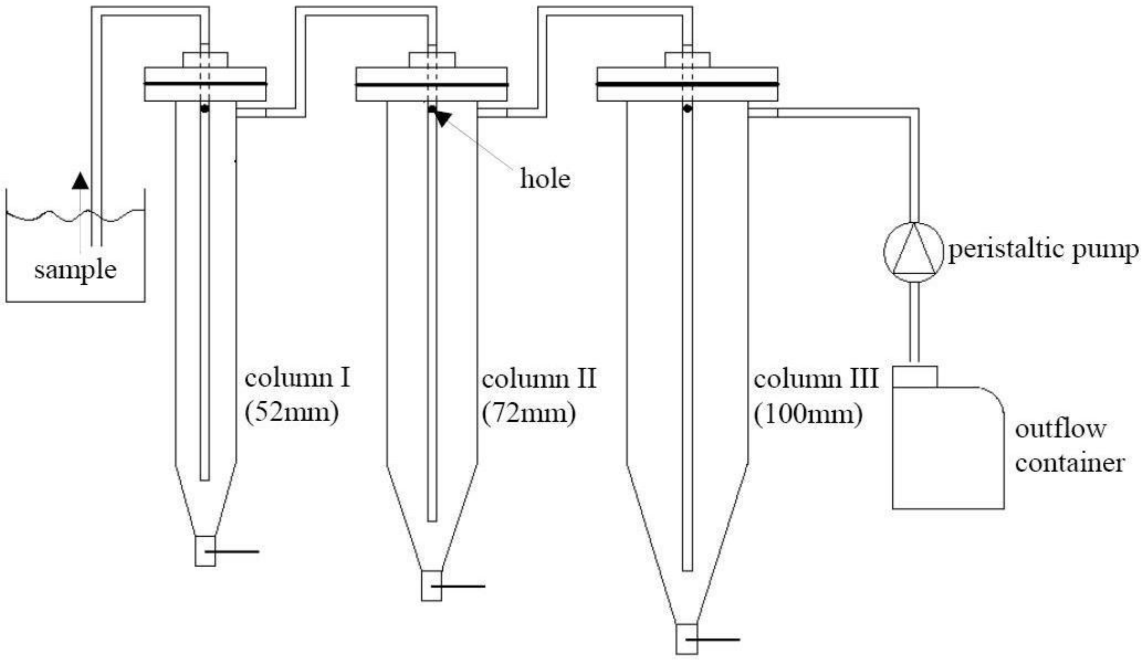



**Figure 3.3: Schematic view of water elutriation system (Maus et al., 2008)**

The diameters of the chambers increase progressively in the downstream direction, with corresponding decrease of flow velocities allowing finer and finer particles to settle in the successive columns. The custom-built apparatus used in this study is illustrated in Figure 3.3.

The cylindrical columns have internal diameters of 52, 72 and 100 mm, respectively. The sampling inflow to the system is provided by a plastic tube with 9 mm internal diameter. The connecting tubes have an inner diameter of 12.5 mm. The peristaltic pump has a flow rate of 0.60 l/min which results in an upward flow velocity of 20, 10 and 5 m/h approximately in the columns.

For the automatic operation it is necessary that the system is self-priming. A small hole provided at the head of the inner tube avoids ascending air bubbles in the columns while the columns are filled. Otherwise air bubbles can’t exhaust from the inner tube expect for the inlet in the column and then they disturb the elutriation process enormously when they ascend.

The particle size is analyzed by Laser Diffraction Particle Size Analyzers for in-situ use. The LISST-ST (Sequoia Scientific, Inc., Bellevue, USA) is a submersible field instrument developed for in-situ observation of the settling velocity distribution of suspended particles in the aquatic environment (Pedocchi & Garcia, 2006). The analysis of the flow conditions in the sedimentation columns is done with the tracer test. The residence time plays an important role to analyze the separation process of the water elutriation system. Tracer tests were carried out in each column in order to examine the flow patterns inside the columns. The objective of the tracer test was to investigate the hydraulic conditions in the columns, to study the effects of diameter and inflow and outflow construction. The analysis of the efficiency of the separation process of each column was tested separately by means of a suitable well defined particle tracer. Objective of the test was the efficiency and reproducibility of the sedimentation process.

### 3.4.3 Benoist and Lijklema method

Benoist and Lijklema split six samples from overflow units by using a protocol based on the principle of the homogeneous suspension (Benoist & Lijklema, 1990).

The majority of the samples were fragmented into five classes. Five columns were utilised for this protocol, as shown in Figure 3.4. Each column has a height of 40 cm and a diameter of D = 8cm, so a volume of 2 Liters. The filling of the columns is made by gravity. At time t=0, the columns are filled with the sample. At each time t=ti a sample of 100ml is extracted from column i for a decantation hi. On each fraction and on the initial sample, the concentrations are measured on SS, Cu, Pb, Zn and Cd.

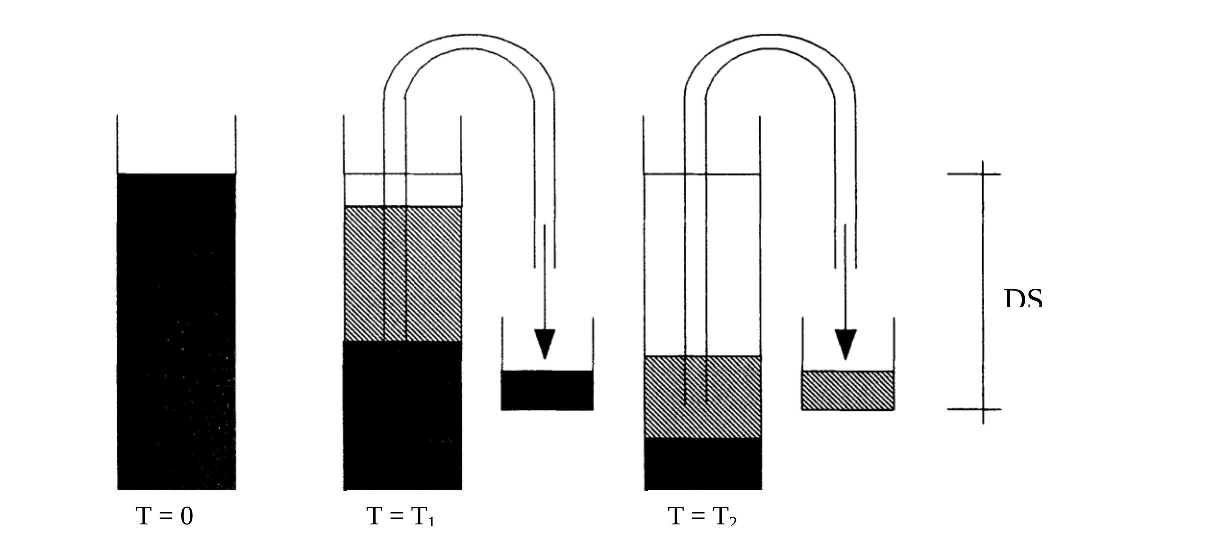



**Figure 3.4: Principle of measuring the distribution of sedimentation rates using settling tubes (Benoist & Lijklema, 1990)**

This protocol is very interesting because it is possible to evaluate directly the percentage of the particles which have a settling velocity lower a given value. The measurement can be carried out quickly without preliminary treatment of the sample.

In particular, (Benoist & Lijklema, 1990) do not give any indication on the methods utilized for the homogenization of the initial sample; the filling of the various columns of decantation and for the sampling at times $t_i$. The principal difficulties of this protocol would be on the one hand to ensure the homogeneity of the initial effluent between the various columns and on the other hand, to ensure a sample taking of the fractions within a layer the most horizontal possible.

### 3.4.4 Tyack Method

The settling apparatus used by the British scientist Tyack is developed for the determination of the settling velocity. The description of the apparatus is given as below (Tyack et al., 1996):

A 10 L sample of sewage is taken from the inlet to the wastewater treatment works returned to the laboratory and refrigerated overnight, which is one of the drawbacks of this procedure.

The following morning the sample is split into two using a specially designed riffle box. With reference to the figure below as Figure 3.5, the entire length of the settlement column, including the end cells, is filled with a well-mixed sewage sample and is left in the vertical position, valves 2 and 3 open, for 3 hours. This results in the sinking fraction being collected in the bottom cell and the floating fraction in the top cell. At the end of the settlement period the contents of the end cells are drained into separate containers. With valves 2 and 3 closed, the sinking fraction is poured back into cell B, cell A is filled with clean water. The column is rotated so that cell B is uppermost, valves 2 and 3 are opened and the stop clock started. At time interval, valve 3 is closed and cell A emptied into a container. Cell A is refilled with clean water. 1 min after t1, the column is rotated so that cell B is uppermost, valve 3 is opened and the test continues. At the end of the test, the contents of cell B are drained into a container. Cell B is then filled with the retained floating fraction and the test repeated, but with cell B at the bottom of the column and cell A uppermost collecting the floating particles. At the end of the test the contents of cell B and the central column are drained into separate containers. The sub-samples are filtered to obtain the mass of suspended solids, from which a settling velocity distribution can be plotted.

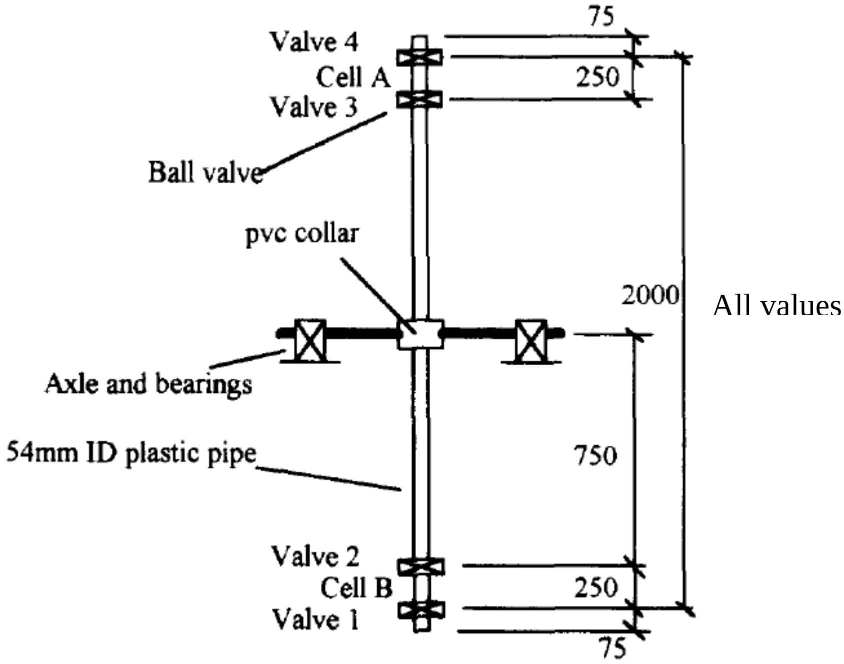



**Figure 3.5: Construction of settling velocity measurement column (Tyack et al., 1996)**

The length of the column is its positive point as physically 1:1 height is needed. The filling volume of 5 L means that the sample is more representative for the sampling and the fact having a larger mass of the fine slow settling fractions the mass of suspended solids was detectable on the balance. Another weak point constitutes a possible turbulence which cause some transfer of fine suspended solids because of the big volume of the column.

### 3.4.5 VICAS Protocol / Method

A settling protocol named 'VICAS Protocol' has been developed in the CEREVE research laboratory by French scientists G. Chebbo and Gromaire to measure the suspended solid settling velocities within urban drainage under both dry and wet weather conditions (Chebbo & Gromaire, 2009). This protocol is considered one of the best methods in France. The demand and interest of this protocol is increased after the publications of VICAS results in an international conference (Gromaire et al., 2007; Torres & Bertrand-Krajewski, 2008).

#### *3.4.5.1 Description of the device*

The fractionation device associated with the VICAS protocol is composed of the following elements (Figure 3.6).

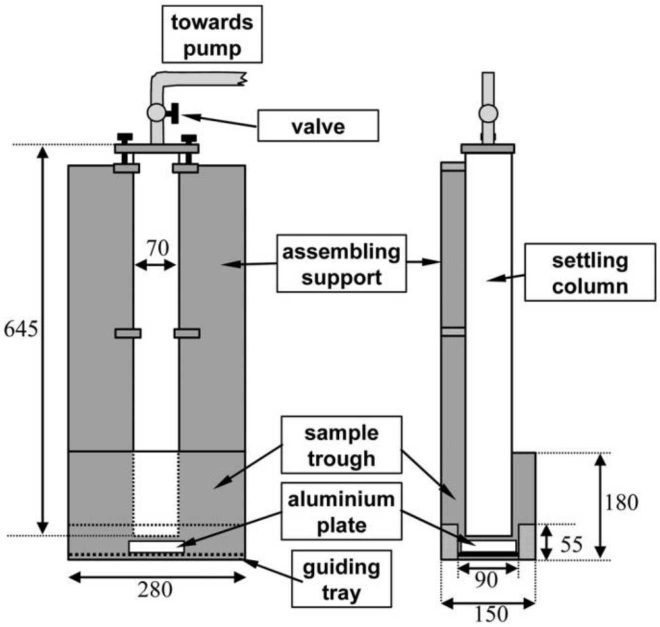



**Figure 3.6: VICAS experimental setup _adapted from Chebbo et al. 2003 (Chebbo & Gromaire, 2009)**

- A Plexiglas sedimentation column with an internal diameter of 70mm and a height of 64cm
- A sample trough made of PVC (length:28cm, width: 15cm, height:18cm) with at its bottom a guiding tray 9cm wide, 5.5 cm deep and 27cm long at the bottom.
- A fastening support that ensures maintaining the column positioned above the sample trough while keeping the device upright.
- A vacuum pump, connected to the top of the column by a hose fitted with a valve that easily allows filling the column

- Aluminum plates 70 mm in diameter and plate holders, used to collect particles settled at the column base
- A chronometer.

#### *3.4.5.2 Operating Procedure*

The sample to be analyzed, which occupies a volume of 4.5 L, is sieved at a 2 mm opening to eliminate papers and larger debris capable of disturbing the measurement. It is then homogenized and three subsamples of 150 mL each are extracted to determine the initial concentration *Co*.

The remaining volume once again gets homogenized and then poured into the trough, where it is sucked up by means of vacuum pressure into the sedimentation column. When the water level in the column has reached approximately 60 cm i.e., the water level remaining in the sample trough covering both the top of the guiding tray and the column base, the valve serving to isolate the column from the pump is closed, and the column is held in a vacuum pressure state for the remainder of the measurement. This filling phase is very fast: 2–3 s.

An aluminum plate filled with distilled water is immersed in the trough and glided along the guiding tray underneath the column base. The chronometer then gets activated. Once sedimentation time *ti* has elapsed *ti*=1 min, 2 min, 4 min, 8 min, 16 min, 32 min, 1 h, 2 h, 4 h, etc., the loaded receptacle is removed and replaced by a new one. The particles settled within the first receptacle during sedimentation time *ti*=*ti*−*ti*−1 are collected by means of filtration on Whatman fiberglass filters GF/F, which had been preliminarily washed, calcined and weighed. The settled mass *mi* is determined after drying the filter at 105°C for 90 min.

Once the last receptacle has been removed, the column base is plugged and its contents collected in a bucket and homogenized. Three subsamples are extracted to evaluate the final concentration $C_f$.

This experimental manipulation can be performed by a single operator and requires at least 5 h of manpower. Several measurements may be undertaken in parallel, with a slight time lag upon initiating the various steps. In the case of samples with low settling velocities wastewater, surface runoff, it is advised to leave the column, following the 4-h sedimentation time, until the next day, thus extending the last sedimentation time in the order of16–24 h.

#### *3.4.5.3 Guiding principal inherent in VICAS Protocol*

The VICAS protocol has been based on the premise of homogeneous suspension, which is the only way to avoid any pretreatment and sample modification. Upon initiating the measurement, solids are uniformly distributed over the entire sedimentation height. The solids settled during a predefined time interval are recovered at the bottom of the sedimentation column. Their mass is then weighed, a step that enables determining the evolution in cumulative mass of the deposit versus time. Two models were then proposed for making the transition from cumulative mass versus time t ($M_t$) to settling velocity distribution curve *F(Vs)*, with this step indicating the cumulative percentage *F* in % of the total mass of particles displaying a settling velocity of less than *Vs* expressed in $mm/s^{-1}$. After different tests, the two methods were found to give similar results, and the second one which is the simplest to implement has been selected for a standard application of VICAS. Calculations are performed automatically via an Excel file associated with the protocol.

#### *3.4.5.4 Protocol validation and reproducibility*

Protocol validation has served to evaluate both the measurement sensitivity to analytical uncertainties and protocol reproducibility. The standard deviations on *FVs* induced by the analytical uncertainties alone vary depending on the calculation method used and on the target settling velocity, yet in all cases remain less than 21%. Overall measurement uncertainty is highly correlated with fractionation manipulation. However, based on our repeatability tests, the overall uncertainty at the 95% confidence threshold on *FVs* does not exceed 15%, when the fractionation operation is performed carefully by a well trained operator.

## 3.5 Mathematical modeling of sedimentation

Particle sediment in water if additional outside forces affect the particles (gravitation, buoyancy, centrifugal forces, inertia, magnetic forces). Thus, particles are diverted from the flowing water (Figure 3.7) (Gujer, 2008).

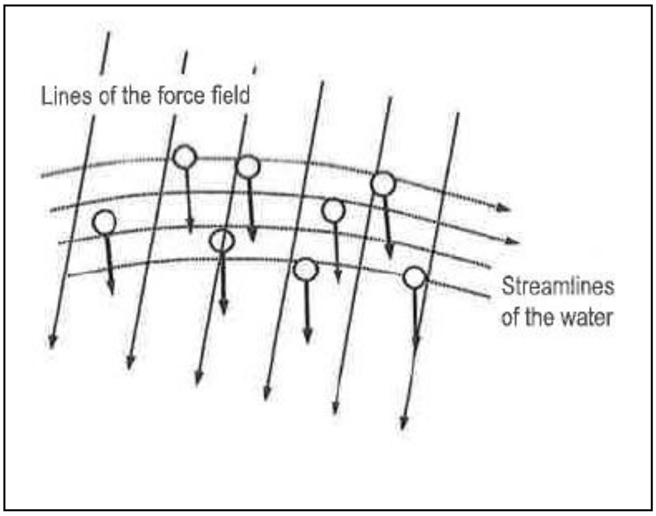



**Figure 3.7: if outside forces affect particles, they are diverted from the flow field by sedimentation (Gujer, 2008) Page 45)**

Stoke (1851) deduced what later became Stoke's law, which describes the interaction of smaller particles with the surrounding fluid. It applies to spherical particles within the laminar sedimentation range ($Re_p$<1, small sedimentation velocities):

$v_s = \frac{1}{18} \cdot \frac{\rho_p - \rho_w}{\rho_w} \cdot \frac{g}{v_w} \cdot d_p^2$ [m/s] if $Re_p < 1$ ………….………Eq. 2.13

$Re_p = \frac{v_s \cdot d_p}{v_w}$ = Reynolds number for sedimentation ………….………Eq. 2.14

Where $v_s$ = sedimentation velocity [$LT^{-1}$]

$\rho_p, \rho_w$ = density of the particle and the water [$M_iL^{-3}$]

g = acceleration due to gravity, g = 9.81 [$m/s^2$]

$v_w$ = Kinematic viscosity of the water, 1.0034 [$mm^2/s$] at 20 °C

$d_p$ = ball diameter of the particle [L]

For sedimentation in the turbulent range ($Re_p$ > 2000) one finds empirically approximately:

$v_s = \sqrt{\frac{8}{3} \cdot \frac{\rho_p - \rho_w}{\rho_w} \cdot g \cdot d_p}$ [m/s] based on a drag coefficient of $C_w$ = 0.5 ……Eq. 2.15

Equations 2.12 and 2.14 are plotted in Figure 3.8. The sedimentation velocities of bacteria ($d_p \approx 1\mu m$) up to stones with a diameter of 1cm vary by a factor $10^7$.

If sedimentation and advection overlay, then the two flows of the material add:

$$\overrightarrow{J_{tot}} = \overrightarrow{J_A} + \overrightarrow{J_S} = (\vec{v} + \overrightarrow{v_S}) \cdot C \qquad \text{.............Eq. 2.16}$$

The intensive mass balance equation in one dimensional form becomes:

$$\frac{\partial C}{\partial t} = -(v - v_s) \cdot \frac{\partial C}{\partial x} + r \qquad \text{..................2.17}$$

Since sedimentation and advection frequently occur in different directions, a one-dimensional model may not be sufficient to capture the details. Different mathematical models regarding sedimentation can be determined by considering different aspects e.g. sedimentation in centrifuge, sedimentation of bacteria and algae, temperature and sedimentation, Gravitation and sedimentation.

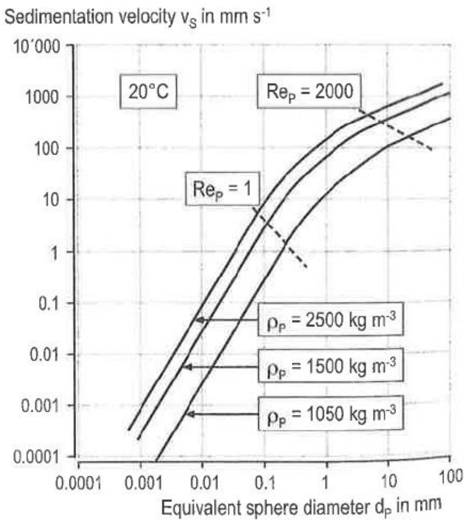



**Figure 3.8: Sedimentation velocity of spherical particles under gravity in pure water at 20 °C (Gujer, 2008)**

# 4 Chapter – 4 Experimentation/Field Study

This chapter discusses the materials and methods used for sampling, development of new apparatus and experimentation in this research work.

In the first part of chapter, the sampling is discussed in detail including sampling site selection and sampling procedures. The development of new apparatus will be presented in the next part including the procedure for selection of this apparatus. The third and last part discusses the experimental procedures for this newly developed apparatus along with variation at laboratory and on-site

## 4.1 Sampling

Sampling is one of the basic parameter in the reliability of any experiment / result. It is very important to consider all the things required for a comprehensive sampling. There are different types of sampling mentioned in books and literature i.e. grab sampling, composite sampling, random sampling. The experiments in this research work were performed by using all types of sampling to see how the experiments behave with different types of sampling. In the end the best method of sampling was chosen on the basis of results. Sampling was done by adopting the standard method ÖNORM EN ISO 5667-3. The sampling location matters a lot in collection of a representative sample. So many points were investigated for the obtaining the representative sample. The target area is highlighted in Figure 4.1 in the diagram of Graz WWTP.

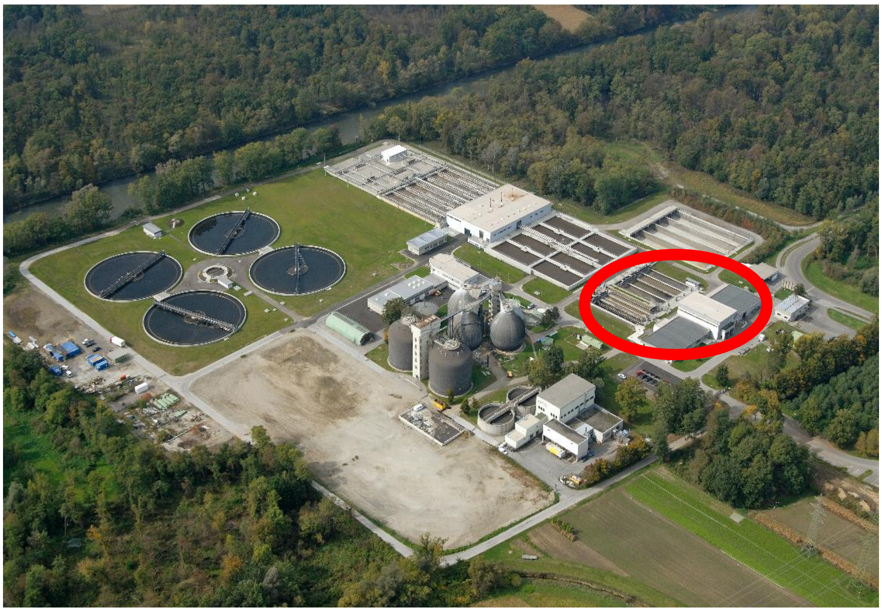


**Figure 4.1: Target Area at Graz WWTP and sampling points**

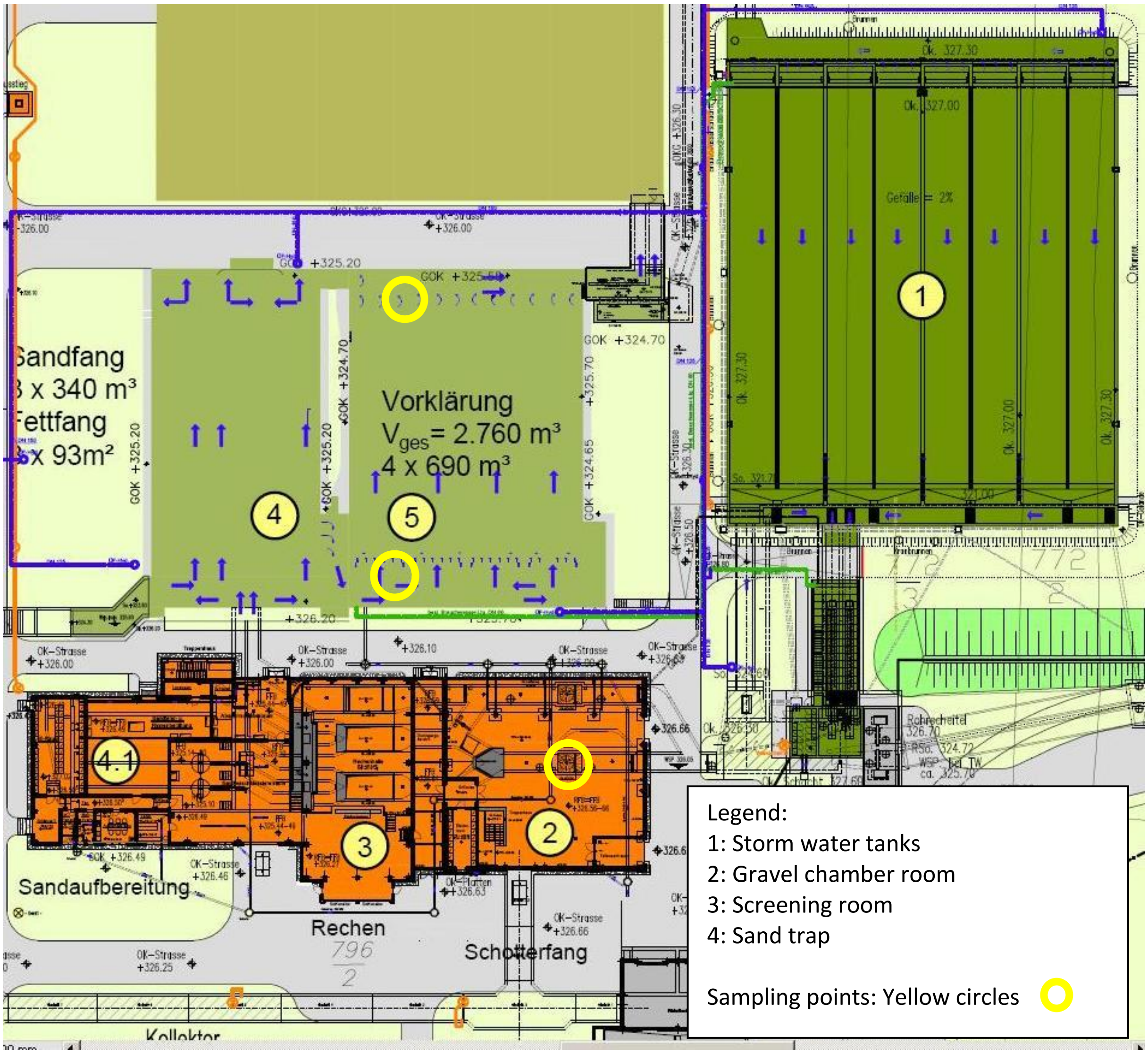



**Figure 4.2: Sampling points at Graz WWTP**

There were three places from where samples collected. These three places are shown in one glance as yellow circles in Figure 4.2.

### 4.1.1 Gravel Chamber

The sampling for raw wastewater was done at the entrance point of Wastewater treatment plant prior to any treatment/screening. There were two chambers at the entrance of Graz Wastewater Treatment Plant, from where samples can be collected. One chamber was mostly in operation. Other chamber became operational in case of excess flow. In this strongly aerated chamber, there was a lot of turbulence which is very good for mixing the wastewater, as shown in Figure 4.4. There was a good chance to obtain a good representative sample from here. The layout plan of the gravel chamber is shown in Figure 4.3, in which the sampling points are also shown as sampling point A & B. Sampling point A is used in most of the experiments at laboratory level and for first two experimental campaigns of Onsite experiments.

Sampling point B is used in all experiments of the final campaign of Onsite experiments at Graz WWTP.

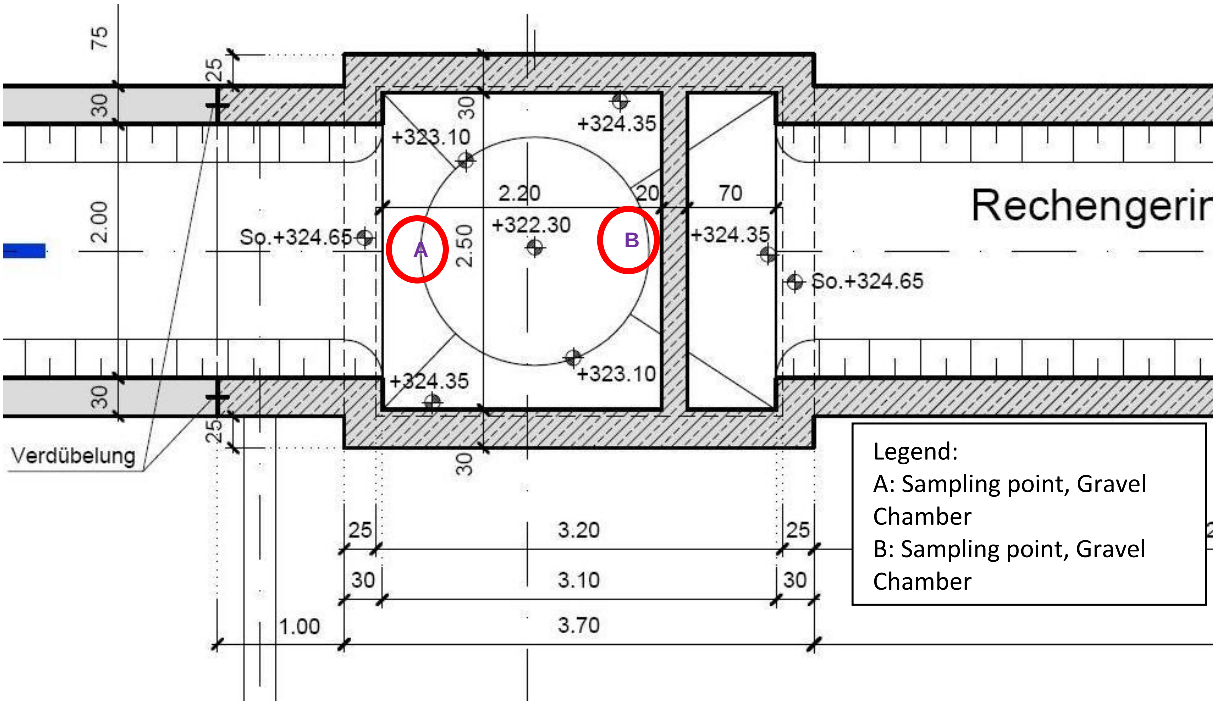



**Figure 4.3: Layout plan of Sampling site Gravel Chamber**

**Figure 4.4: Sampling site Gravel Chamber**

The cross-section of the gravel chamber is shown in Figure 4.5. The depth of the gravel chamber can be seen from the figure. The samples were collected from half meter above the bottom level of the gravel chamber. An assembly is made for this purpose with the help of technical staff of my Institute 'Institute of Urban Water Management and Landscape Water Engineering'.

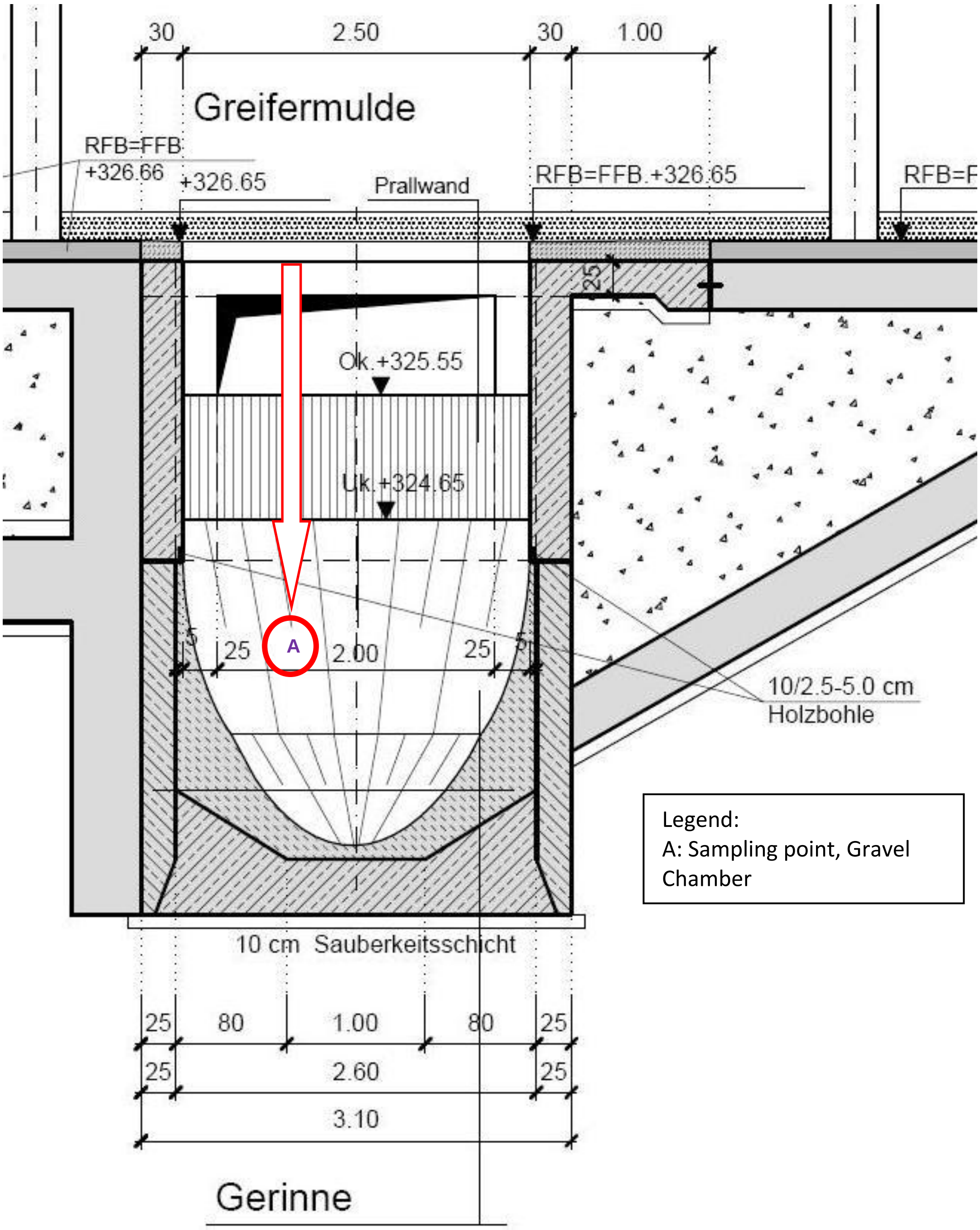



**Figure 4.5: Cross-section of the sampling location – Gravel Chamber**

This assembly constituted on a Wood column of length more than 4m. Sampling pipe was clamped on one side of wooden post, while other side was free. When this wooden side was inserted in the chamber, the free/blank side of wood was in front of the flow of waste water while sampling pipe is behind the wooden post. The purpose of this arrangement was to avoid blockage in the pipe. If there are fewer blockages, frequent and best sample can be obtained. This wooden post was fixed in such a position so that sample can be collected from the centre of chamber, as shown in Figure 4.6. The auto-sampler was used for composite and grab sampling. This auto sampler can take sample at the flow rate of 4L/min.

**Figure 4.6: Assembly for collection of sample from Gravel Chamber**

### 4.1.2 Influent Primary Settling Tank

There was a point selected in between the sand filtration tank and primary sedimentation tank where wastewater was properly mixed and there was greater chance of getting a representative sample from this point. The layout plan of the primary settling tank is shown in Figure 4.7. This figure highlights the sampling points at both selected ends of the primary settling tank. The sampling point ‘C’ was selected to collect the sample for Influent Primary Settling Tank, while sampling point ‘D’ was selected to have a representative sample of effluent of Primary Settling Tank. The Figure 4.8 highlights the sampling point for Influent primary settling tank. The exact location of sampling can be seen from the figure. This sampling point is at the channel which transports the wastewater from sand filtration tank to primary settling tank.

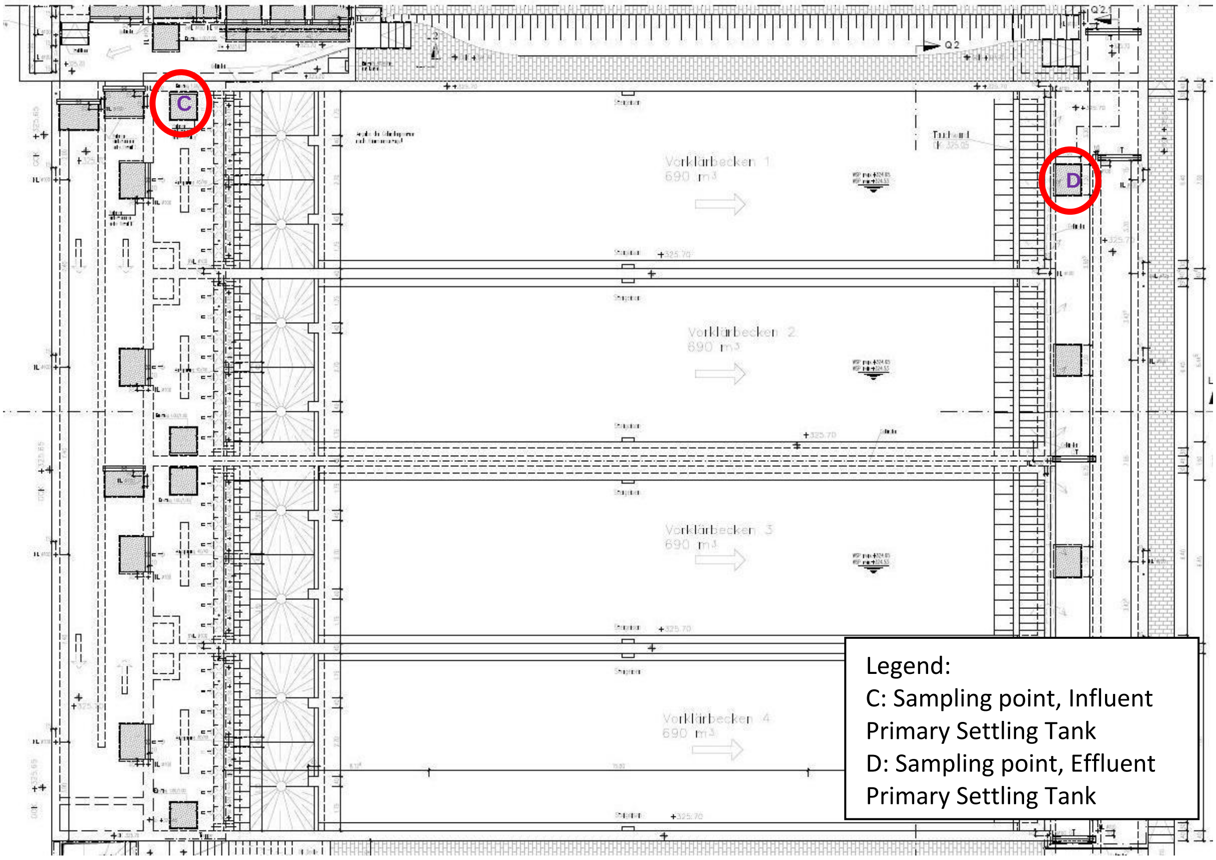



**Figure 4.7: Layout plan of Sampling points at Primary Sedimentation Tank**

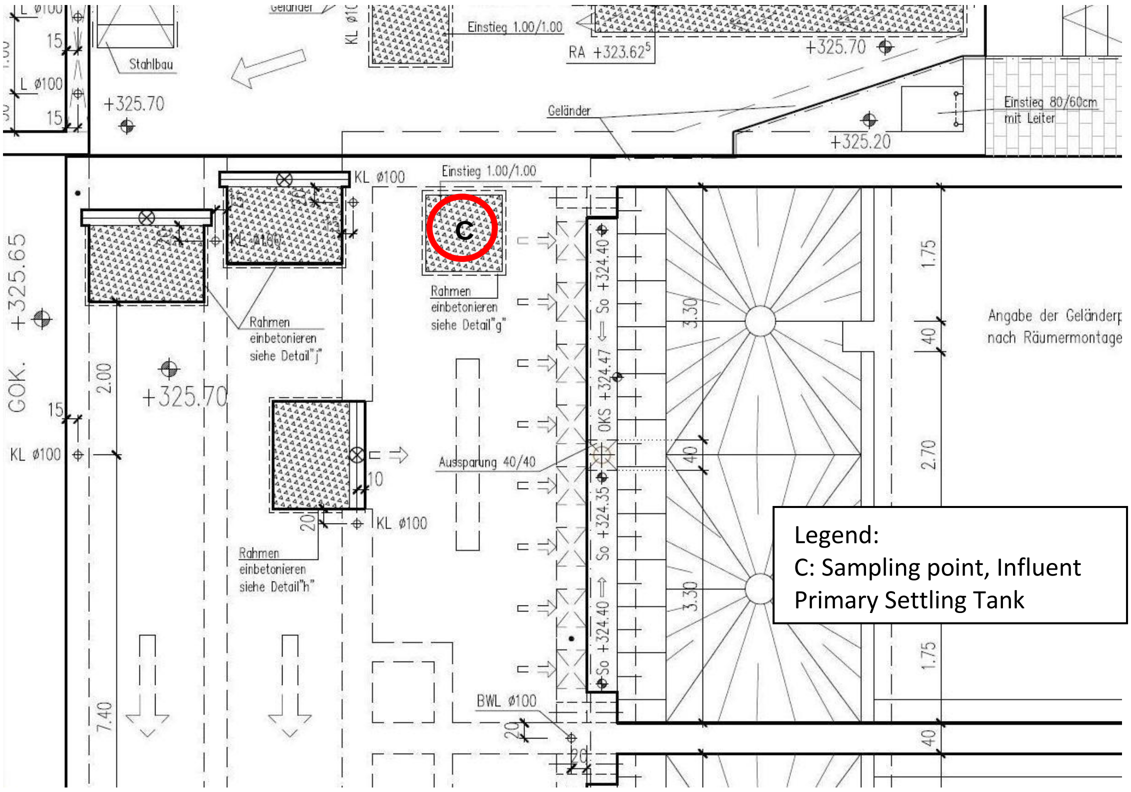



**Figure 4.8: Layout plan of Sampling point at Inlet Primary Sedimentation Tank**

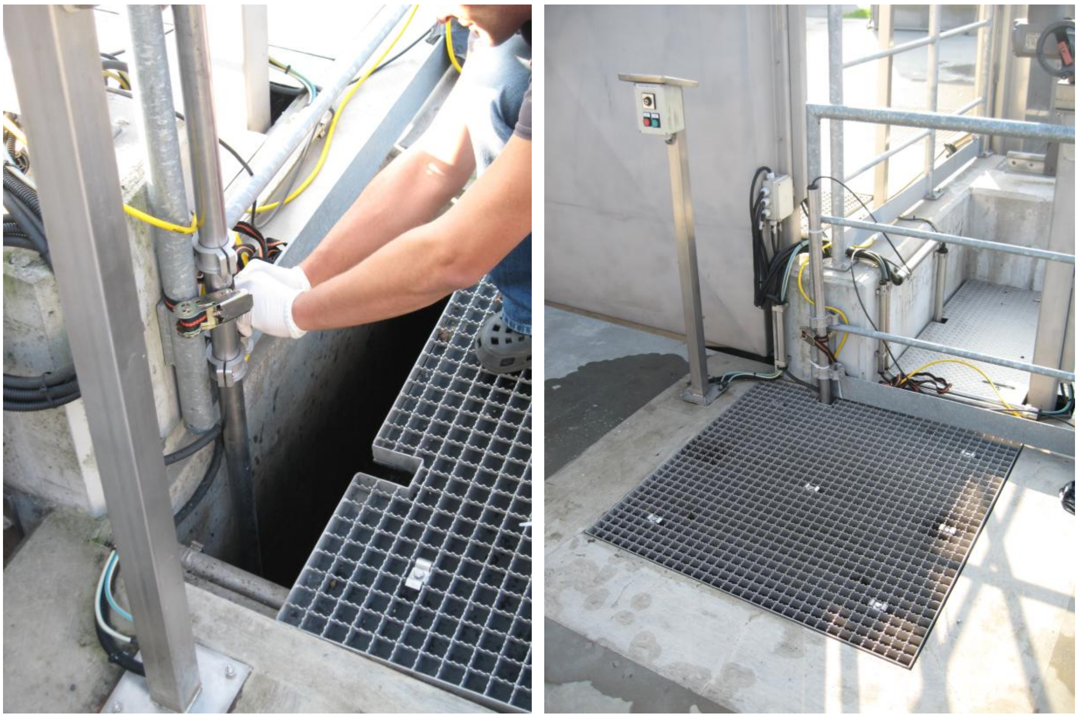


**Figure 4.9: Sampling point at Influent Primary Sedimentation Tank**

A special arrangement was made for this purpose. A sampling hose was attached with L-shape steel bar and inserted in the wastewater at a proper depth so that we can collect sample from the centre of the chamber, as seen in Figure 4.9 and Figure 4.10. The exact position of the sampling point can be seen from the Figure 4.11, in which the cross-section of the sampling point is shown. The same arrangement was done with this steel bar to avoid any blockage in the sampling hose. An auto sampler was used to collect the sample with the sampling hose with the flow rate of 4L/min. A 10 Litre sample was collected at once for one time usage for the experimentation work.

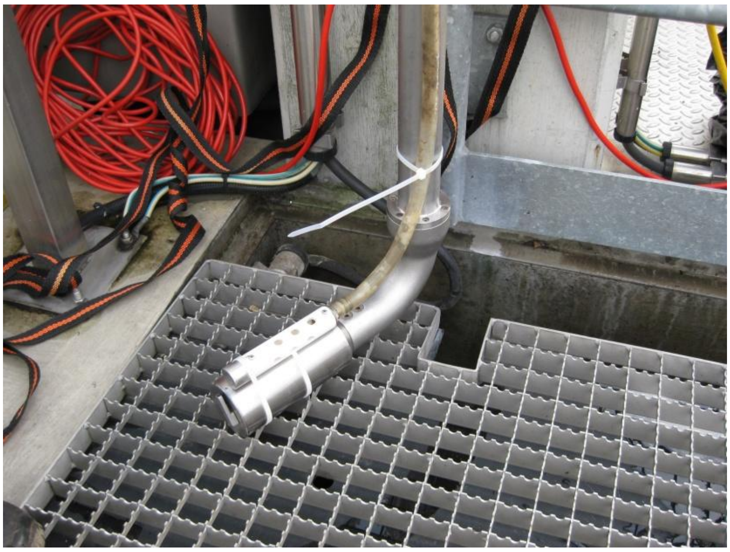


**Figure 4.10: Solitax and TS-probe parallel**

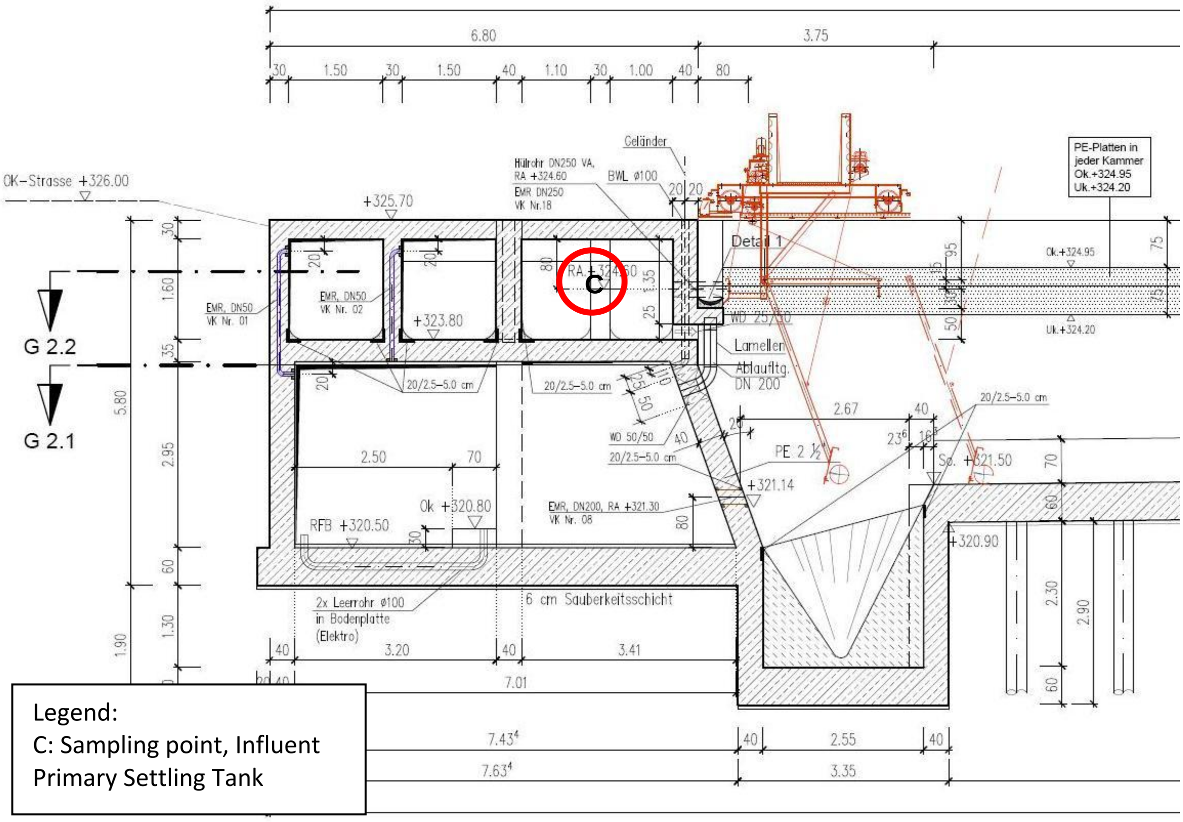



**Figure 4.11: Position of sampling point in cross-section – Influent Primary Settling Tank**

### 4.1.3 Effluent Primary Settling Tank

The third sampling point was at the exit of the primary sedimentation tank of Graz Wastewater Treatment Plant. The chamber was selected for sampling where wastewater after primary sedimentation goes into the biological tanks. Sample was taken almost from the centre of the chamber to obtain a representative sample. The same assembly was made for collection of sample as for influent primary settling tank, as shown in Figure 4.13. Auto-sampler was used for taking the sample at the flow rate of 4L/min. The sample volume for one time experimentation in duplicate required about 10 L. The layout of the outlet of the primary settling tank is shown in figure Figure 4.12, in which the sampling point for collection of effluent sample is highlighted with red circle and named as ‘D’. The cross-section of this sampling point is shown in Figure 4.14 from which it can be estimated that at which height the sample is collected.

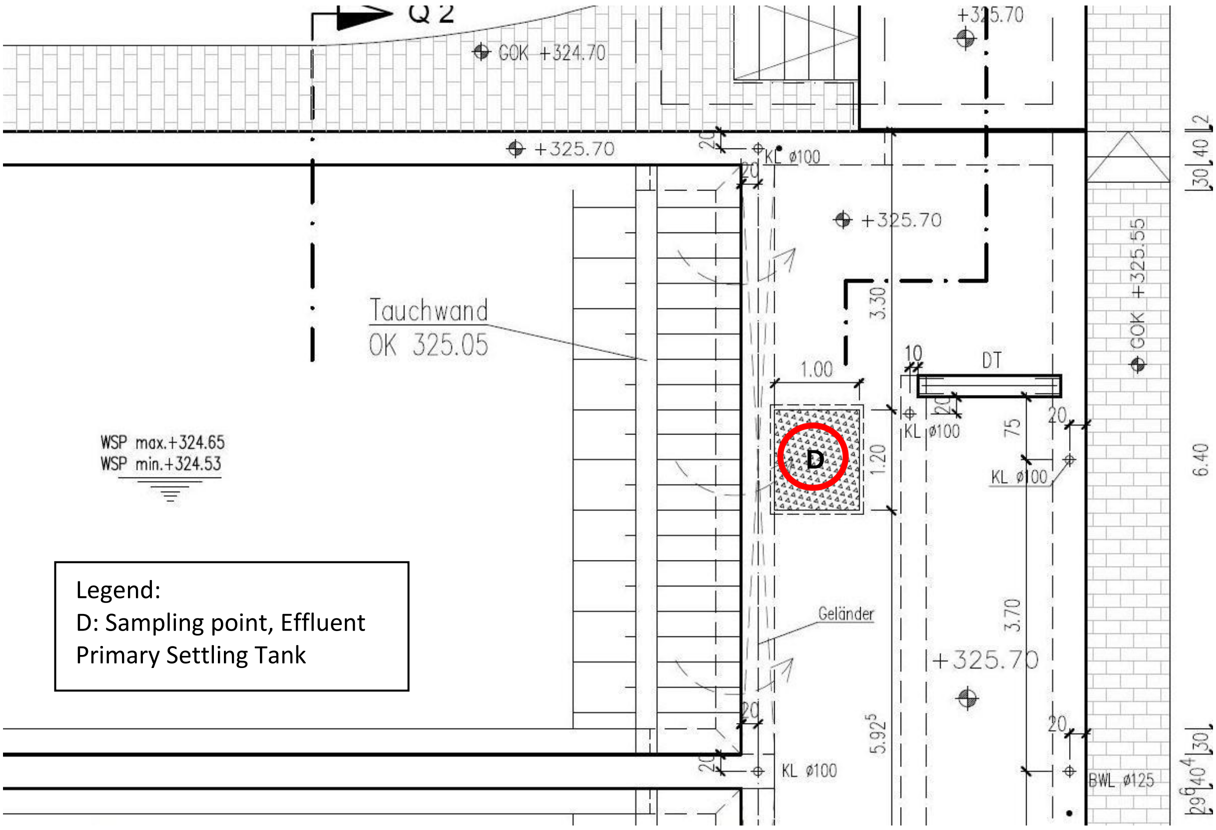



**Figure 4.12: Layout plan of Sampling point at Outlet Primary Sedimentation Tank**

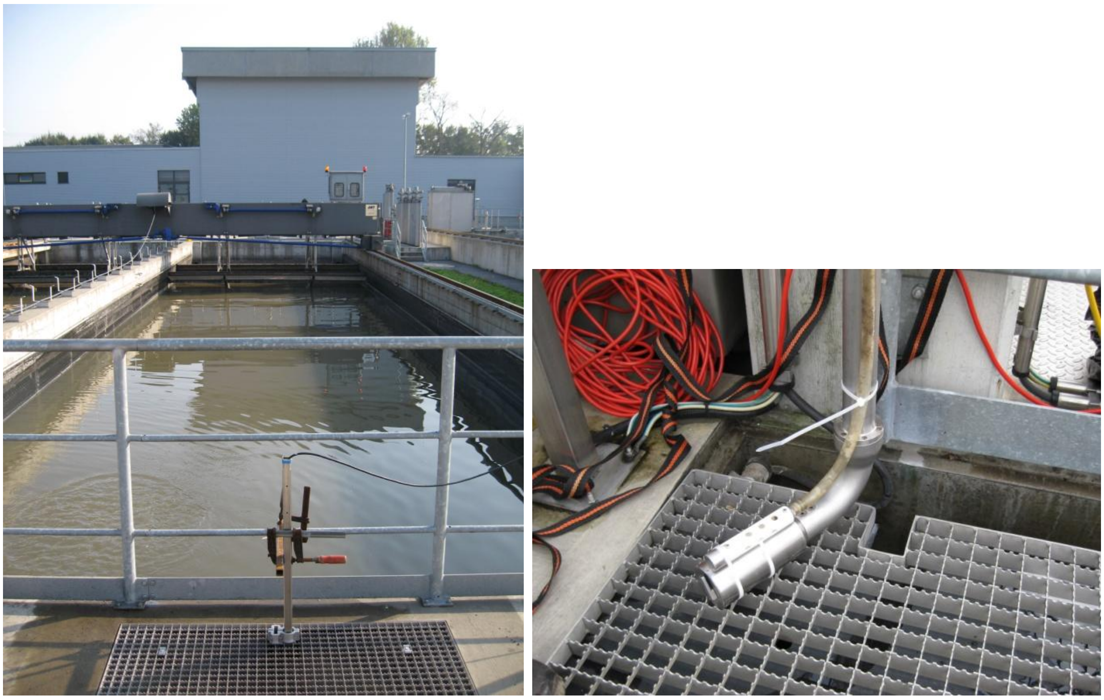


**Figure 4.13: Sampling point at Outlet Primary Sedimentation Tank (Camera Image) / Solitax and TS-probe parallel**

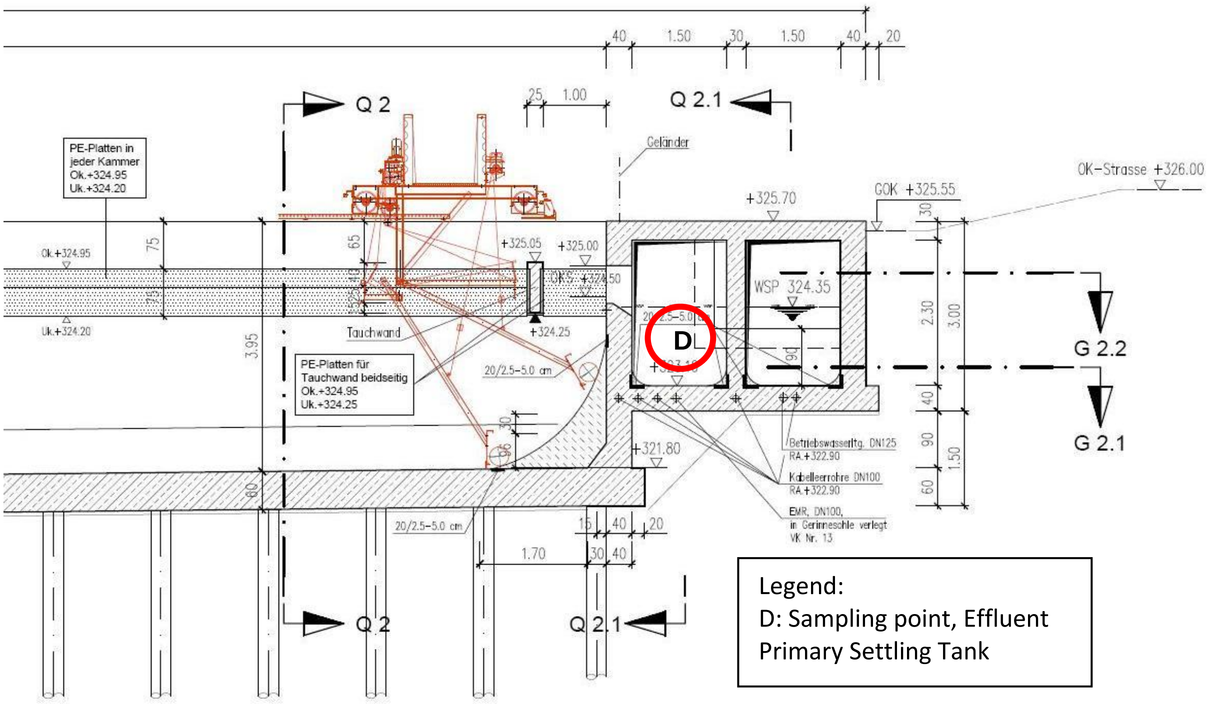



**Figure 4.14: Position of sampling in cross-section – Outlet Primary Settling Tank**

### 4.1.4 Sampling Time Interval

Sampling time interval means the difference in time for collecting sample from all three different locations. This is one of the main considerations which one has to keep in mind before making a sampling plan. If the almost exact time interval is known then it will be possible to have almost the same sample at three different locations. This depends on the flow rate and the processes in between these three points and weather conditions. It has been calculated that the Graz WWTP wastewater needs about 20 – 25 minutes to travel from Gravel Chamber to Primary Settling Tank and theoretically the retention time for primary settling tank is 01 hour (Vicuinik, 2012). It means that if a sample is collected at 8 a.m. from Gravel Chamber then next sample should be collected from influent Primary Sedimentation Tank at 08:20 a.m. The next sample from effluent Primary settling tank should be taken at 09:20 a.m. It complete one sampling cycle. This calculation applies only for Graz WWTP. It can be different for different wastewater treatment plants.

## 4.2 Settling Apparatus

A settling apparatus (Figure 4.15) has been developed at the Institute of Urban Water Management and Landscape Water Engineering at Graz University of Technology (Aslam et al., 2010). This apparatus was constructed with some major modifications in the apparatus reported by (Tyack et al., 1996). They used this apparatus for the determination of settling velocity.

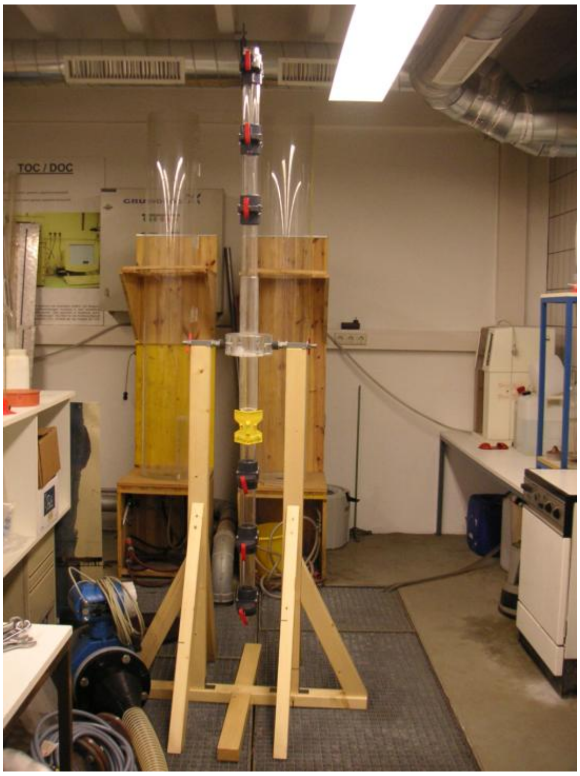



**Figure 4.15: Settling Apparatus in real (Aslam et al., 2010)**

There were many other apparatuses constructed/used by many researchers (Aiguier et al., 1996; Michelbach & Woehrle, 1993; Tyack et al., 1992; Maus et al., 2008) for the determination of one or two settling Parameters i.e. Settling Velocity etc. The purpose of this innovation was to develop a single tool to address all the settling parameters which are necessary for settling studies. The settling apparatus shown in Figure 4.15, was constructed due to the following reasons; To measure the maximum possible fractions in wastewater (05 fractions in this column); To use the real height of column (2m), presenting a physical model; The diameter of the column is such that no blockage can occur, which shows real time picture of the settling tanks; To mix the wastewater sample properly by rotating at 360 degree, after filling it.; To make the visual analyses of particle size and settling velocity with the help of videos; A volume of 4 Litre sample is required, which is quite fair enough to make the settling experiments.; With this construction, it is possible to take wastewater samples from all the five fractions separately. These samples then can be analysed in the laboratory for different parameters of settling and pollution associated with the particles present in wastewater sample.

The characteristics of the raw wastewater are very much different from secondary sludge. In raw wastewater the solids are in scattered form. They don't form complexes so easily. It is very difficult to measure all the settling parameters at one place.

With this apparatus the settling fractions, the settling behaviour in each fraction, settling velocities of each fraction, size and shape of particles, organic and inorganic solids, and flow of wastewater were determined. In addition to these parameters, the quality parameters were also measured in laboratory and on-site i.e. Chemical Oxygen Demand (COD), pH, Conductivity, Temperature etc. This information about the settling of solids with this apparatus will be helpful in improving efficiency of the primary sedimentation tanks, storm water tanks and a better understanding about the sedimentation efficiency of solids in raw wastewater. The quality parameters help us to understand about the pollution load carried by these solids in raw wastewater.

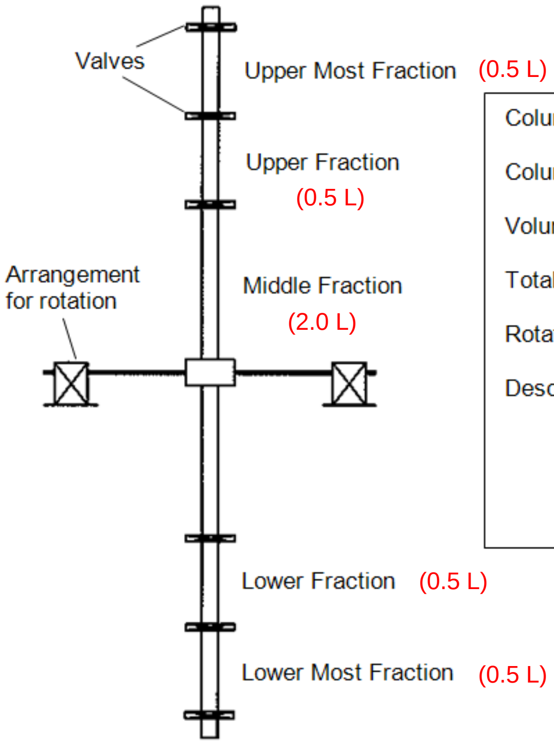
### 4.2.1 Construction of Apparatus

The settling apparatus consists of a long transparent column of about 2 meter in length and 50 mm in diameter. The material used is acryl glass. The transparent material is used to have a clear view about the settling processes in the column. Five fractions were made by using six valves as shown in Figure 4.16. These valves are made in such a way that it opens and close in the sliding way. This type of valves helps us to perform experiments without disturbing the wastewater in that fraction at the time of opening and closing that particular fraction.

**Figure 4.16: Valves of the settling column**

There is some space given on both sides on both sides of column to hold on the last valves. This big column is fixed on the wooden rest as shown in Figure 4.15 and Figure 4.18, so that it can be rotated at 360 degree. The construction of this apparatus is very easy and it is also not expensive. It can be moved easily from one place to another.

**Figure 4.17: Assembly for holding the settling column**




| | |
|---|---|
| Column diameter: | 50 mm |
| Column length: | 2.194 m |
| Volume used in column: | 4 L (approx.) |
| Total zones: | 5 |
| Rotation facility at 360 degree: | Yes |
| Description of zones (fractions): | Lowermost, Lower, Middle, Upper, Uppermost fraction. |

**Figure 4.18: Sketch of Settling Apparatus (Aslam et al., 2010; Aslam et al., 2011b)**

### 4.2.2 General Procedure

The operation of this apparatus is described below:

1. An approximate 4 Litre sample of raw wastewater is required to perform experiment on this apparatus.
2. As shown in Figure 4.18, the column has five different zones. Each zone is controlled by valves. Both the lower and upper zones have an approximate volume of 500 mL. The fifth zone in the middle of the column is the largest, with a volume of 2000 mL.
3. The column is filled with well mixed wastewater with the help of a peristaltic pump.
4. This wastewater is filled with the peristaltic hose entering the column from the top and leaving wastewater at the bottom of the column, so that no pre-settling can occur. The filling time is less than one minute.
5. After filling the column, the column is rotated at 180 degree and stay there for one minute, and then the column is rotated again at 180 degree. The settling process of the solids starts afterwards. This step is performed to mix wastewater within the column.
6. The settling fractions can be controlled and separated with the help of easy going valves.
7. After the desired time, the valves will be closed according to the fractions required.
8. Empty all the fractions, mark them and then analyze these fractions for TSS and other selected parameters in the laboratory.

Normally there are 5 different fractions in this column, but some experiments were also performed with different possibilities of fractions, i.e. 2, 3, 4 etc. These trials were tested for settling time ranges from 3 minutes to 2 hours. These procedures were implemented in the laboratory as well as on site at Graz wastewater treatment plant.

## 4.3 Experimentation in Laboratory

The initial experiments were performed in the institute laboratory to evaluate the newly developed apparatus and to make a base for broader level studies. The newly developed apparatus is first tested many times with the clean water to check the leakage and functions of its valves. The wastewater samples were collected initially only from Gravel Chamber of Graz wastewater treatment plant to have a clear and comprehensive picture about raw wastewater.

### 4.3.1 Procedure

- A 20 Litre sample of wastewater is collected from Gravel Chamber of Graz wastewater treatment plant.
- It is transported immediately from Graz WWTP to Institute Laboratory according to standard sampling, storage and transfer procedure.
- As 4 Litre sample is used for one time experiment in settling apparatus, so this samples was tested 5 times for different settling fractions and settling time variations.
- The experiment was performed following the general procedure as mentioned above in 4.2.2. with a slight variation at the laboratory level which is mentioned as below:
    - The settling column was filled with the help of peristaltic pump with the flow rate of 4L/min.
    - After filling the column, the uppermost valve is closed after slight movement in the column so that if there is any air in the column, it will be blown away.
    - As the column is closed from both sides so now it is rotated at 180 degree and stay in this position for 01 minute and then rotated again at 180 degree. This step is done to properly mix the wastewater and to avoid any fast settling during filling of column.
    - A settling time of 2 hours is given for the first experiment, as for Immhoff cone the standard settling time is 2 hours.
    - After 2 hours, all the other five valves were closed.
    - The wastewater from all the fractions was taken out in the designated bottles.
    - These five fractions were analyzed in the laboratory for total solids with membrane filtration method in duplicate.
- The quality parameters were also analyzed which will be discussed in the next heading.

#### 4.3.2 Quality Parameters

The understanding about the pollution associated with the solids in wastewater is necessary to plan a comprehensive policy about the reduction of solids from wastewater. The critical situation caused by these solids can be known with the quality control checks. If the intensity of pollution caused by the solids (which are discharged in the water bodies without any treatment) is known, then the importance of these settling processes and practices can be realized.

The following parameters were analysed for all the experiments at Wastewater Treatment Plant Graz:

- Total solids
- Organic Solids
- Inorganic Solids
- Settelable solids
- Non-Settelable Solids
- Chemical Oxygen Demand (COD)
- pH
- Conductivity
- Temperature

All these parameters were tested in the Institute laboratory with the help of expert laboratory staff according the standard procedures (APHA, 2005).

Total Solids are measured in by using a membrane method (ÖNORM M 6273). The wastewater sample is properly homogenized. A specified volume of water sample is taken from homogenized wastewater sample. The volume of wastewater sample depends on the contamination of wastewater. Normally 50mL sample is taken. Take a membrane filter paper and weigh it. Fix the membrane filter paper at the bottom of the measuring cylinder. Put the sample in the cylinder and open the vacuum attached to this cylinder. After a specified time, the cylinder is detached. Take the filter paper and then dry it in oven at 100 – 105 °C. When the filter paper gets dried then cool it at room temperature and then take a weight. Now use the formula to determine the TSS concentration in wastewater. It is measured in mg/L

Organic and inorganic solids are determined by using the standard method ÖNORM M 6274. These solids are after the determination of TSS concentration. The dried filter paper after the TSS determination is placed in the crucibles. Take the weight of the empty crucibles and note it down. After placing the dried filter paper in crucibles, weigh it again and note it down. Put the crucibles in an oven at a temperature of more than 800 °C. After specified time, turn off the oven and cool down the crucible at room temperature. Take the weight of crucibles again. Use the formula for the determination of organic and inorganic solids. It is normally measured in grams and percentages.

Settleable/Non Settable solids are measured by Imhoff cone with the standard procedure of determining the settleable solids . The settling time is given 02 hours. After some time the wastewater in the Imhoff cone is stirred gently so that the wastewater should not be disturbed. This experiment is done in triplicate to get the reliable results. It is normally measured in volume (mL/L)

The COD test is measured for the samples of wastewater from different fractions in the Institute laboratory, by using the standard method ÖNORM M 6265. The samples are properly homogenized before testing. HACH method is used for testing COD. A specific volume of the sample is to be poured in the HACH vial, depending on the concentration of COD. Then this vial is placed in a HACH digestion apparatus for 02 hours at a temperature of 150 C for digestion. After 02 hours, the vials are cooled down at room temperature. When these vials attained room temperature, then HACH colorimeter is used to determine the concentration of COD. This concentration is measured in mg/L.

The last three parameters pH, conductivity and temperature are measured on-site by using the respective calibrated meters (pH meter, Conductivity meter) of the Laboratory of Institute of Urban Water Management and Landscape Water Engineering, Graz university of Technology Graz. The standard methods used for the measurement of pH, Conductivity and temperature are ÖNORM M DIN 19266, ÖNORM EN 27888 and Din 38404-4 respectively.

## 4.4 Experimentation at Graz WWTP

After a successful experimental campaign at laboratory level, it was decided to extend the experimental work at broader level. Three more same settling apparatuses were constructed at the Institute. These three apparatuses were constructed to do parallel experiments with the fresh samples On-Site. The sampling points were also increased from 01 to 03. These three sampling sites include Gravel Chamber, Influent Primary Sedimentation Tank and Effluent primary Sedimentation Tank. The sampling procedures were already described. These three sampling sites were selected to have a better understanding about the chemistry of solids in raw wastewater, in wastewater after screening and Grit removal chamber and in wastewater after primary sedimentation. With this study it is possible to have a better look on the settling behaviour of solids prior to biological tanks.

About 30 more trials were performed at Graz WWTP on these four settling apparatuses. These trials includes

- Experiments with the same laboratory procedure but with the direct on-site samples and from all three sampling sites. These experiments were performed to see any difference between Onsite samples and transferred samples (samples transferred from Graz WWTP to Institute, as used in laboratory experiments).
- Detailed experiments with different settling time of less than 10 minutes i.e. 3 minutes, 5 minutes and 10 minutes.
- Detailed experiments with the settling time of 10 minutes and 30 minutes for dry and wet weather events, for all three sampling sites.
- Experiments with different procedures from laboratory.

### 4.4.1 Procedure of experiments

There are three types of procedures other than the laboratory procedure, mainly used for experiments at Graz WWTP. These procedures can be classified on the basis of filling the column with the wastewater. A lot of difference in results is observed and estimated by changing the filling method. The procedures are as given below.

#### *4.4.1.1 Procedure – filling of column with autosampler / peristaltic pump*

- The wastewater is taken from the Gravel Chamber with the help of autosampler/peristaltic pump at the flow rate of less than 4L/min.
- The settling column is filled with this autosampler / peristaltic pump directly from the Gravel Chamber.
- The settling column is filled in less than 1 minute and proper measures are taken to avoid any pre-settling.
- After filling the column, the same procedure is applied as in general procedure or laboratory procedure.

- The settling fractions were reduced to three at Graz WWTP experiments on the basis of laboratory results and also initial On-Site results.

#### *4.4.1.2 Procedure – filling of column with Normal pump*

- The sample of wastewater is taken from Gravel Chamber with the help of Normal pump. It was a very strong pump.
- The pump was dropped in the centre of the Gravel Chamber to obtain a good representative sample.
- It fills the column with a lot of pressure and in few seconds.
- After filling the column, the same procedure applied as in General Procedure.
- The drawback of this filling method is that due to enough pressure there is wastage of sample during filling. There is also a less chance of representative solids in this wastewater.

#### *4.4.1.3 Procedure – Manual direct filling of column*

- The wastewater sample is taken from the sampling site with the help of normal pump in one bucket of 10 Litre. It fills in few seconds.
- The sample collected in the bucket is mixed with a strong stirrer and transferred more than 4L in beaker.
- This beaker is then stirred gently and inserted in the settling column manually at once.
- It will be filled in few seconds without any wastage of the sample.
- After filling the column, the same procedure applies as described in general procedure.
- It is considered as most reliable and improved method on the basis of results.
- The initial experiments were also performed again with this method and found reliable method.

### 4.4.2 Comparison with Solitax

An online system was operated in parallel to experiments on settling apparatus. This instrument used in this system is named as SOLITAX. It consists of a steel L-shaped rod having sensors at the bottom front and connected to the computer. It measures the online concentration of TSS and flow in influent and effluent of the primary settling tank (Vicuinik, 2012). The results of the experimental campaign – 3 is compared with Solitax and presented in next chapter.

### 4.4.3 Quality Control

The quality parameters were also tested for all the experiments at Graz WWTP. The tests for Chemical Oxygen Demand were reduced due to some financial limitations. Other tests were performed with the same frequency.

## 4.5 Final procedure

The finalized procedure for operation of this apparatus is described below:

1. An approximate 4 Litre sample of raw wastewater is required to perform experiment on this apparatus.
2. As shown in Figure 4.18, the column has five different fractions. Each fraction is controlled by valves. Both the lower and upper fractions have an approximate volume of 0.5 L. The fifth fraction in the middle of the column is the largest, with a volume of 2 L. The finalized fractions are reduced to three fractions. These fractions are classified as lower fraction (0.5 L), middle fraction (2.5 L) and upper fraction (1L)
3. The column is filled with the help of the following method:
   - The wastewater sample is taken from the sampling site with the help of normal pump in one bucket of 10 Litre. It fills in few seconds.
   - The sample collected in the bucket is mixed with a strong stirrer and transferred in beaker.
   - This beaker is then stirred gently and inserted in the settling column manually at once.
   - It will be filled in few seconds without any wastage of the sample.
4. After filling the column, the column is rotated at 180 degree and stay there for one minute, and then the column is rotated again at 180 degree and the settling process of the solids start. This step is performed to mix wastewater within the column.
5. The settling fractions can be controlled and separated with the help of easy going valves.

6. After the desired time, the valves will be closed according to the fractions required.
7. Empty all the fractions, mark them and then analyze these fractions for TSS and other selected parameters in the laboratory.

# 5 Chapter – 5 Results and Discussion

This chapter discusses the results of the experimentation both at laboratory and On-Site at Graz wastewater treatment plant. In the first part of chapter the results of the laboratory experiments performed on the settling apparatus will be discussed. The results of On-Site experiments will be discussed in the second part. In the end the results are compared with some other tools. The difference in dry and wet weather results, method improvement and mass balances are discussed in the end. The statistical graphs and table are used to explain and discuss the settling parameters. Microsoft Excel is used in this context.

## 5.1 Laboratory Experiments

The experiments on the newly constructed settling apparatus have been started in the laboratory of Institute of Urban Water Management and Landscape Water Engineering at Graz University of Technology. About 20 experiments have been performed in the laboratory on this apparatus with different procedures. These procedures include variation in filling method, settling fractions and settling time.

The wastewater tested in these experiments was taken from Gravel Chamber of Graz Wastewater Treatment Plant and Weiz wastewater treatment plant. Graz wastewater treatment plant was constructed for 500,000 population equivalent. It consumes all urban wastewater from Graz. Weiz is the neighbouring small city of Graz. The Weiz WWTP is constructed for 30,000 population equivalent. The wastewater samples are collected from Weiz wastewater treatment plant for comparing the results of different wastewater treatment plants.

The laboratory experiments were performed in dry as well as wet weather to analyze and understand the behaviour of solids in both cases.

### 5.1.1 Sampling

The wastewater samples are obtained from Gravel Chamber of Graz wastewater treatment plant (WWTP). Gravel Chamber is the first chamber at the entrance of Graz WWTP. The representative sample of urban raw wastewater can best be available at this point. It is mixed by middle bubble sized aeration, so there is best chance of obtaining a well-mixed sample. Sampling is done by using the standard methods (APHA, 2005).

### 5.1.2 Settling Apparatus

The development and procedure of settling apparatus is discussed in detail in the last chapter. In the Figure 5.1, the fractions of settling column is shown along with its volume and number of total suspended solids e.g. (TSS # 1, TSS # 2,…..). TSS#1 is the lower most fraction, TSS#2 is one step higher than the previous fraction called lower fraction, TSS#3 is the middle fraction, TSS#4 is upper fraction, TSS#5 is the uppermost fraction. The fractions will be discussed in the whole chapter with these numbering. The lower two (TSS # 1 & 2) and upper two (TSS # 4 & 5) have same volume of 500mL each. The middle fraction (TSS # 3) has a maximum volume 2000mL. The question is why these five fractions were made? The answer is that as some solids settle fast, these can be best analyzed in the 2 lower fractions and some floats which can be best accommodated in the upper fraction, there are some solids which remain suspended and don't go in the upward or downward direction, they will be accommodated in the middle fraction. The height of 2 meter is given to column so that it gives an orientation of the sedimentation tank.

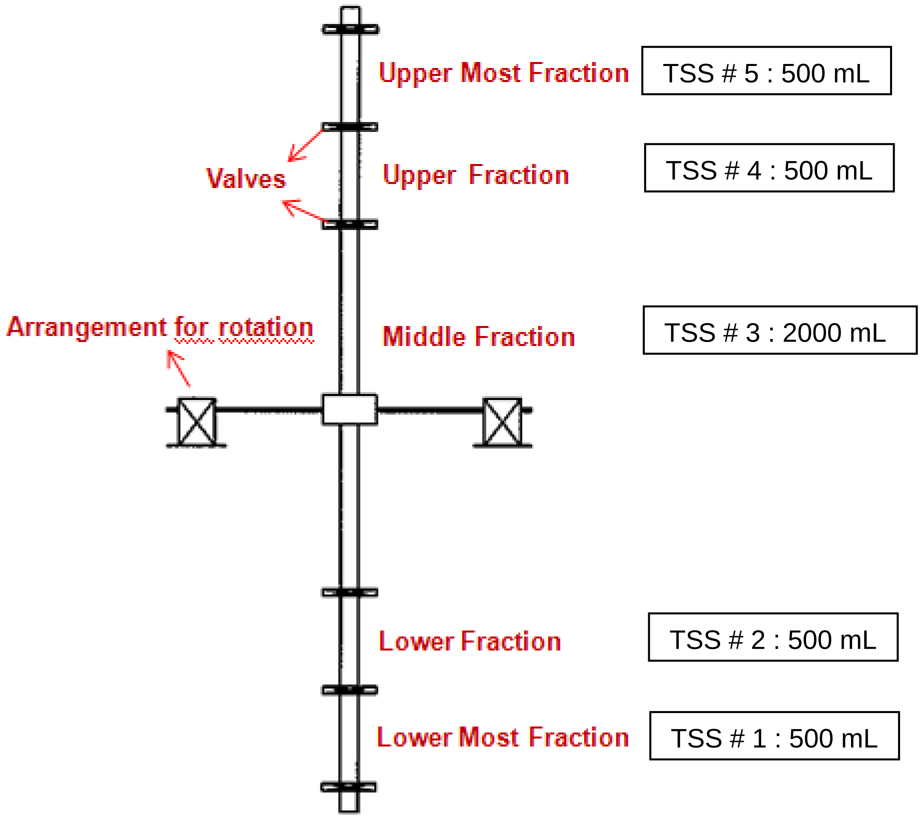



**Figure 5.1: Settling Apparatus with names, numbering and volume of fractions**

The effort is to make such a tool which can better explain the settling processes in dry and wet weathers and can be helpful in the estimating efficiency of Primary Sedimentation Tank and Combine Sewer Overflow Tanks or Strom Water tanks.

### 5.1.3 Settling fractions and settling time

Initial experiments were performed with the complete 05 fractions as the instrument highlights with the standard settling time of 02 hours. Later on the experiments were performed with less settling fractions and variant settling time. The procedures of filling and rotating the column, were also changed during further trials. These different options were used to understand the settling processes in different conditions.

#### *5.1.3.1 05 Standard Fractions with settling time of 02 hours*

The standard method to determine settling of solids in wastewater is by using Imhoff cone with settling time of 02 hours (APHA, 2005). The settling apparatus is also used first for the settling time of 02 hours and with five fractions. The solids behave differently in different weathers. In dry weather the solids have good mixture of organic and inorganic solids, while in wet weather the rain water take different type of material with it in the sewers. In wet weather the flow of wastewater is also excessive and it completely fills the sewers sometimes, so it takes the solids attached to the sewer pipes inside. It can be said that the ratio of organic and inorganic solids is disturbed in wet weather as compared to dry weather. It is therefore necessary to evaluate and study the behaviour of settling of solids in both conditions. The two events were selected even for initial experiments i.e. Dry weather event and Wet weather event. The results of the dry and wet weather are discussed as follows:

##### *5.1.3.1.1 Dry Weather*

The experiment was performed with the standard procedure mentioned in the previous chapter. The results show the concentrations of total suspended solids (TSS) in five fractions. The maximum concentration is more than 1200 mg/L and it is in the lower most fraction. Figure 5.2 shows that there are five fractions according to the concentration. TSS # 1 indicates the lower most fraction (0.5 L), TSS # 2 is one step upper fraction (0.5 L), TSS # 3 is the middle fraction (2.0 L), TSS # 4 is upper fraction than middle (0.5 L) and TSS # 5 is the upper most fraction (0.5 L). The interesting result is that there is almost equal concentration in the fraction TSS # 4 (above than lower most fraction) and middle fraction (TSS # 3). These two fractions contain suspended solids which do not settle even for a settling time of 2 hours. The upper two fraction having a volume of 0.5 Litres each, contains the floating solids. The upper two fractions are showing the same concentration. The results show that wastewater have five fractions concentration wise not only due to this that apparatus has five fractions.

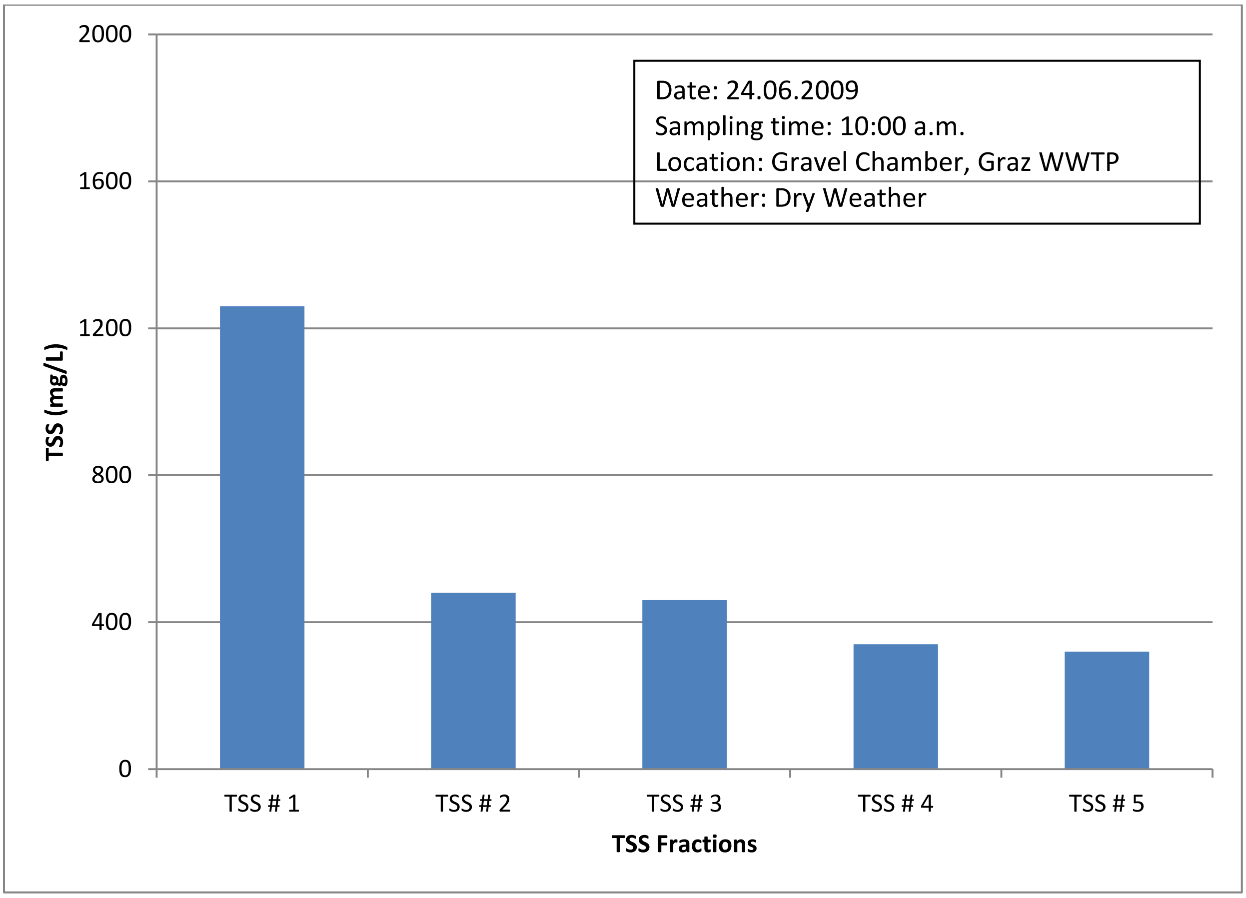



**Figure 5.2: TSS Concentration in 05 fractions with settling time 02 hours**

*5.1.3.1.2 Wet Weather*

The wastewater sample was taken from the Graz wastewater treatment plant and transferred to the Institute laboratory for further experimentation. The results in the Figure 5.3 show that there is an increase in the concentration of total suspended solids in all the fractions especially in the lower most fraction. The overall mass is increased in the wet weather results. The pattern of settling is same as for the dry weather i.e. most of solids settle in the lowermost fraction as usual. The fraction TSS#2 and TSS#3 shows that there are some solids in wastewater which flow upwards with the time and also remain suspended. The upward movement of solids in column starts after certain time. Some experiments were performed for estimating the time for upward movement. It has been estimated that the some solids starts moving upward during filling and in the initial phase of settling. This process remains in this condition till 10 minutes and after that there is a rare movement of particles in upward direction. It is obvious from the results that there are five fractions present in the raw wastewater even in wet weather.

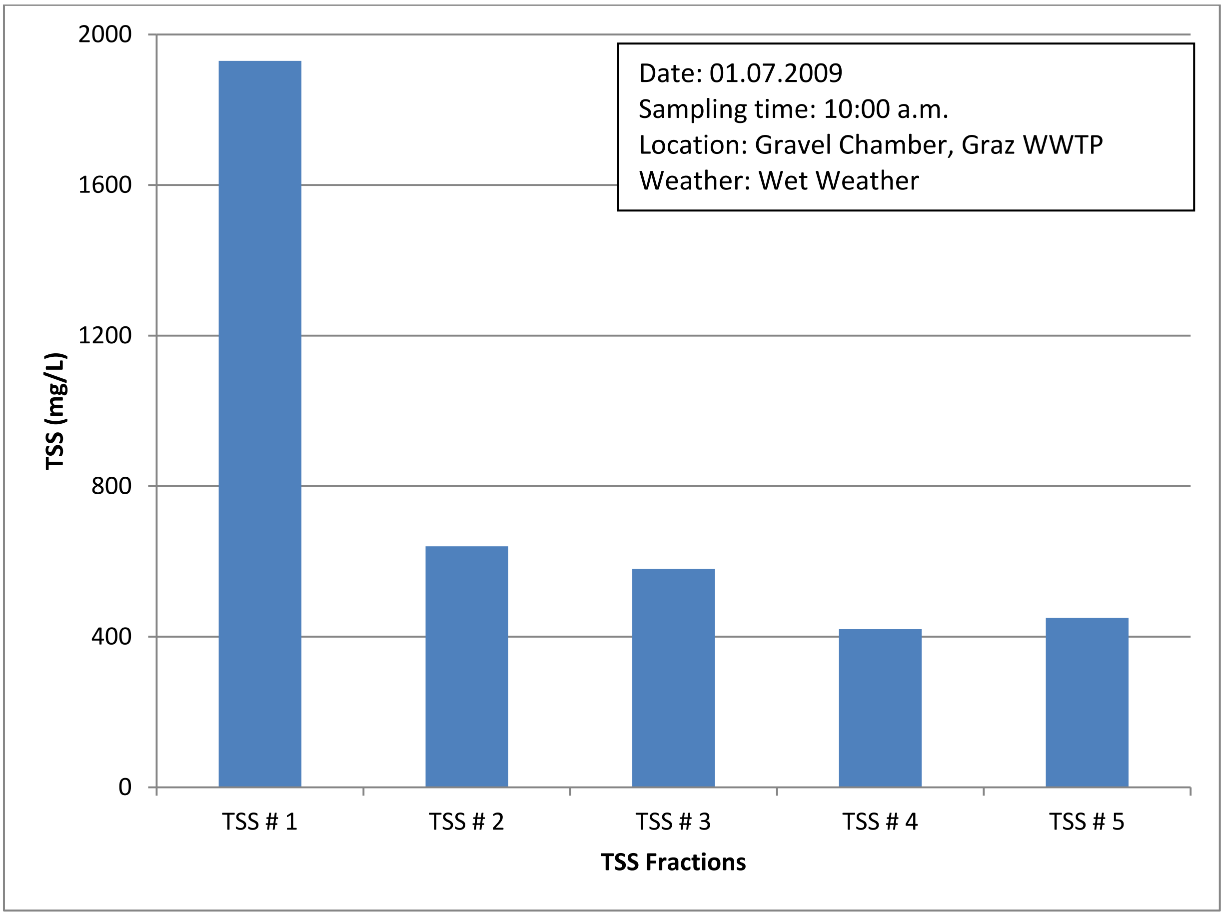



**Figure 5.3: TSS Concentration in 05 fractions with settling time 02 hours**

#### *5.1.3.2 05 fractions with variation in Settling time (10 min. – 02 hours)*

The further experiments were tested using different procedures with variations in settling time. Figure 5.4 shows that a sample is tested for different settling times ranging from 10 minutes to 2 hours. As shown in the figure, most of solids (about 900 mg Mass out of 1400 mg) settle in lowermost fraction within first 10 minutes. It means that after 10 minutes, the fast settling particles have reached the bottom and suspended particles settle slowly. There is an increase of about 14% in settling of solids in lowest fraction with the time from 10 minutes to 2 hrs. The reproducibility of the experiments has been proved good.

It is an indication that the settling time of less than 02 hours, can also be adopted. The only thing is to verify it with experiments that what will be the optimal point. The TSS Mass in other fractions is also considerable. The upper two sections are almost showing the relatively same mass, while the middle and fraction in between lower most and middle fraction showing the same pattern of Mass concentration. 15

different experiments were performed with the five fractions and settling time range as shown in Figure 5.4.

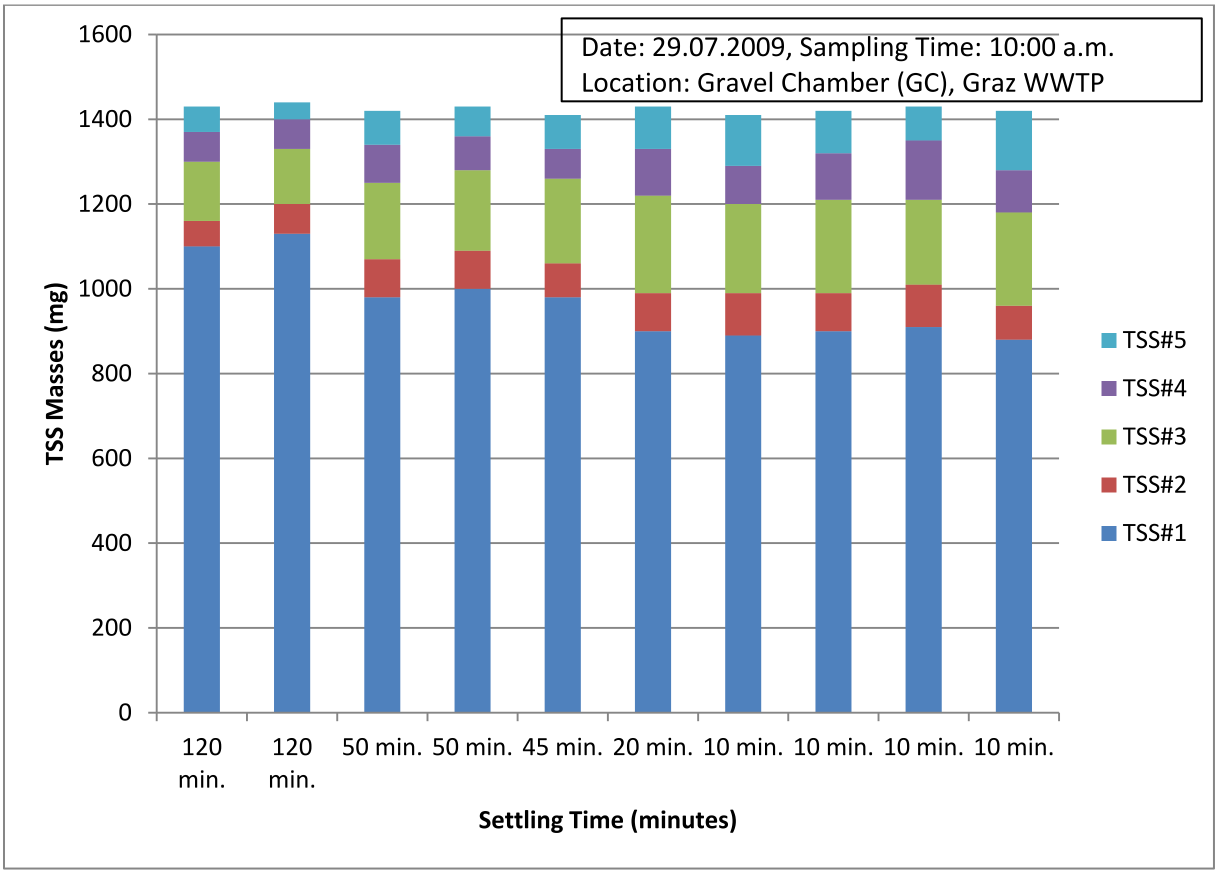



**Figure 5.4: TSS Mass (mg) in five fraction for different settling time (Aslam et al., 2011b)**

The mass of solids in all five fractions in the unit of percentage is also shown in Figure 5.5. This figure shows that almost 80% solids settle in the column in the lowermost fraction for settling time of 02 hours. The percentage of TSS mass in lowermost fraction is reduced to about 10% for a settling time of about 01 hour (45 – 50min.). This percentage reduced to about 4 – 5% for a settling time of 10 minutes. It shows that almost 60 – 65 % solids settle in the lowermost fraction of column within first 10 minutes.

The concentration of the TSS in all five fractions is shown in Figure 5.6. The lowermost fraction has a concentration of more than 2200 mg/L for a settling time of 02 hours. It can be seen from the figure that concentration in middle fraction (TSS#3) is less than other four fractions. The upper two fractions (TSS#4 & TSS#5) have even more concentration than the middle fraction (TSS#3). It shows that floatable solids have more concentration than suspended solids in the middle fraction. The fraction (TSS#2) also has higher concentration than middle fraction (TSS#3).

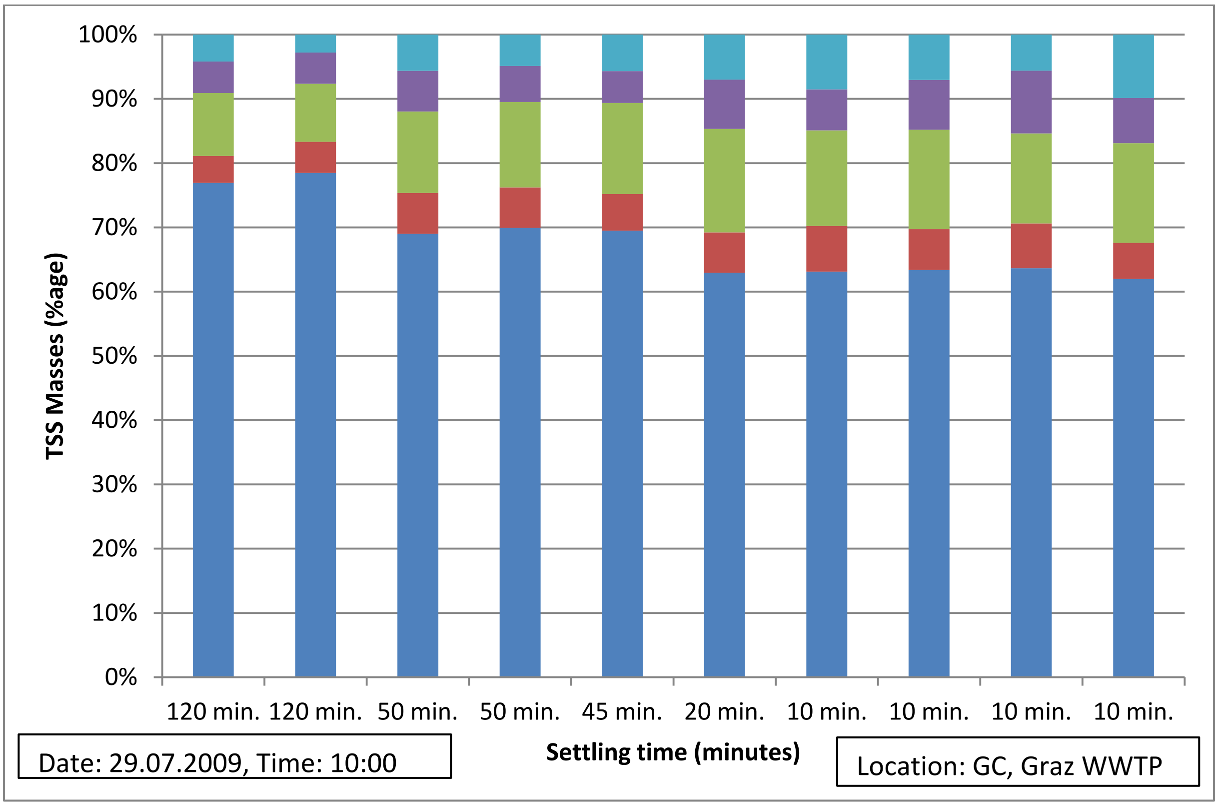



**Figure 5.5: TSS Mass (Percentage) in five fraction for different settling time**

It means that there are five fractions present in raw wastewater on the basis of concentration. The Figure 5.6 shows that lowermost fraction (TSS#1) has TSS concentration in the range of 1750 – 1830 mg/L for a settling time of 10 minutes.

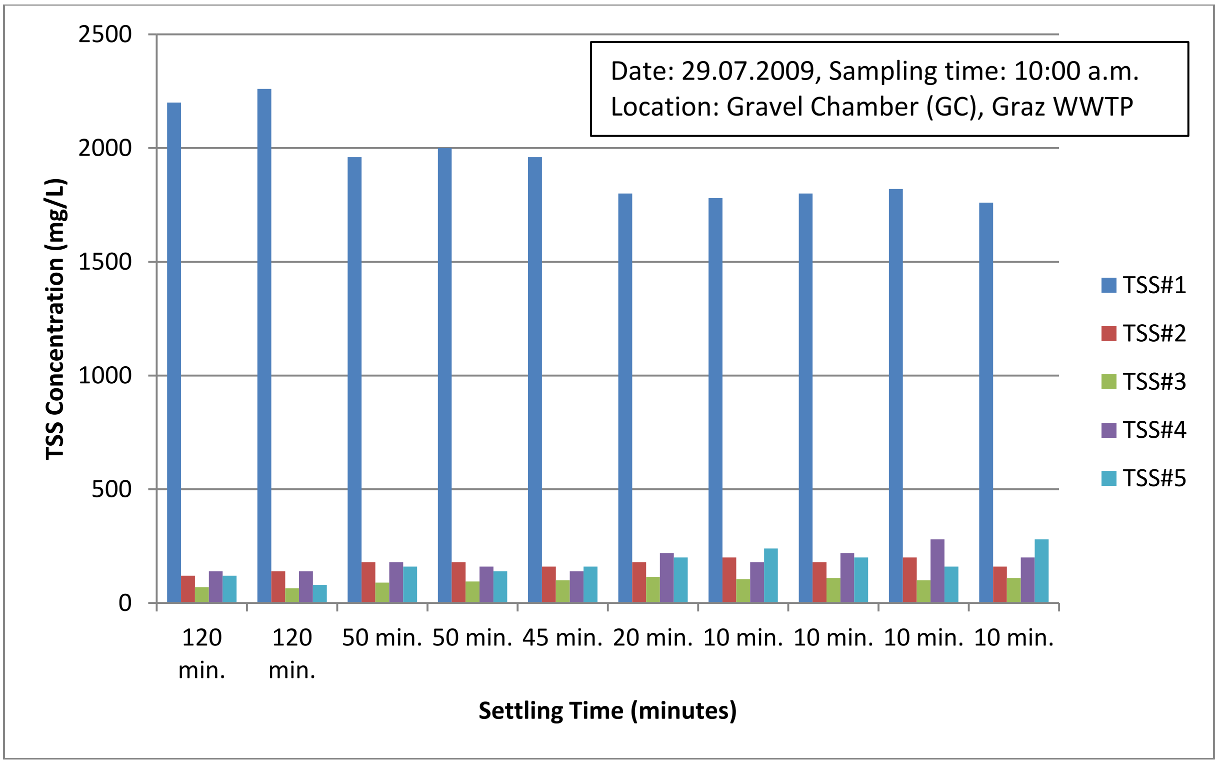



**Figure 5.6: TSS Concentration (mg/L) in five fraction for different settling time**

It shows that there is an increase of about 17 – 20% in the concentration of solids in the lowermost fraction with the increase in the settling time from 10 minutes – 02 hours. The behaviour of the TSS mass in the lowermost fraction with respect to different settling times, as shown in Figure 5.7. This figure shows that about 900 mg Mass is settled in first 10 minutes, about 980mg Mass settled in 45-50 minutes and about 1100mg Mass settled in 2 hours. The figure shows a linear trend after 10 minutes.

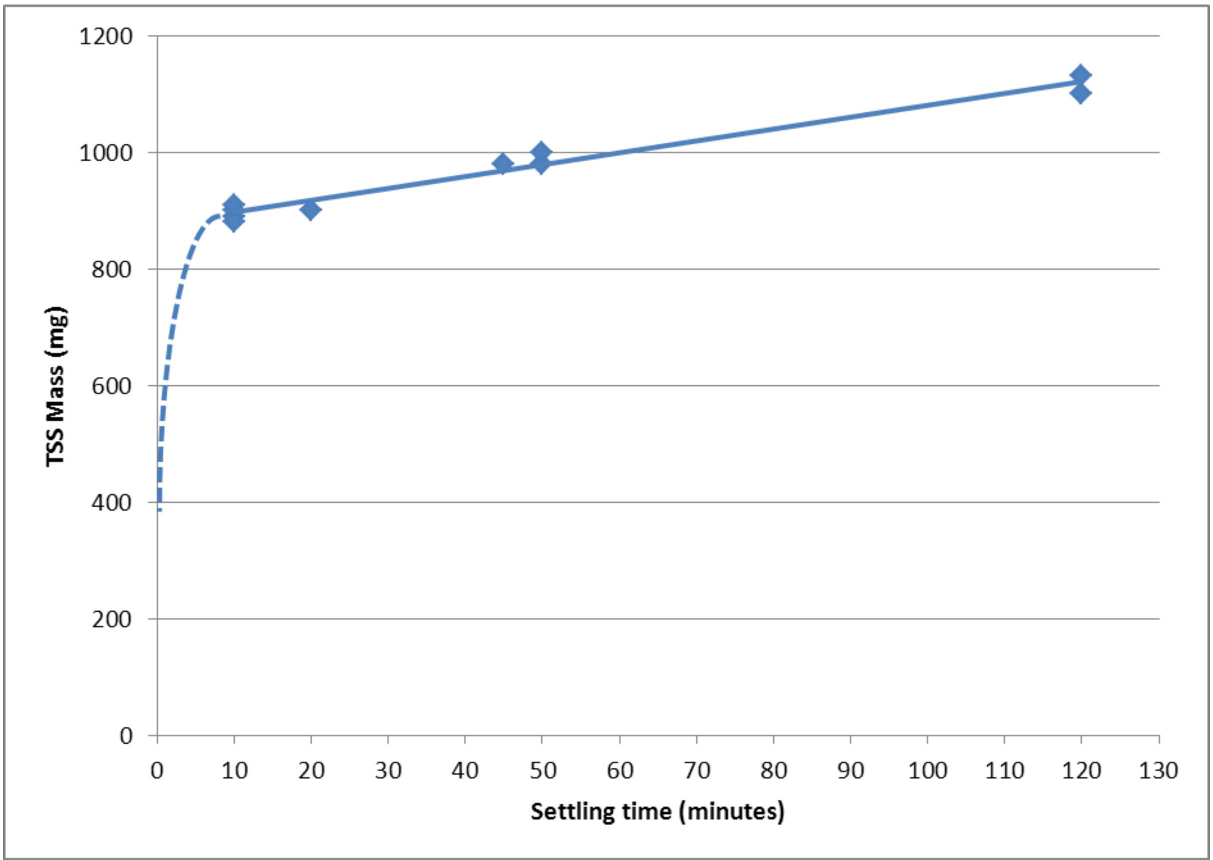



**Figure 5.7: TSS Mass settling with respect to different settling time**

It is clear from all three above figures (Figure 5.4 – Figure 5.7) that the settling processes shows the maximum settling in the lower most fraction within first 10 minutes. It concludes that 10 minutes is considered as best settling time for raw wastewater of Graz WWTP.

The settling fractions shows different behaviour, in some cases, all the above four fractions have relatively same concentration. In 70% of experiments, the lower most fraction can be clearly stated one fraction of solids. The other four fractions were very closely observed and estimated. The upper two fractions (TSS # 4 & 5) shows the concentrations of TSS in same numbers with slight ignorable difference. The middle and lower fraction (TSS 2 & 3) also show the same concentration with TSS # 2 slightly lower than the middle fraction. This pattern is to be verified with the following experiments.

### *5.1.3.3 Settling fractions with settling time 10 min.*

The further experiments were tested with the settling time of 10 minutes but with the variation in the settling fractions. The settling fractions are reduced to two and three fractions in this section. The purpose is to evaluate the option of reducing five fractions to best suitable reduced fractions.

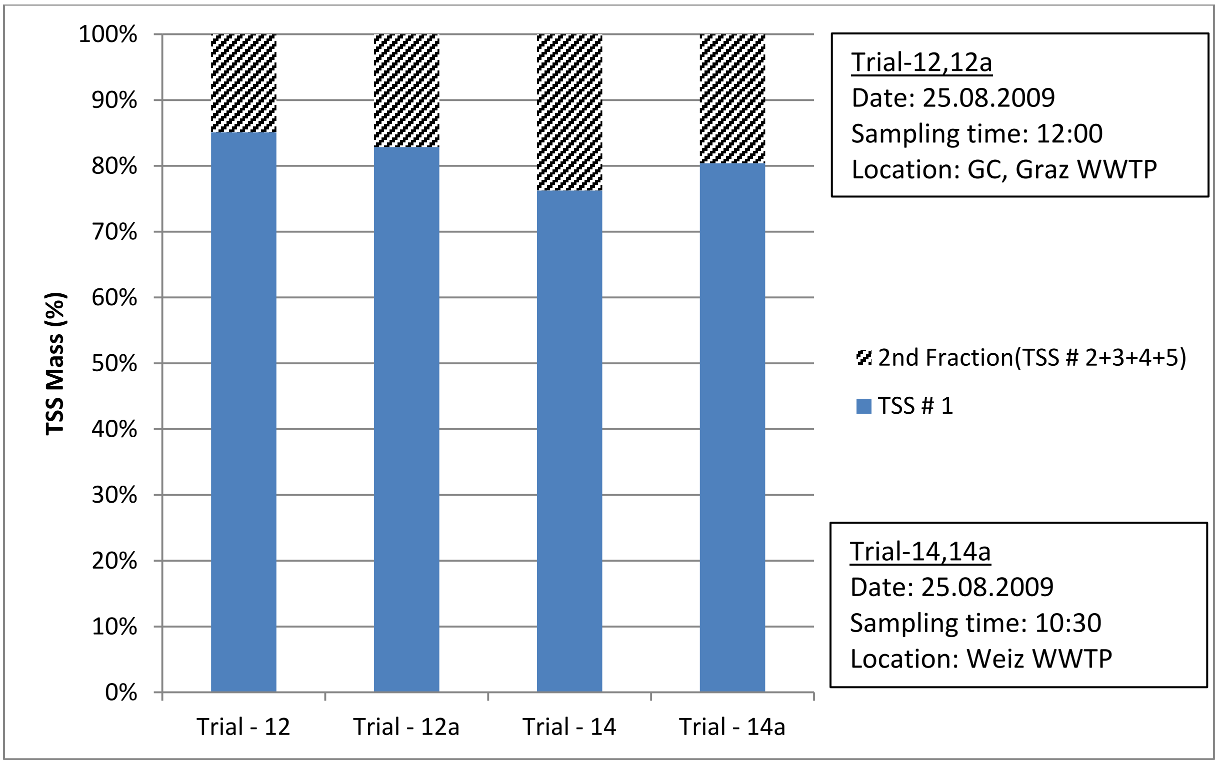



**Figure 5.8: Total suspended solids (%age) with two fraction and settling time 10 minutes**

Figure 5.8 shows the results with two fractions. The first fraction is TSS#1 and the second fraction is the addition of all remaining fractions (TSS 2+3+4+5). The above figure shows that about 75 - 85% solids settle in the lowermost fraction (TSS#1). The other fraction contains all other solids which are not higher than 25%. The problem in the two fractions is that it cannot differentiate the floating solids and suspended solids (solids settled with medium speed and remain suspended in the column). The 2$^{nd}$ fraction combines the suspended solids and floating solids, due to that real picture about the settling behaviour of solids in raw wastewater cannot be shown in two fractions.

Some experiments were performed with the settling fractions reduced from five to three. These three fractions constitute lower fraction (TSS#1), middle fraction

(TSS#2+3), and upper fraction (TSS #4+5). These fractions are made on the basis of the results of previous Heading 5.1.3.2.

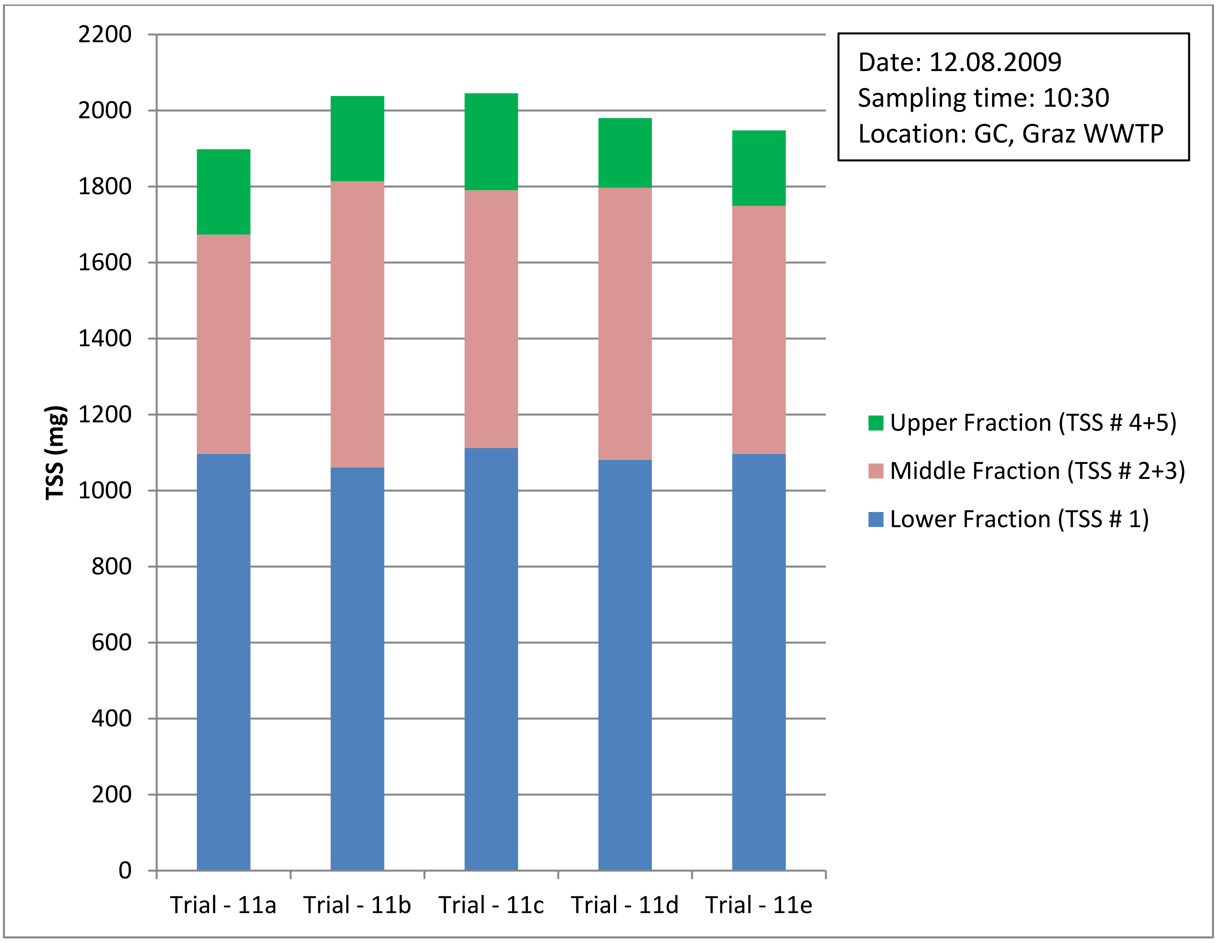



**Figure 5.9: Total suspended solids Mass (mg) with three fractions and settling time 10 minutes**

The lowermost fraction of five fractions remained same also in three fraction but named Upper fraction having volume of same 0.5 Litre. The fraction (TSS#2) and middle fraction (TSS#3) have almost similar concentration in case of five fractions, so these two fraction are joined together and now it is named as Middle fraction having volume of 2.5 Litre. The upper two fractions (TSS#4 & TSS#5) have almost equal concentration of the floating solids, so it is combined in one fraction and named Upper fraction having volume of 1 litre.

The TSS concentration is shown in Figure 5.10. The results in this figure show that lower fraction has a TSS concentration of more than 2100mg/L in all the samples. The modified middle fraction (TSS# 2+3) has mostly higher concentration than that of modified upper fraction (TSS# 4+5). It is also observed that fast settling solids settle in the lower fraction in first 10 minutes and it stays at the bottom of the lower fraction. The remaining portion of the lower fraction seems like the middle fraction (TSS# 2+3). It can be assumed that concentration in the remaining portion of lower fraction may be equal to the concentration of modified middle fraction. It will be helpful in the determination of the primary sludge.

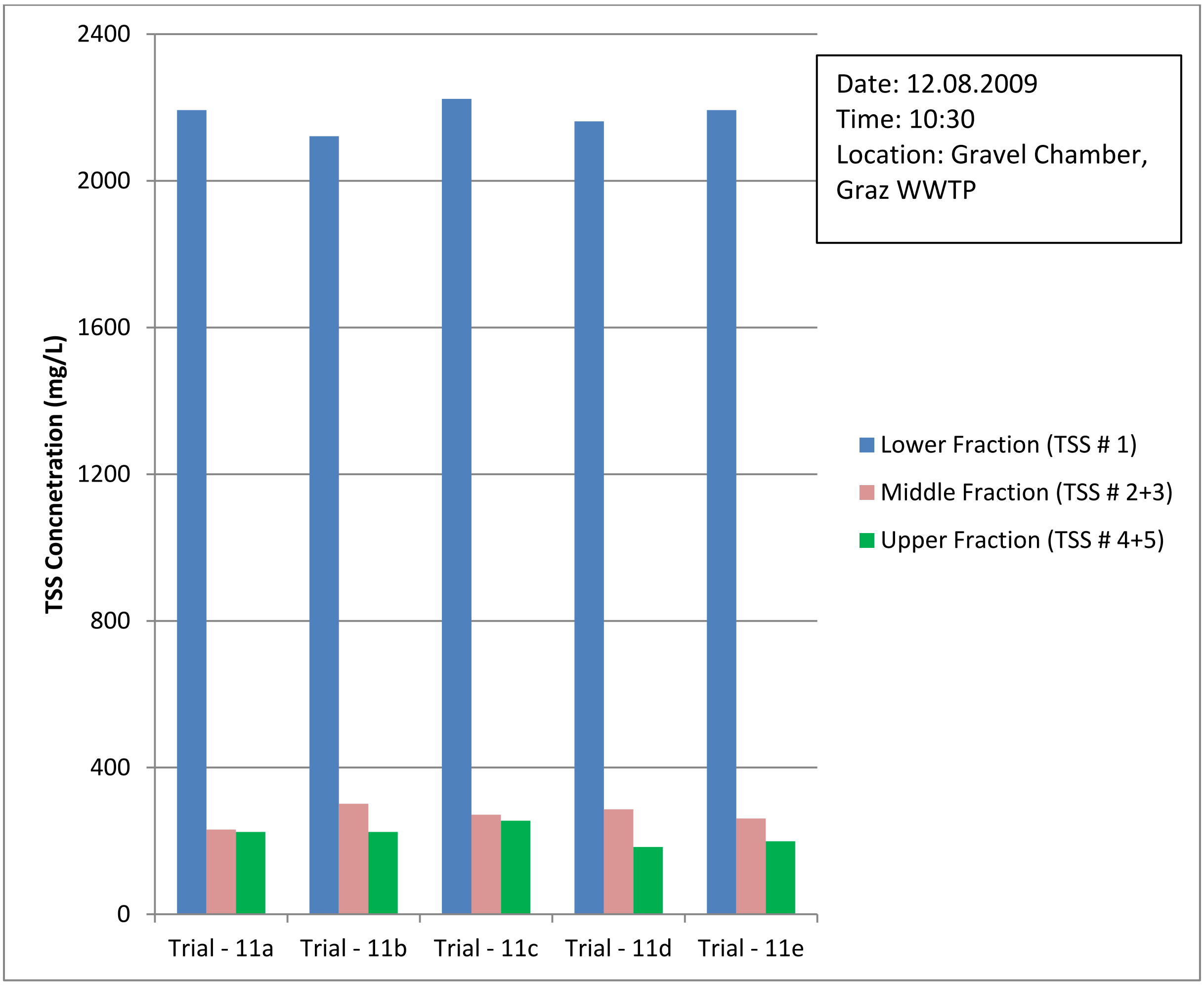



**Figure 5.10: TSS Concentration in three modified fractions with settling time 10 minutes**

Figure 5.9 shows the TSS mass (mg) in three fractions for a settling time of 10 minutes while Figure 5.11 shows the TSS mass in percentage. Five experiments were performed to have good reproducibility of the results. The results in Figure 5.9 and Figure 5.11 shows that about 52 – 58% solids settle in the lower most fraction in the first ten minutes of settling. The TSS mass in the middle fraction constitutes the 30-35% of total solids, as the volume of this fraction is 2.5 L. These solids comprises of suspended solids and other solids which don't settle with in first 10 minutes. The floatable solids are about 10% of total solids and it have volume of 1 L. These experiments with three fractions shows the best picture of the settling behaviour of solids in raw wastewater, as it covers all possible types of solids regarding settling.

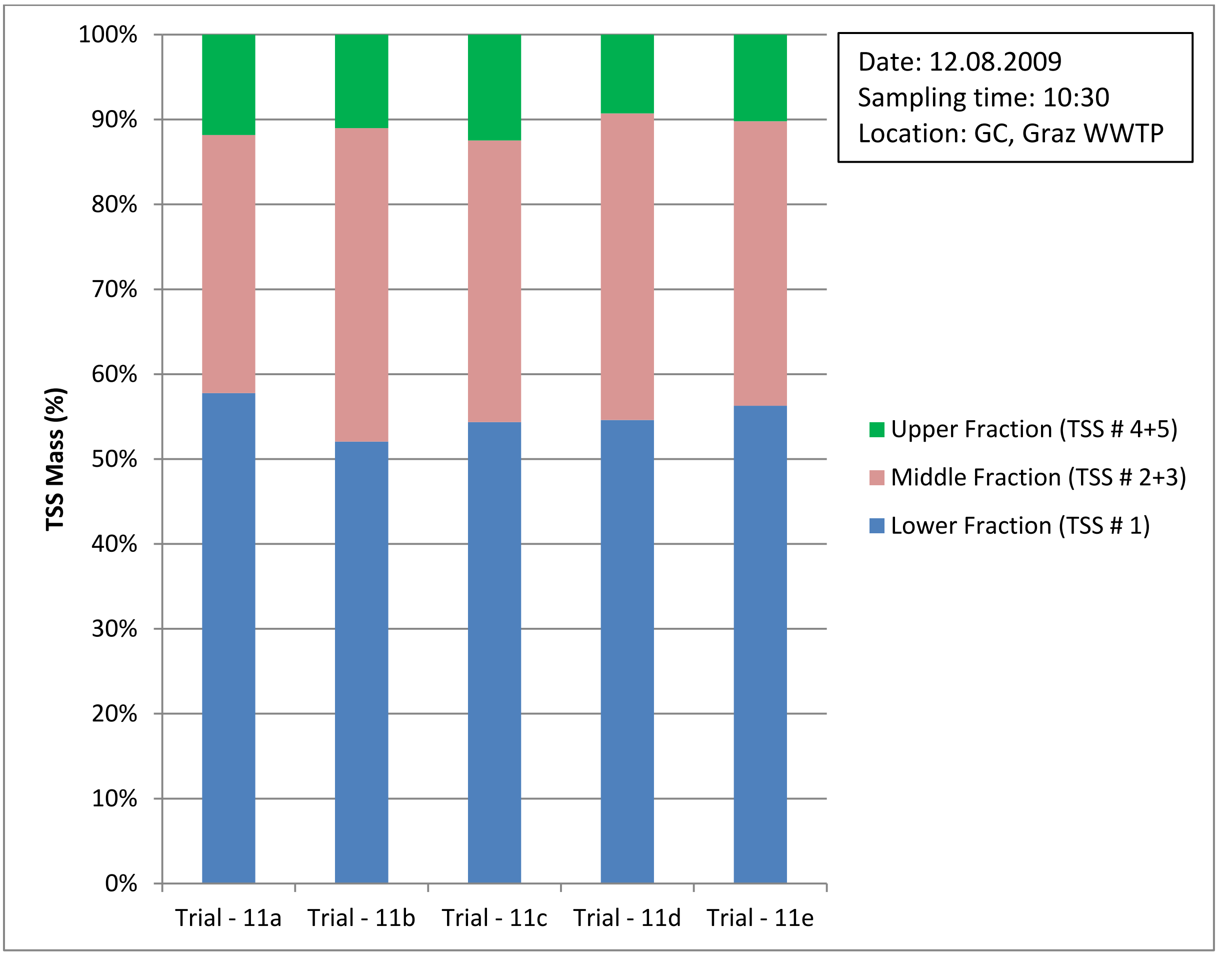



**Figure 5.11: Total suspended solids Mass (%age) with three fractions and settling time 10 minutes**

The discussion so far shows that the settling time can be reduced from 02 hours to 10 minutes and settling fractions from 05 to 03. This new development was tested and verified with a series of experiments both at laboratory level along with its implementation at broader level.

### *5.1.3.4 Description of 03 fractions with settling time 10 minutes*

A number of experiments were performed to finalize the settling fractions of solids along with best suitable settling time. The discussion in previous two headings (Heading 5.1.3.2 & 5.1.3.3) shows that the settling time was reduced from 02 hours to 10 minutes and settling fractions from 05 to 03. The description of the three fractions is shown in detail in Figure 5.12.

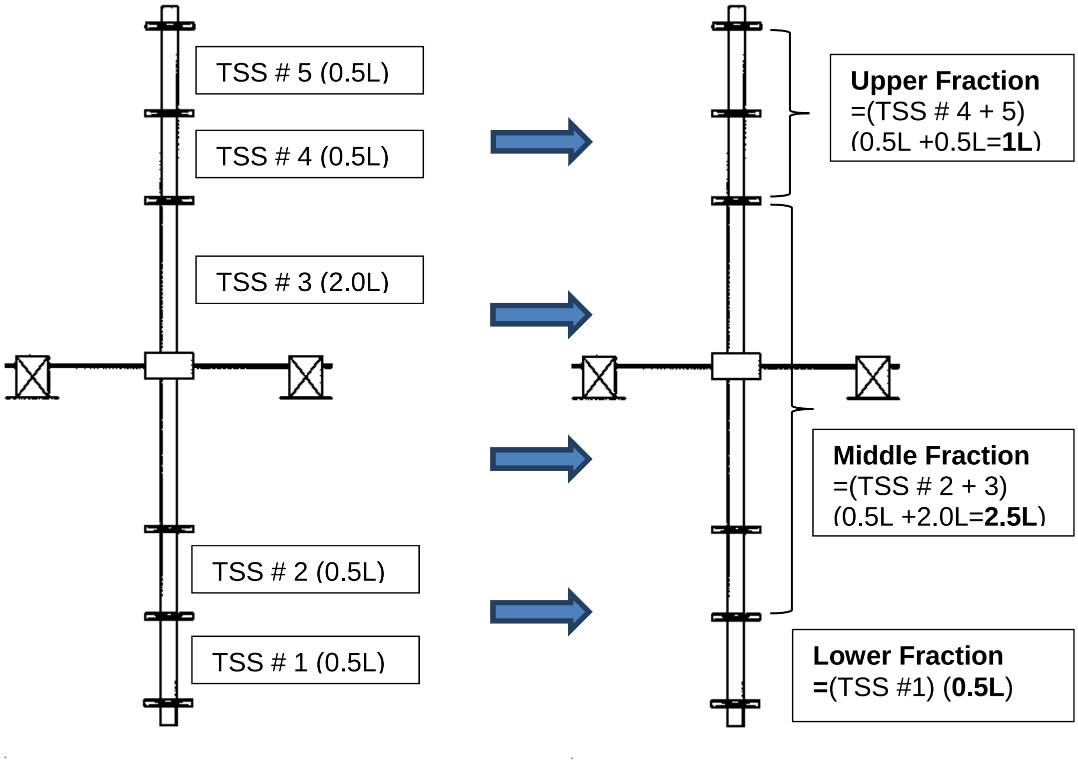



**Figure 5.12: Description of three fractions**

The newly defined three fractions were given different names to differentiate it from previously defined five fractions. These three fractions are given as below:

1. **Lower Fraction**

   This fraction is the same as lowermost fraction in five fractions. It was named previously TSS # 1. It has a volume of 0.5 Litres. It contains the fast settling solids which settle in first 10 minutes.

2. **Middle fraction**

   This fraction is the combination of fraction immediately above than lower most fraction i.e. TSS # 2 and middle fraction TSS # 3. The new name of this combined fraction is middle fraction (TSS#2 + TSS#3). It has a volume of 2.5 Litres. This fraction contains suspended solids and solids with medium speed which don't settle fast in first 10 minutes.

3. **Upper Fraction**

   This fraction comprised of two upper fraction previously named as TSS # 4 and TSS # 5 in case of five fractions. The new name is Upper fraction (TSS#4 + TSS#5). This fraction has a volume of 01 Litre and contains floatable solids.

### 5.1.4 Experiments for wastewater of Weiz wastewater treatment plant

The experiments were also performed on the settling apparatus using other than Graz wastewater. Weiz is the neighbouring small city. It has a wastewater treatment plant of capacity 30000 population equivalent. The wastewater was collected from the entrance point of Weiz WWTP. Figure 5.13 shows the results of TSS concentration in mg/L.

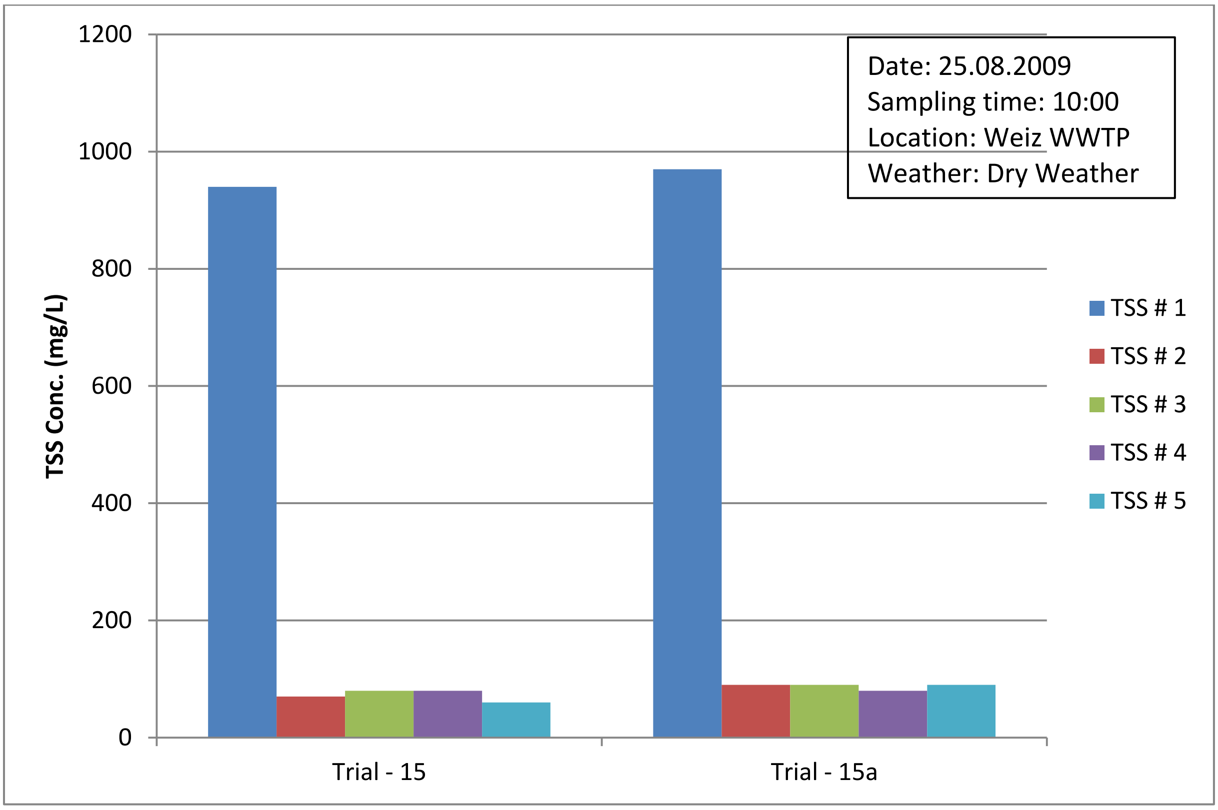



**Figure 5.13: TSS Concentration (mg/L) in five fractions with settling time 10 minutes**

Trial 15 shows that there is almost same concentration of TSS in all the four fractions other than the lowermost fraction. The difference here is very large between the concentration of lowermost fraction and other four fractions. The results show that other four fractions is 10% of the concentration of the lowermost fraction.

The TSS mass in percentage is shown in Figure 5.14. The results highlight the picture of settling behaviour of solids in small wastewater treatment plant in Trial 15. The TSS mass in the upper two fractions are similar, so they can be replaced by one fraction. The other two fractions (middle and lower) in Trial 15 can also be replaced by one fraction. so it totally makes three fractions.

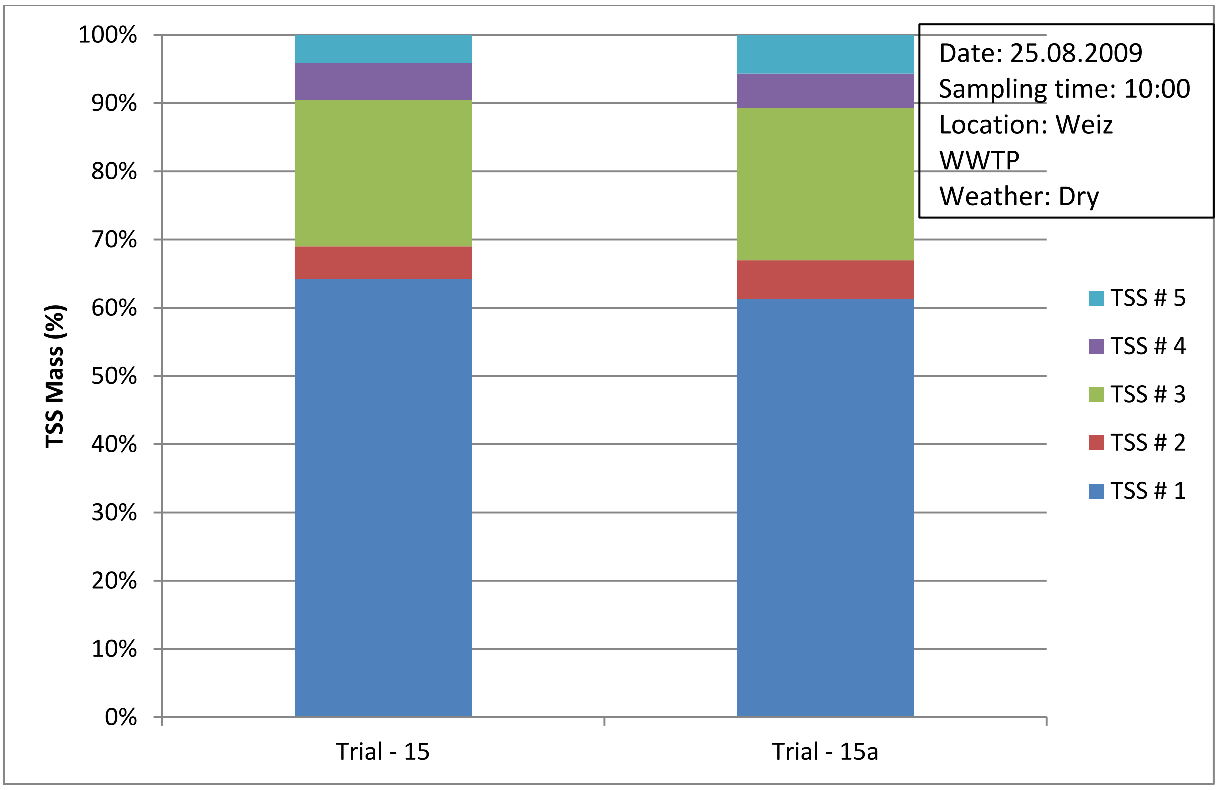



**Figure 5.14: TSS Mass (%) in five fractions with settling time 10 minutes**

The experiments were performed with the two fractions in Trial 14 which can be seen in Figure 5.15 and Figure 5.16. The results of Trial 14 show that about 80% solids settle in lowermost fraction in first 10 minutes while other fraction shows the remaining 20% of solids. As weiz has a small wastewater treatment plant, so the nature of wastewater is also not so complex. The results in above figures (Figure 5.13 & Figure 5.14) shows that solids of Weiz raw wastewater settle in two fractions, which can be described as fast settled solids fraction and suspended/floated solids fraction.

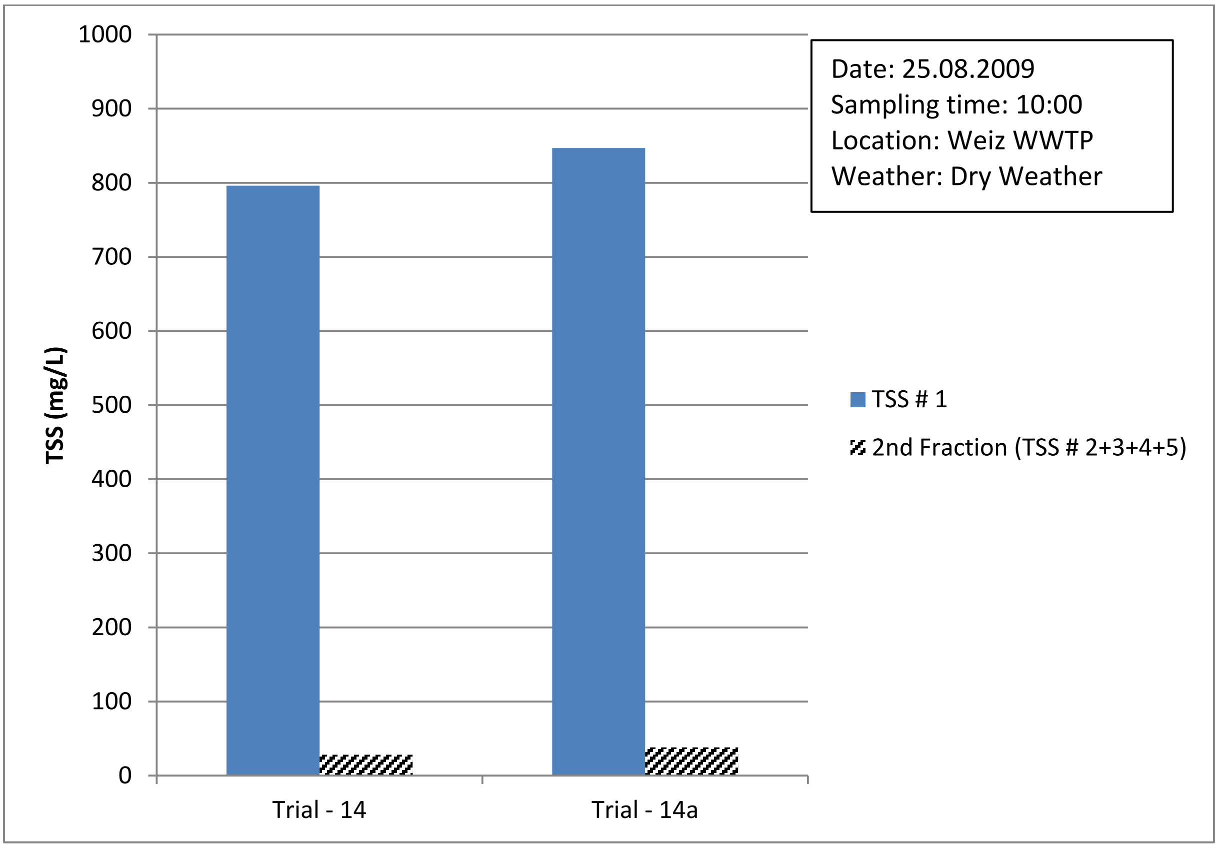



**Figure 5.15: TSS Concentration (mg/L) in two fractions with settling time 10 minutes**

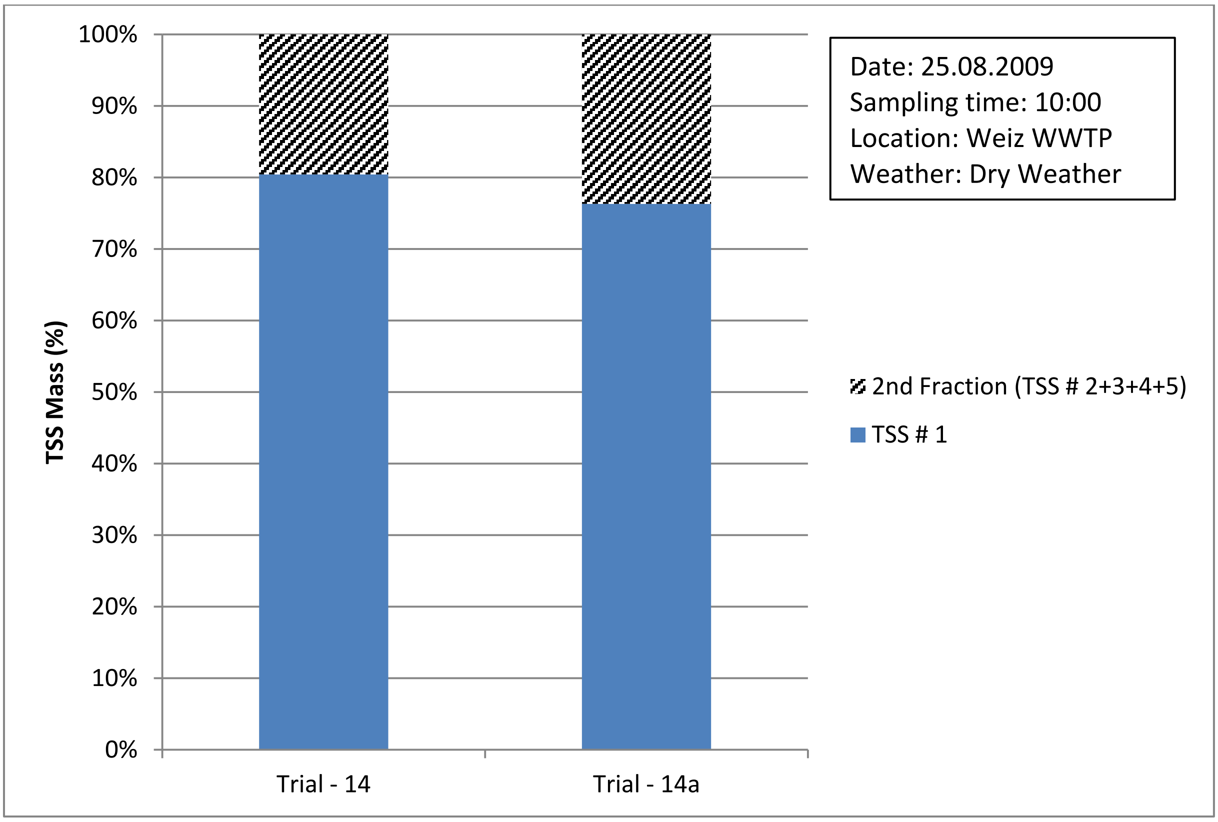



**Figure 5.16: TSS Mass (%) in two fractions with settling time 10 minutes**

## 5.2 On-Site Experiments

The experiments were expanded to broader level on the basis of laboratory results. Three new apparatuses were constructed for performing the experiments in parallel with a lot of variations. The purpose behind is to consider all the aspects and parameters of settling which play a vital role in settling of solids in raw wastewater.

In the first section of On-Site experiments, the experiments were performed at Gravel Chamber. Settling time of 3 minutes, 5 minutes and 10 minutes were used in settling columns. Column was filled by using the peristaltic pump with velocity of less than 4 L/min. The column was filled by putting the pipe vertically down in the column to avoid any pre-settling. The experiments were performed for whole 24 hours. The quality parameters were also analyzed to quantify the pollution load due to these solids, which are discussed in detail in next part of the chapter.

Sampling sites has been increased in the second section of On-Site experiments. The settling time of 10 and 30 minutes is considered in this section. There were some discrepancies found in the experimental method, so an improvement in the method was proposed and then verified by the further experiments (see Heading 5.2.3.3). Better results were obtained with this improved method.

The last section of On-Site experiments covers a final experimental campaign for a selected time interval during the day according to flow rate and the settling time of 10 and 30 minutes. Both dry and wet weather results are discussed in this section. The mass balances was also prepared and discussed in this section. The last but not the least, the results of the On-site experiments were compared with Standard method of online monitoring system 'Solitax' running in parallel with experiments on settling apparatus.

### 5.2.1 Flow rate of wastewater at Graz WWTP

The Graz wastewater treatment plant has a maximum inflow at the flow rate of 1.6 $m^3$/sec in the dry weather and 3.2 $m^3$/sec in wet weather. Figure 5.17 shows the inflow of wastewater throughout the 24 hours. It shows that at morning about 4 – 5 a.m., the inflow is minimum. At 6 a.m. it rises little bit but at 8 a.m. it shoots up and reach at maximum peak at about 10 – 11 a.m. After that the flow drops down slowly but remain stable till 11 p.m. and starts declining till 4 a.m.

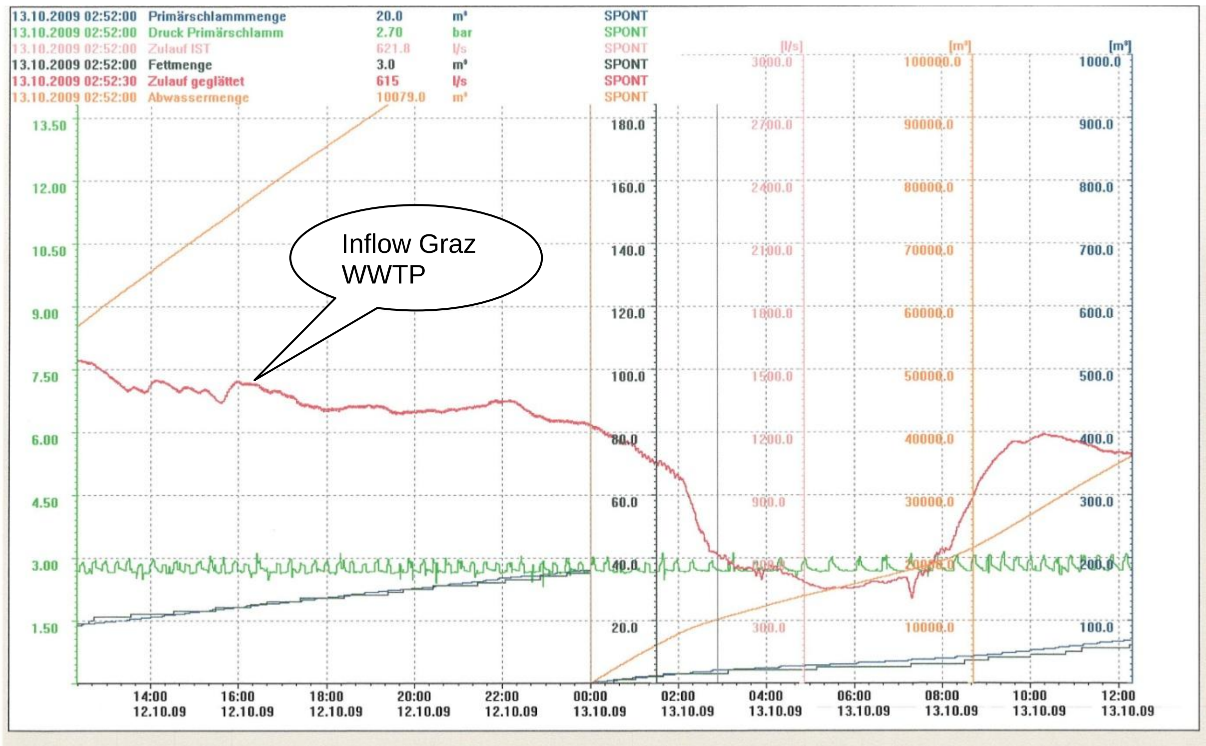



**Figure 5.17: Flow diagram of Graz WWTP**

### 5.2.2 Experimental Campaign – 1

The wastewater used for settling apparatus in this campaign is sampled from the Gravel Chamber. The four settling apparatuses were placed near the sampling site. The wastewater is filled in the settling column directly from the Gravel chamber with the help of peristaltic pump at the flow rate of less than 4 Litres/min. The results from the laboratory experiments are a base for this campaign. The settling fractions are limitized to 03 (Lower, middle and upper fraction; as mentioned in Heading 5.1.3.4) and the settling time as concluded in the laboratory experiments was 10 minutes. In this campaign, a settling time of 03 minutes and 05 minutes are also tested along with 10 minutes. The question is why the settling time of less than 10 minutes will be tested. The answer is to see that is there any possibility to have better settling with less than 10 minutes. The samples were tested for the whole 24 hours. The time interval was made according the flow diagram of Graz WWTP. These experiments were performed in September and October 2009.

#### *5.2.2.1 Experiments with settling time of 03 minutes round the clock*

The mass of total suspended solids (TSS) is measured for settling time of 03 minutes. The results in Figure 5.18 show that there is very less settling in the lowermost fraction. About 10 – 25% of solids settle with in first 3 minutes. The remaining solids stay in the upper fractions.

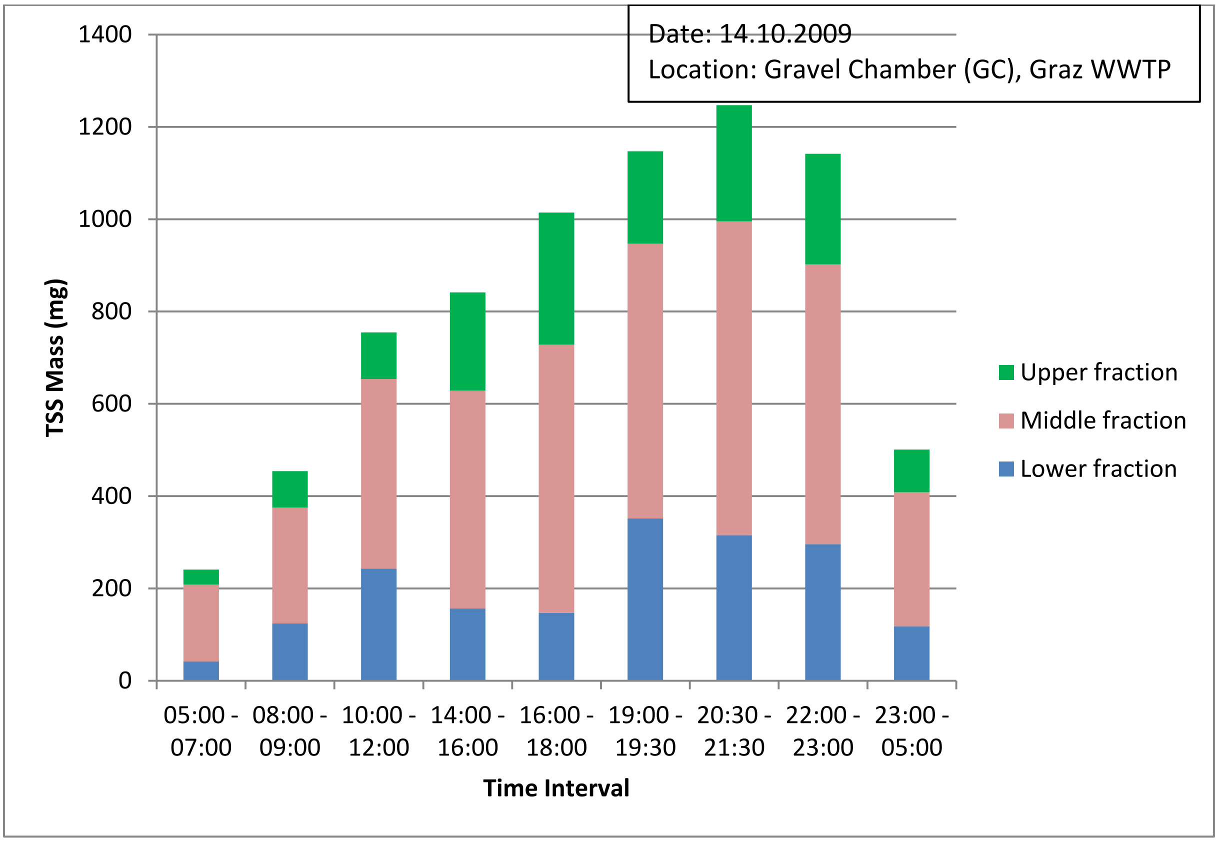



**Figure 5.18: TSS mass with settling time 03 minutes**

At the morning time the wastewater has a very less mass as expected. The overall mass starts to rise at the time interval 10:00 – 12:00 and it remains higher in the late afternoon / evening. It shows that the TSS mass is not mainly dependent to the flow rate of inflow in some cases, it differs with the different timings of the day.

### *5.2.2.2 Experiments with settling time of 05 minutes round the clock*

The results in Figure 5.19 show that there is an increase in the settling of solids in first 05 minutes with the increase of 02 minutes. It can be seen from the figure that settling of solids vary with the different timings of the day. In the time interval 10:00 – 12:00, almost 50% solids settle in the lower most fraction. In the evening time (19:00 – 23:00), there is a constant increase in the settling of solids in raw wastewater. Overall about 35% solids settle in the lowermost fraction within first 05 minutes which is not enough for good settling. There is any additional time needed by the solids to settle in the settling column.

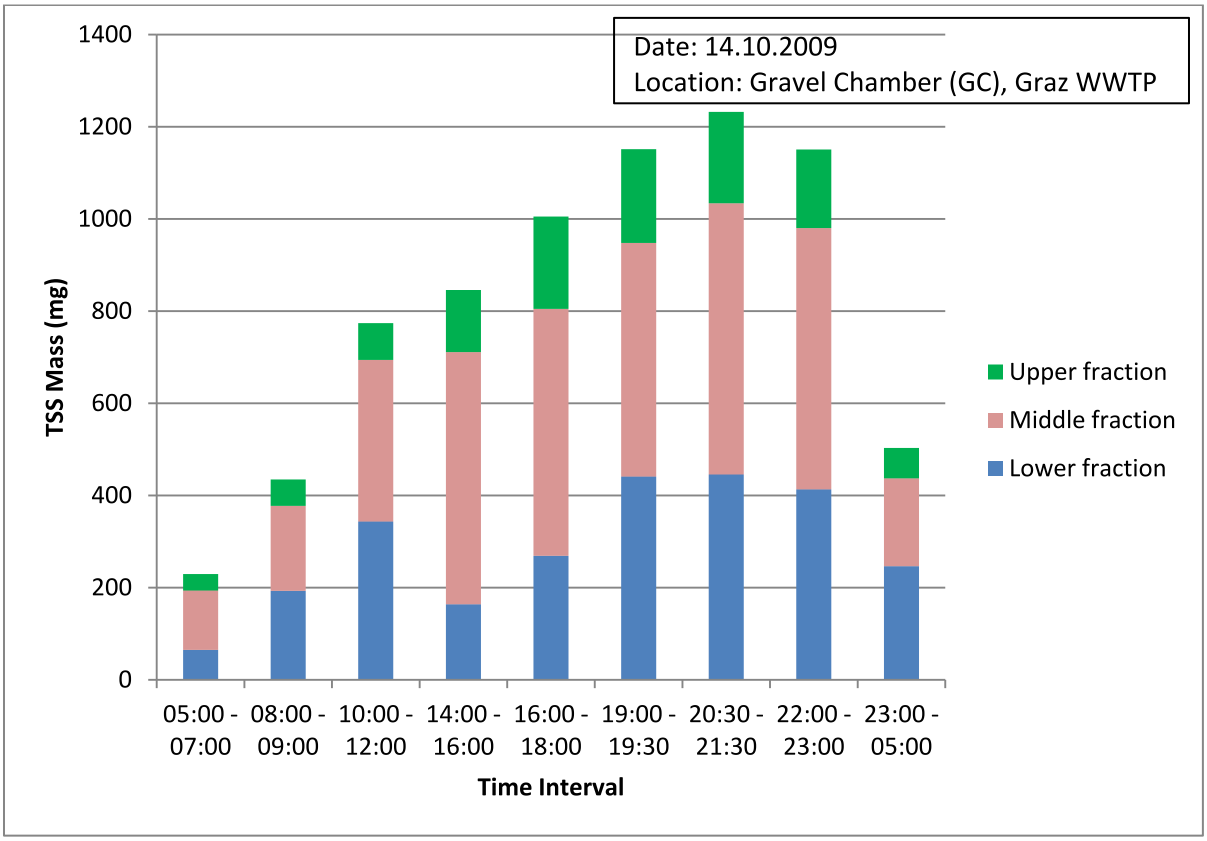



**Figure 5.19: TSS mass with settling time 05 minutes**

### *5.2.2.3 Experiments with settling time of 10 minutes round the clock*

The settling of solids is very good with the settling time of 10 minutes as shown in the Figure 5.20. The maximum solids (about 70%) settle in the lowermost fraction at time interval 10:00 – 12:00. About 55 – 60% solids settle in the lowermost fraction in almost all the time intervals throughout the day. The one of the interesting results is that there are lots of floatables in the afternoon session as compared to the other timings of the day. It is once again verified that settling time of 10 minutes is best for settling of solids in raw wastewater with 03 settling fractions.

The increase in the TSS mass in the lowermost fraction with the increase of settling time from 03 to 10 minutes is shown in Figure 5.21. This figure shows that there is uniform increase in TSS Mass with increase of settling time from 3 – 5 minutes and from 05 to 10 minutes. In the morning time, it is more linear. In the afternoon the increase from 3 – 5 minutes is less as compared to 5 – 10 minutes settling time. The raw wastewater at evening time also shows linear relationship for increase in settling of solids in settling column. The TSS mass increase with the increase of settling time from 3 to 5 minutes, ranges 25 – 110%, while from 5 – 10 minutes settling time the increase lies in the range of 35 – 170%. The total increase in TSS mass from settling time 03 – 10 minutes is in the range of 70 – 245 %.

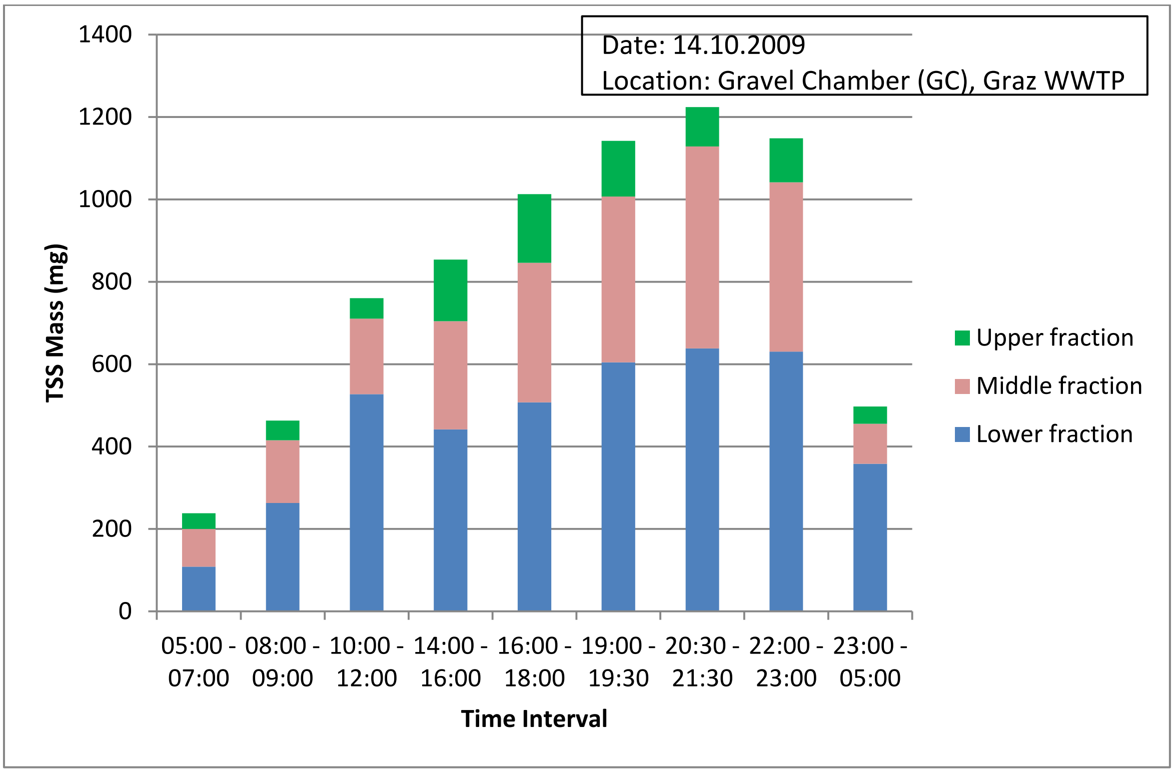



**Figure 5.20: TSS mass with settling time 10 minutes**

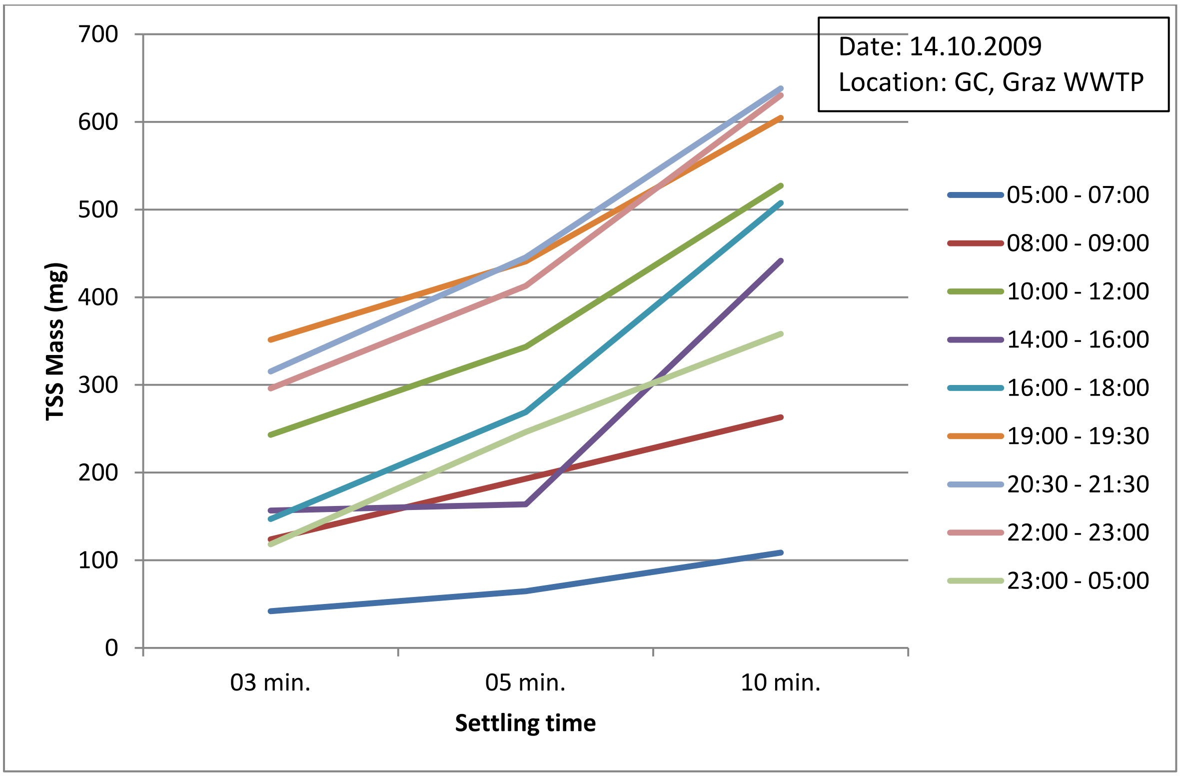



**Figure 5.21: Increase in TSS mass in the lower fraction with settling time increase from 3 – 10 minutes**

This high increase in TSS mass shows that solids takes time to settle in the column and within first 10 minutes maximum solids settle in the lower fraction. In the first 3 minutes, it seems that few solids will settle in next minutes, but when the settling time passes 5 minutes and reaches 10 minutes, most of the solids settle in the lower fraction of column.

#### *5.2.2.4 Quality Parameters*

The quality parameters are very necessary for determining the pollution carried by the solids present in raw wastewater. This information is important to know because if this raw wastewater is discharged in combined sewer overflow (CSO) tanks during wet weather, then one can imagine the how much they are dangerous to the aquatic life in the end. There are some standards of the discharge of CSO tanks, for which one should be aware of it. So it will be good to design a better CSO tank so that these polluted solids remain in these tanks and could not harm the water bodies.

##### *5.2.2.4.1 Organic and Inorganic solids*

The organic and inorganic solids are measured in the Institute laboratory by using standard Method (APHA, 2005). The results in Figure 5.22 shows that about 70 – 85% of solids are organic solids and 15 – 30% solids are inorganic in all the three fractions of the solid for the settling time of 03 minutes.

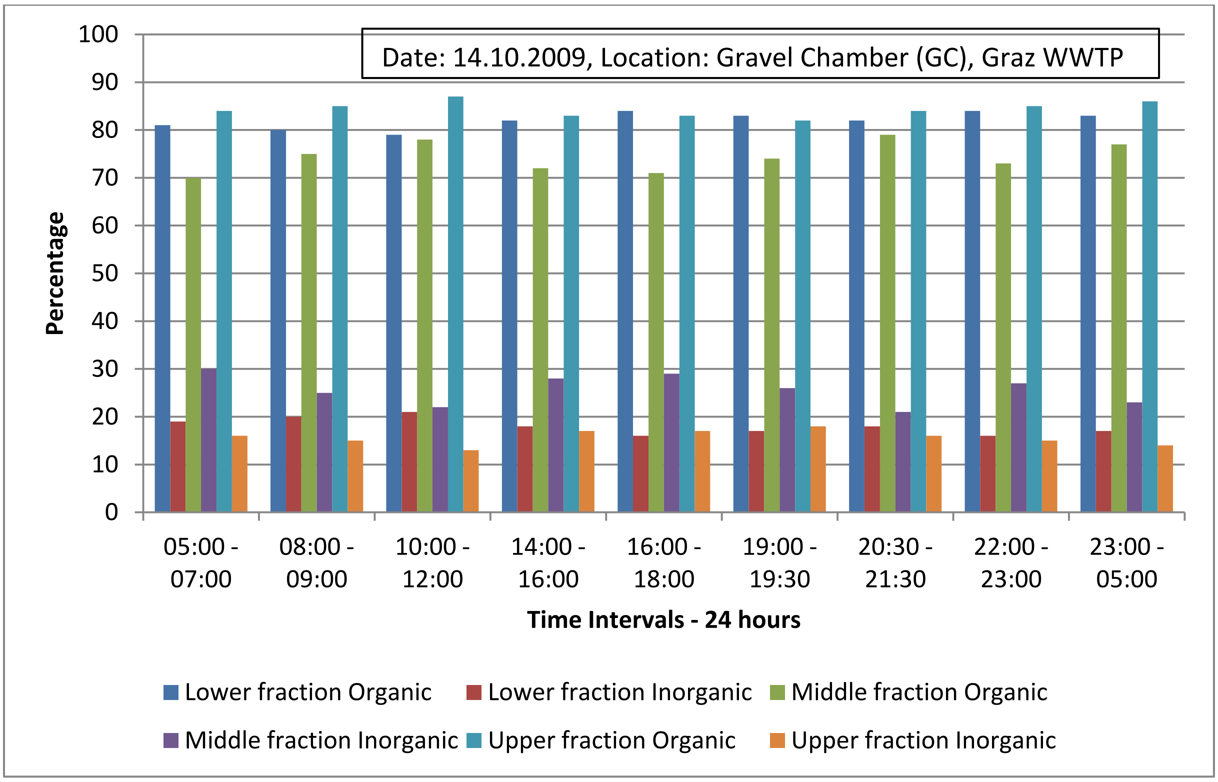



**Figure 5.22: Organic and Inorganic solids in 03 fractions at Settling time 03 minutes**

The Figure 5.23 shows that for a settling time of 05 minutes, about 75 – 88 % solids are organic while 10 – 25 % solids. are inorganic. Organic matter in activated sludge normaly lies in the range of 60 – 65%. It means that 15% more organic solids are present in raw wastewater. It can be concluded that organic matter in raw wastewater is clearly higher than that in activated sludge.

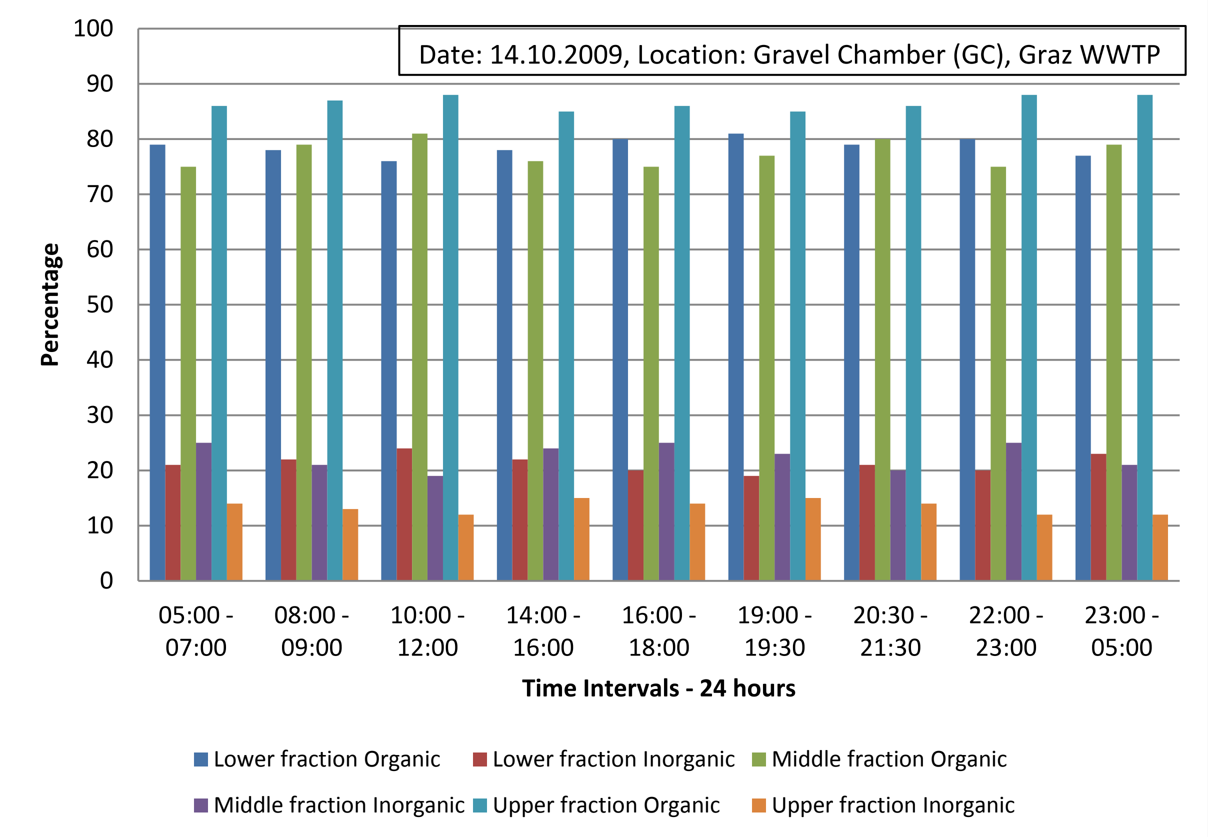



**Figure 5.23: Organic and Inorganic solids in 03 fractions at Settling time 05 minutes**

The Figure 5.24 shows that about 75 – 90 % solids are organic solids while remaining comprises of inorganic solids in the three settling fraction with settling time of 10 minutes. It is quiet natural that the concentration of organic solids is about 80% in the wastewater. These inorganic solids are sand, small gravels etc which can be stopped by the screens and in the grit chamber most of the inorganic portion is removed. The organic portion of solids goes further in the wastewater treatment plant and is treated with different ways.

The results of all three figures (Figure 5.22 – Figure 5.24) show that there is increase of inorganic solids in lower fraction from 03 minutes to 10 minutes. These inorganic solids were present in the middle and upper fractions and when settling time increases from 03 minutes to 10 minutes, these inorganic solids settle down and become a part of lower fraction. The organic solids in the upper fraction shows higher percentages as it contain floatables.

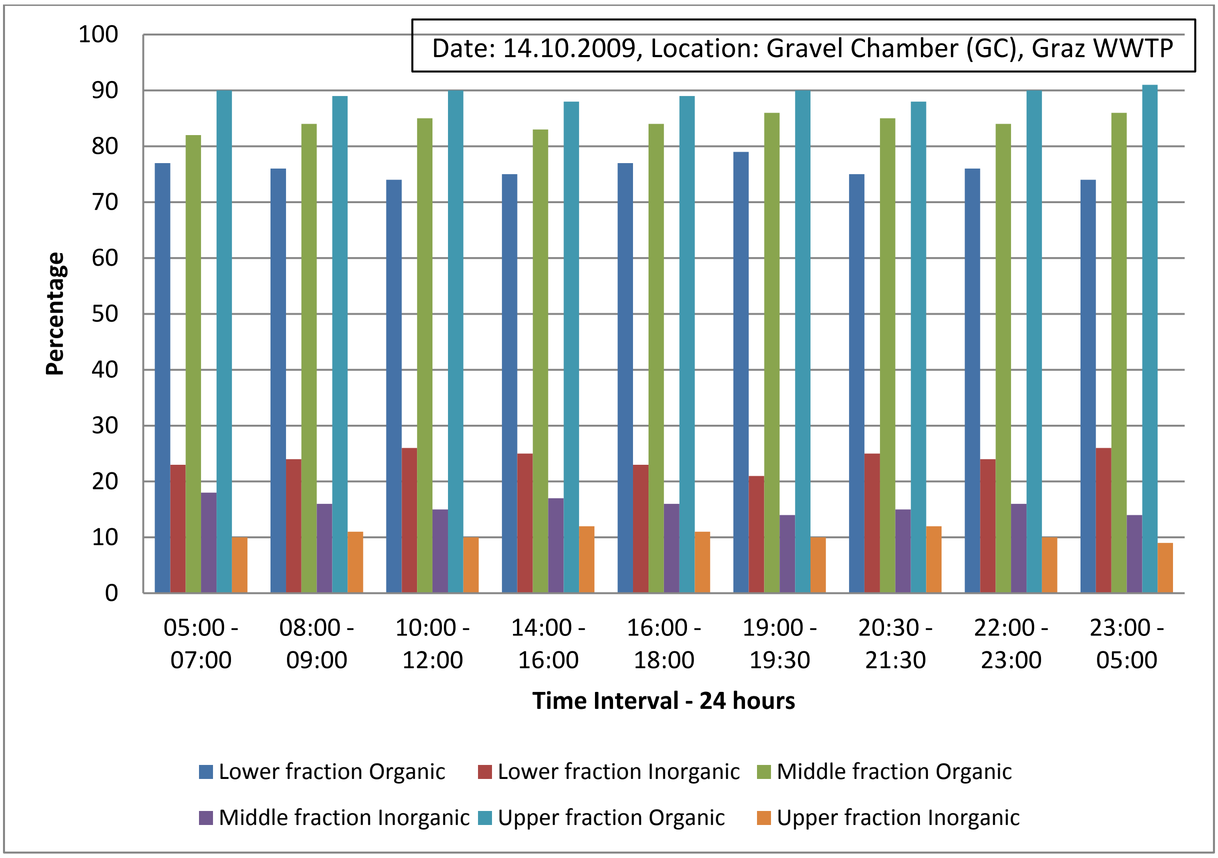



**Figure 5.24: Organic and Inorganic solids in 03 fractions at Settling time 10 minutes**

### *5.2.2.4.2 Settleable solids*

The settleable solids are measured at the site with the other field experiments. The results in Figure 5.25 show that at time interval 10:00 – 12:00 maximum solids settle in Imhoff cone i.e. about 20 mL/L. The settleable solids are stable in the afternoon and evening.

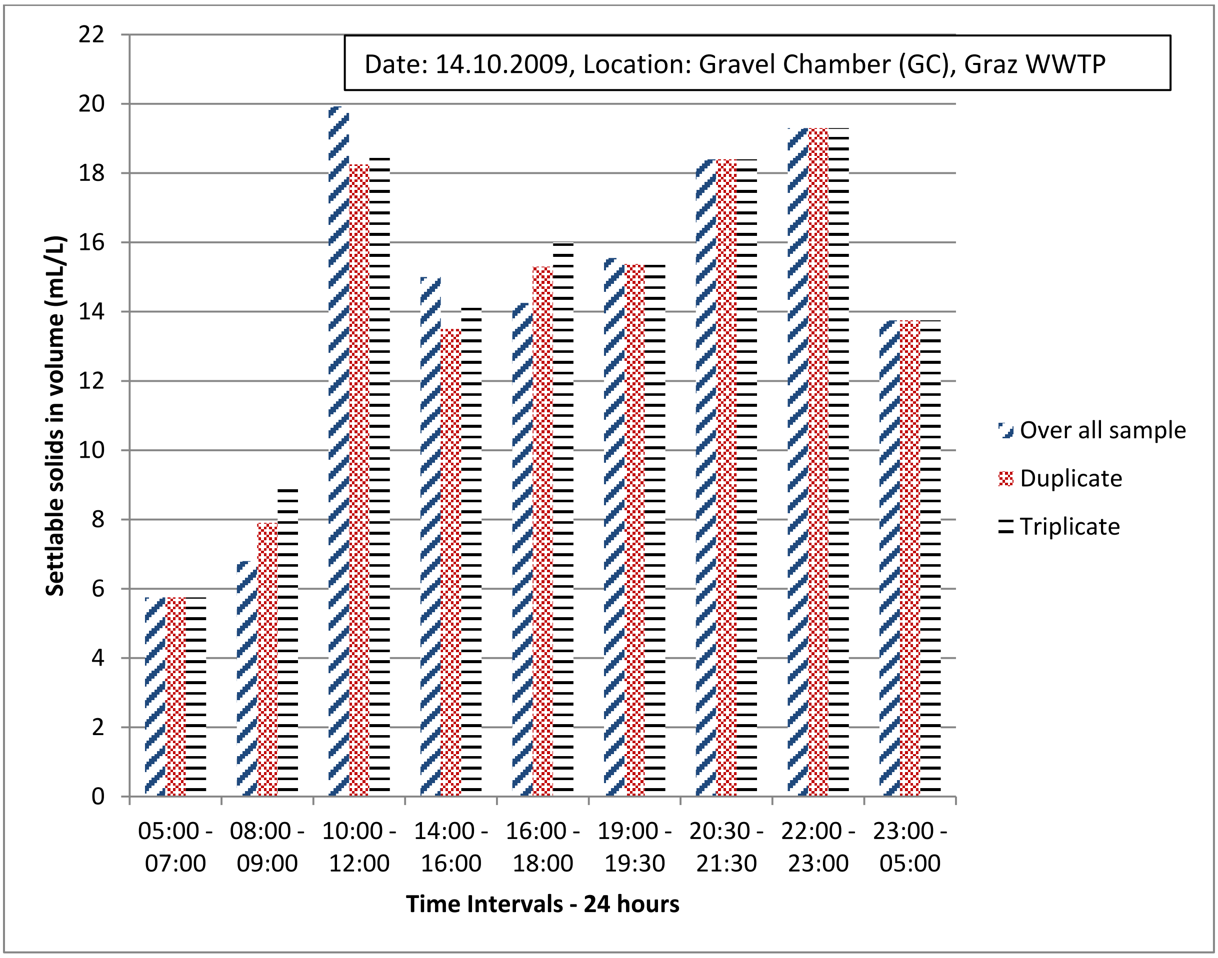



**Figure 5.25: Settlable solids in Imhoff cone**

*5.2.2.4.3 Chemical Oxygen Demand*

Chemical Oxygen Demand (COD) is one of the most important quality parameter. It measures the organic strength of the material. It gives the exact idea of the pollution load carried by these solids with them in the wastewater and also if discharged in water bodies without any treatment. The particles higher in COD are chronic and every type of life is dangered by this parameter.

Figure 5.26 shows the results of COD in the three settling fractions with settling time of 10 minutes. The results show that with the higher flow rate of inflow, the greater the COD is, as in this case at the time interval 10:00 – 12:00 the COD value exceeds 2300 mg/L. The results also show that there are higher concentrations of COD in the 2$^{nd}$ and 3$^{rd}$ fractions of solids also. This is same in the case of Figure 5.27 and Figure 5.28.

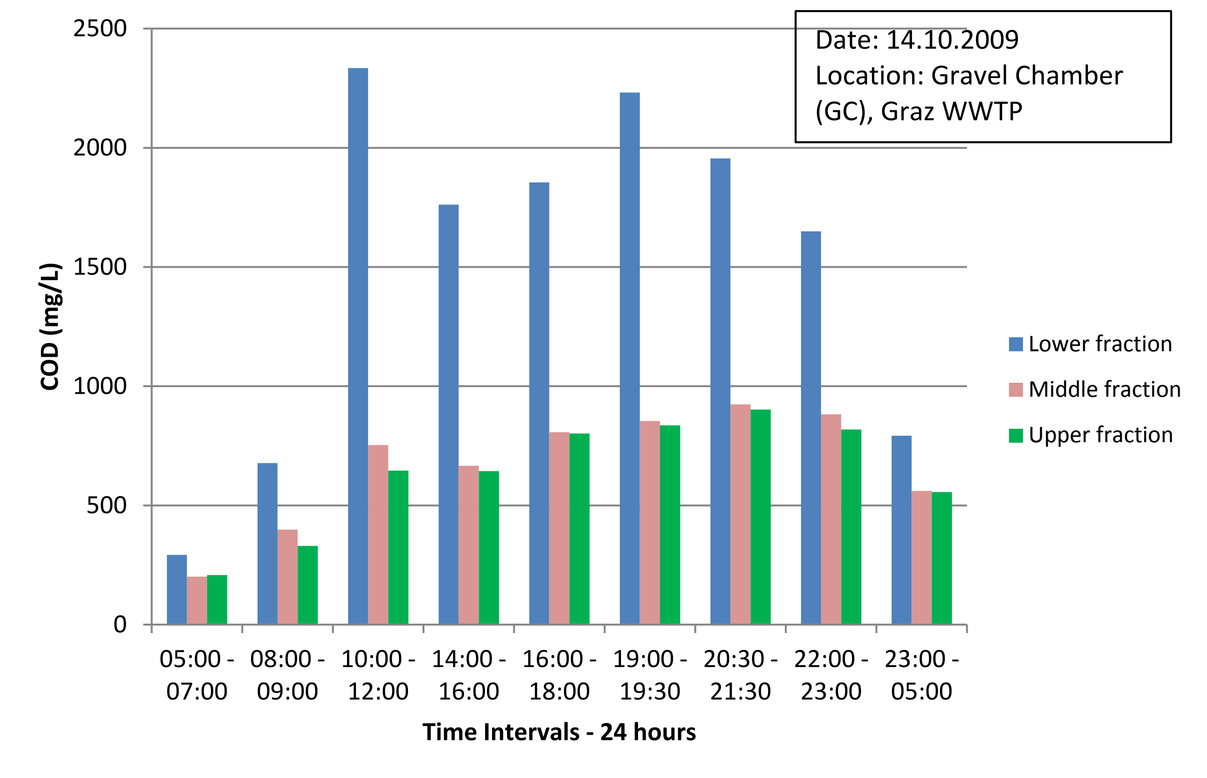



**Figure 5.26: COD Conc. In three fractions with settling time 03 minutes**

The settling time of 05 minutes have not any significant effect on the concentration of COD as compared to settling time of 05 minutes. The COD concentration is similar in the time interval 10:00 – 12:00 and 19:00 – 19:30. In these two timings of the day, COD have highest concentration. While in the afternoon the concentration of COD in lower fraction remain stable. The middle and upper fraction have almost same concentration of COD. In Figure 5.28, the concentration has remarkably increased and gone past 2000 mg/L for almost all the time throughout the day i.e. (10:00 – 23:00). The middle and upper fraction shows the same trend as for 3 and 5 minutes, but for time interval 19:00 – 19:30, upper fraction have higher concentration of COD than middle fraction. It is very necessary to remove these solids with the best way.

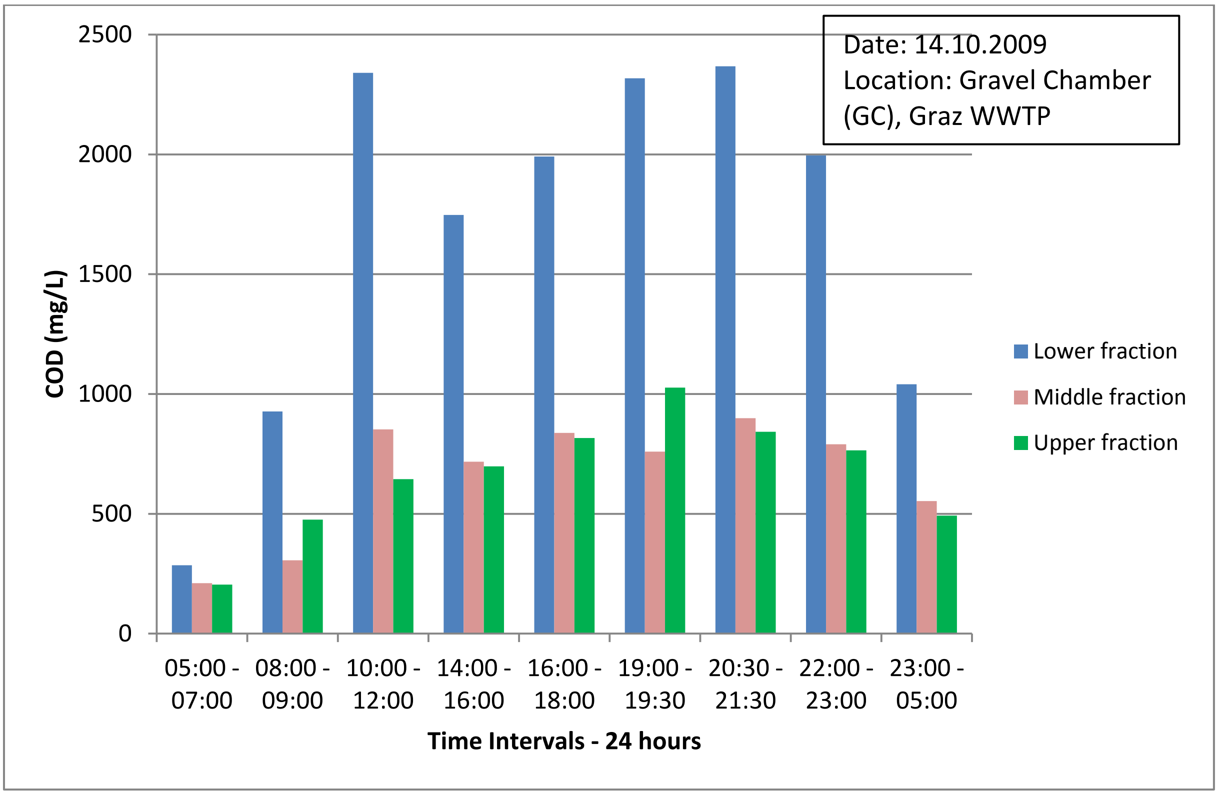



**Figure 5.27: COD Conc. in three fractions with settling time 05 minutes**

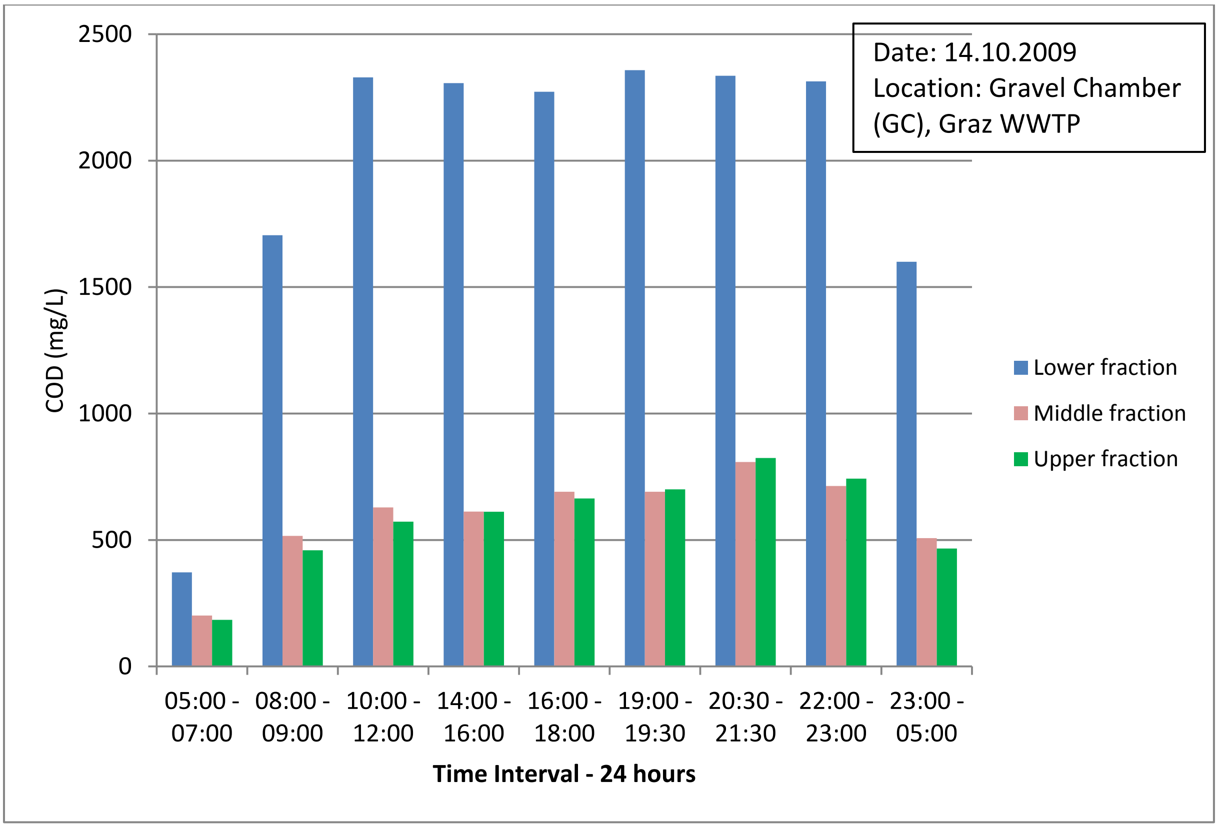



**Figure 5.28: COD Conc. In three fractions with settling time 10 minutes**

### 5.2.3 Experimental Campaign – 2

The 2nd experimental campaign has been started in summer 2010 with some more work to verify and testify the protocols finalized during the previous sections. The experiments were performed in March – May 2010. The sampling points have been expanded from Gravel Chamber to both ends of the primary sedimentation tank. The settling time 30 minutes was considered in addition to 10 minutes. The experiments in this campaign were also performed with three fraction i.e. lower fraction, middle fraction, and upper fraction. In the end, an improvement in the method was proposed and it produced better results. Mass Balances are also prepared and discussed.

#### *5.2.3.1 Sampling Points*

The sampling points were Gravel Chamber, Influent Primary Sedimentation Tank and Effluent Primary Sedimentation Tank.

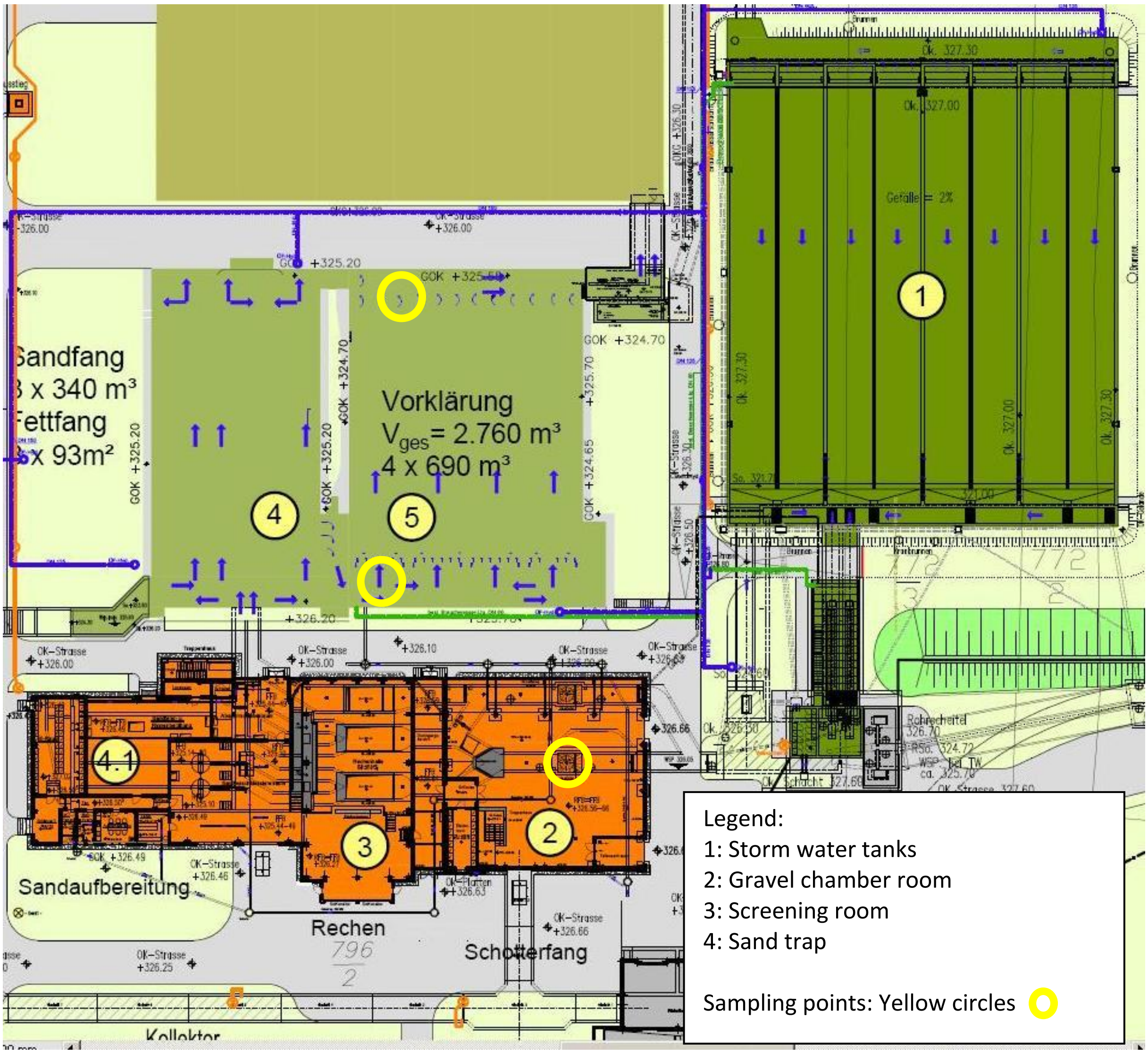



**Figure 5.29: Sampling points marked as yellow circles**

Influent Primary Sedimentation Tanks was the sample taken at the entrance of Primary Sedimentation Tank. Effluent Primary Sedimentation Tanks was the sample taken at the exit point of wastewater from Primary Sedimentation Tank. The sedimentation tank is selected to check the performance of the settling tank and to check these protocols to improve the performance of the tank. It will also be helpful in assessing the efficiency of the storm water tanks or CSO tanks. The sampling points are shown in Figure 5.29 with yellow circles.

### *5.2.3.2 Settling time of 10 min. & 30 min.*

The settling time of 30 minutes was introduced in this section because in most of the primary settling tanks the settling time is around 30 minutes during wet weather conditions. It was therefore decided to test the settling apparatus for 10 and 30 minutes to have an orientation of solids on real time basis. It will straightforwardly help to perform better settling practices in Primary Sedimentation Tanks and Combine Sewer Overflow Tanks.

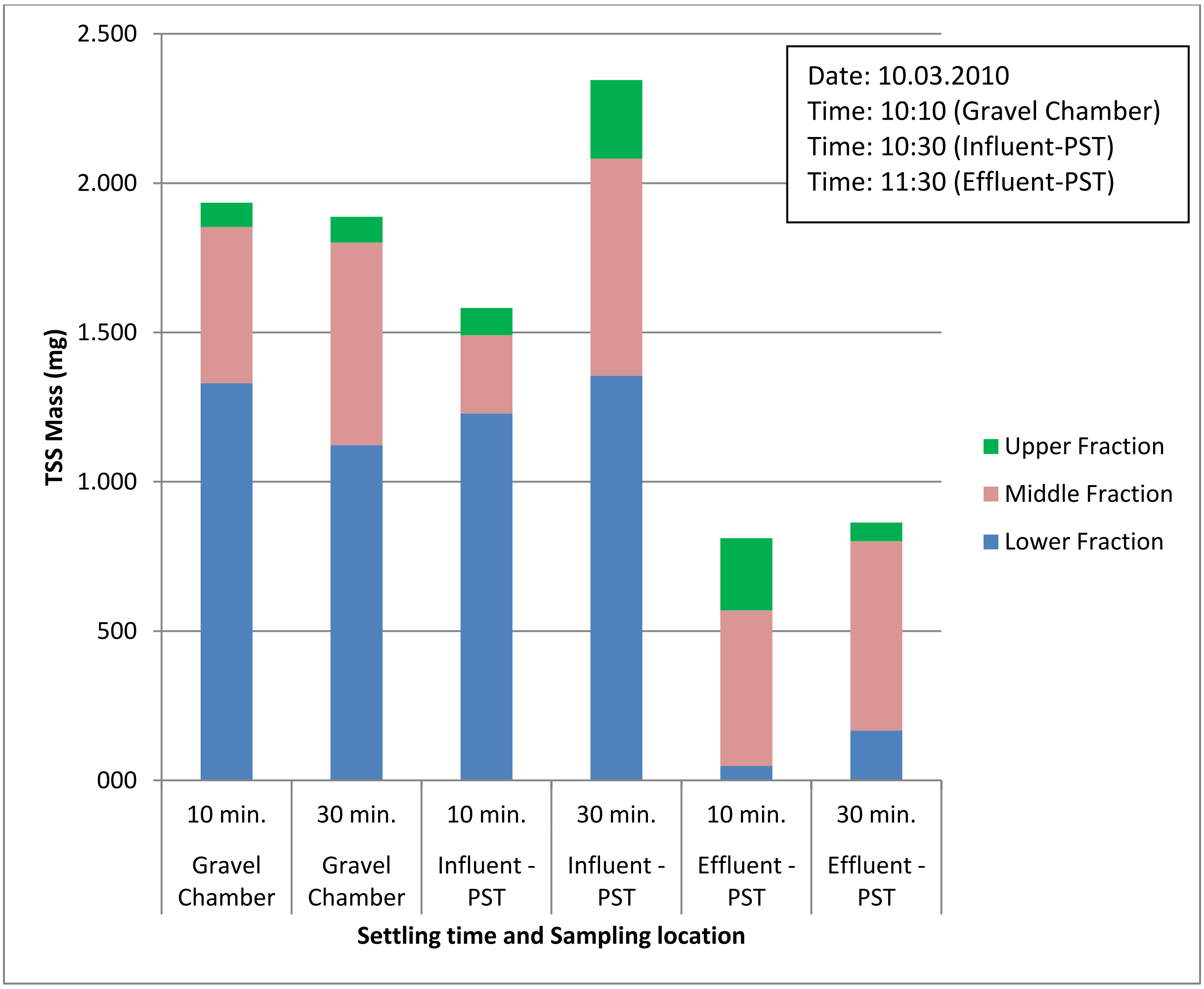



**Figure 5.30: Experiments at 03 sampling sites with settling time of 10 min. & 30 min.**

Figure 5.30 shows the results of TSS Mass at three sampling sites with settling time of 10 and 30 minutes. The results indicate that there is something wrong with them. The samples of gravel chamber show that there is less quantity of solids settle in lowermost fraction for 30 minutes settling time as compared to the 10 minutes. The results of Influent Primary Settling Tank also have shown a high difference in the concentrations of the upper two fractions. In Graz WWTP, The sludge water is pumped back at the entrance of primary settling tank, so it may be reason for more TSS concentration. The experiment was revised some times. It was then decided to change the procedure little bit. The results are very impressive with this change and improvement in the procedure, which will be discussed in the next section.

#### *5.2.3.3 Method Improvement*

There were some small errors in the results in the previous step, so it was decided to change the procedure of filling the column. First the column was normally filled with the help of pump but then the column was filled manually with the help of 5L beaker. All the remaining procedure remained the same. The experiments were performed using this new filling method; a remarkable improvement has been seen. This behaviour is also discussed in Figure 5.31.

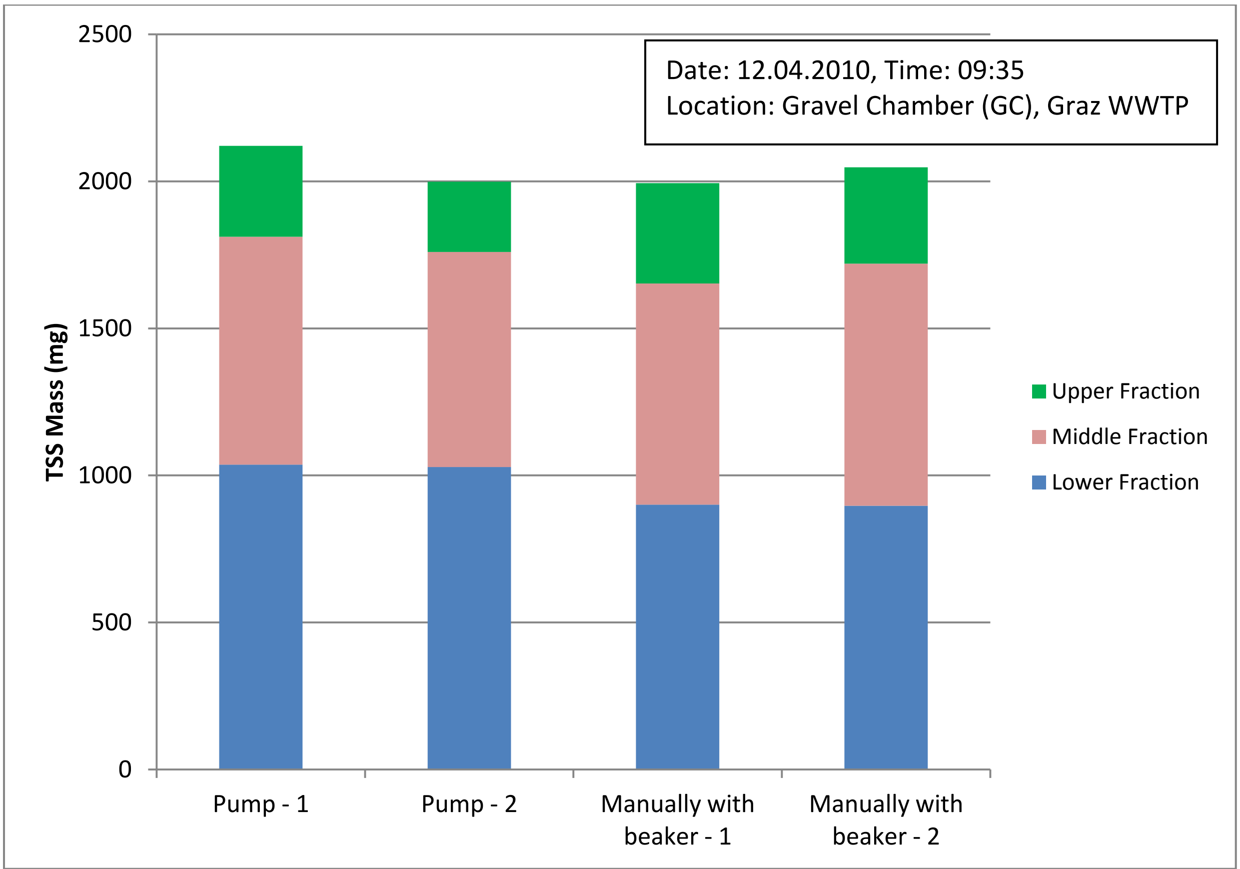



**Figure 5.31: TSS Mass with method improvement – 10 minutes**

It can be seen from the Figure 5.31 with the pump the results have 100mg difference and with direct filling method, the difference is minimal and ignorable. This figure shows the settling of solids in three fractions with settling time of 10 minutes.

The Figure 5.32 also shows that there is an improvement can be seen in the results of experiments filed by pump and by direct filling. There are oscillation in the results by pump method. The results by the method of direct filling is reliable and the difference between the TSS mass of these two same samples is very low and negligible. It can therefore be said that the method of direct filling has less errors than all previous methods.

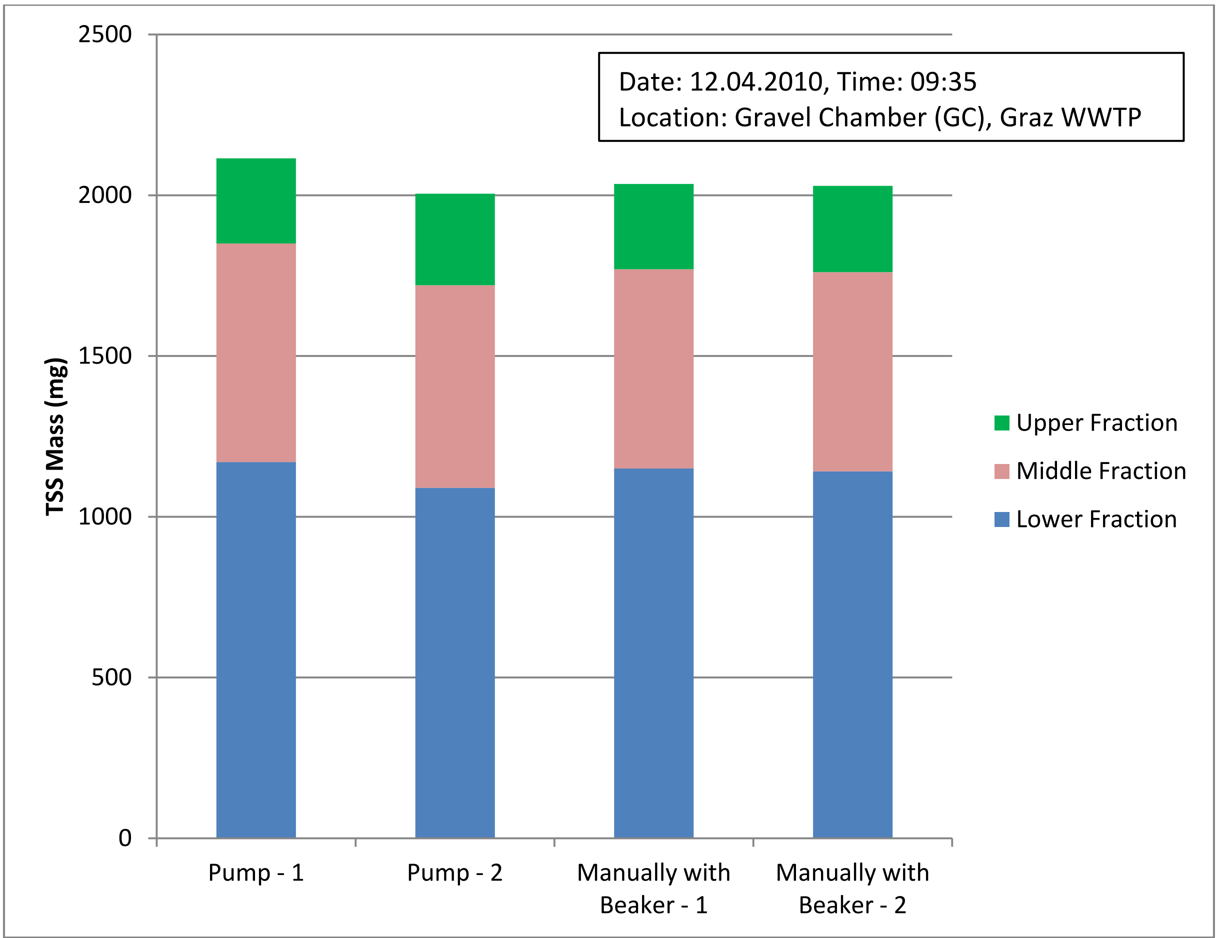



**Figure 5.32: TSS Mass with method improvement – 30 minute**

The improved method is also tested on quality parameters to check relaibility and reproducibility of the method. Chemical Oxygen Demand (COD) has been tested on settling apparatus by both filling methods. It can be seen from the Figure 5.33 that COD results with direct filling method have very less diference in values of same sample. While in case of the pump flling method, the results shows some oscillation. It means that direct filling method also had better and reliable results for the Quality paramter i.e. COD.

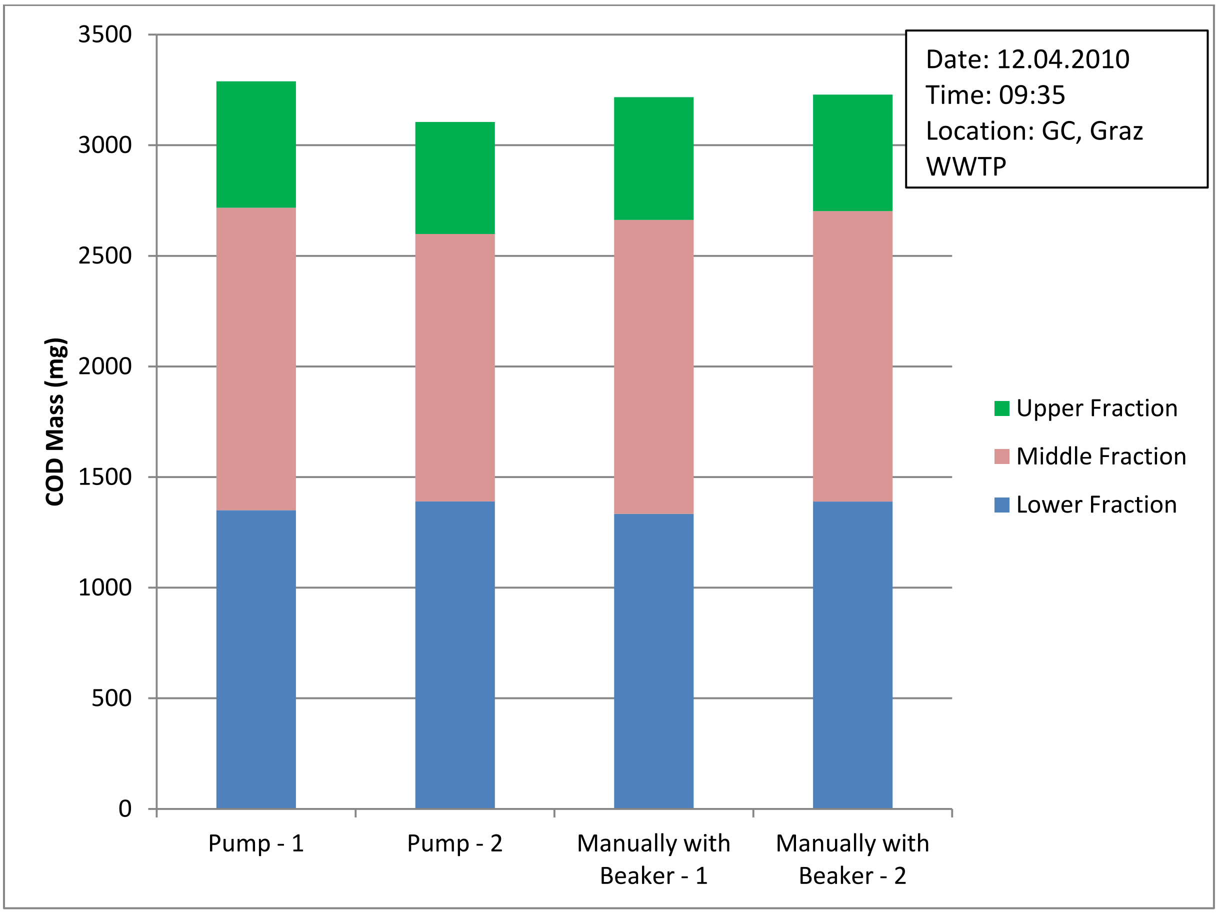



**Figure 5.33: Method Improvement – COD at settling time 10 min.**

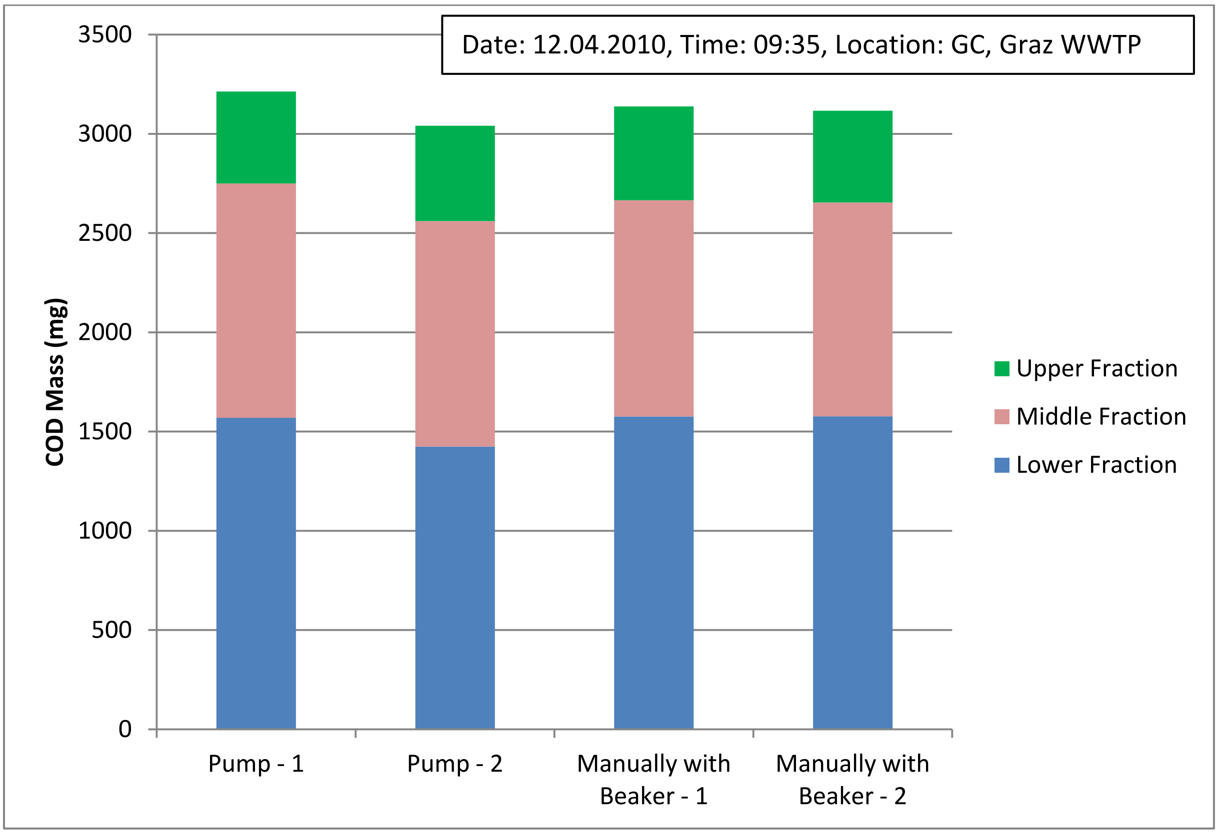



**Figure 5.34: Method Improvement – COD at settling time 30 min.**

Figure 5.34 shows also the same pattern of COD mass with the both the methods. There is not so much difference in results of COD Mass, for both methods but there is a slight improvement in the method of direct filling. It is proposed that in the future experiments, the improved method should be used for all the sampling sites.

### *5.2.3.4 Dry Weather Experiments*

The experiments for the dry weather event are tested with the new improved method. The results in Figure 5.35 shows that almost there is no difference in settling with the variation in settling time from 10 to 30 minutes. It is therefore inferred from the results that 10 minutes results can replace the 30 minutes result.

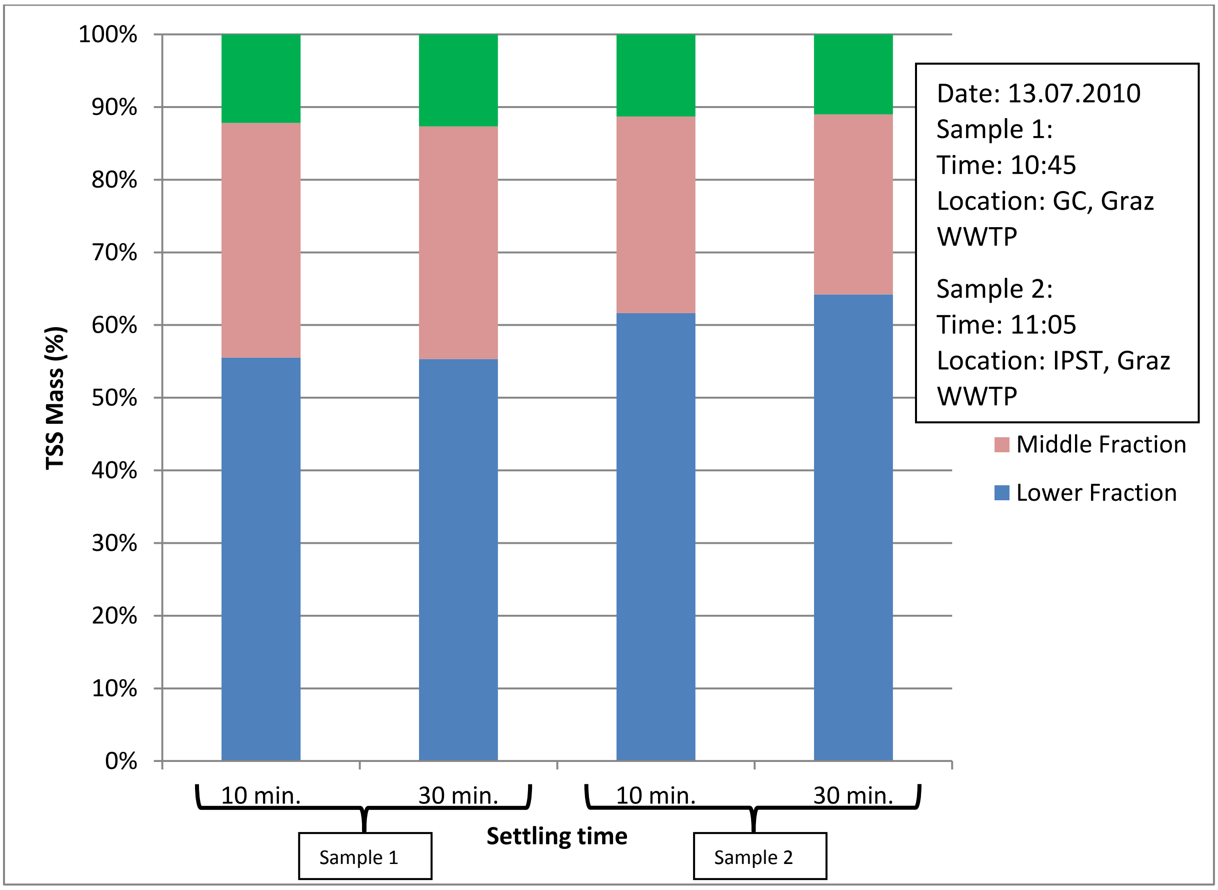



**Figure 5.35: TSS Mass at settling time of 10 & 30 min. for Dry weather**

### *5.2.3.5 Wet weather Experiments*

There is a little difference in the settling of solids with the variation in the settling time from 10 to 30 minutes, as shown in Figure 5.36. The results show an increase of about 5% in the TSS Mass with the increase in time from 10 minutes to 30 minutes. The wet weather results are little bit different in this regard from dry weather events.

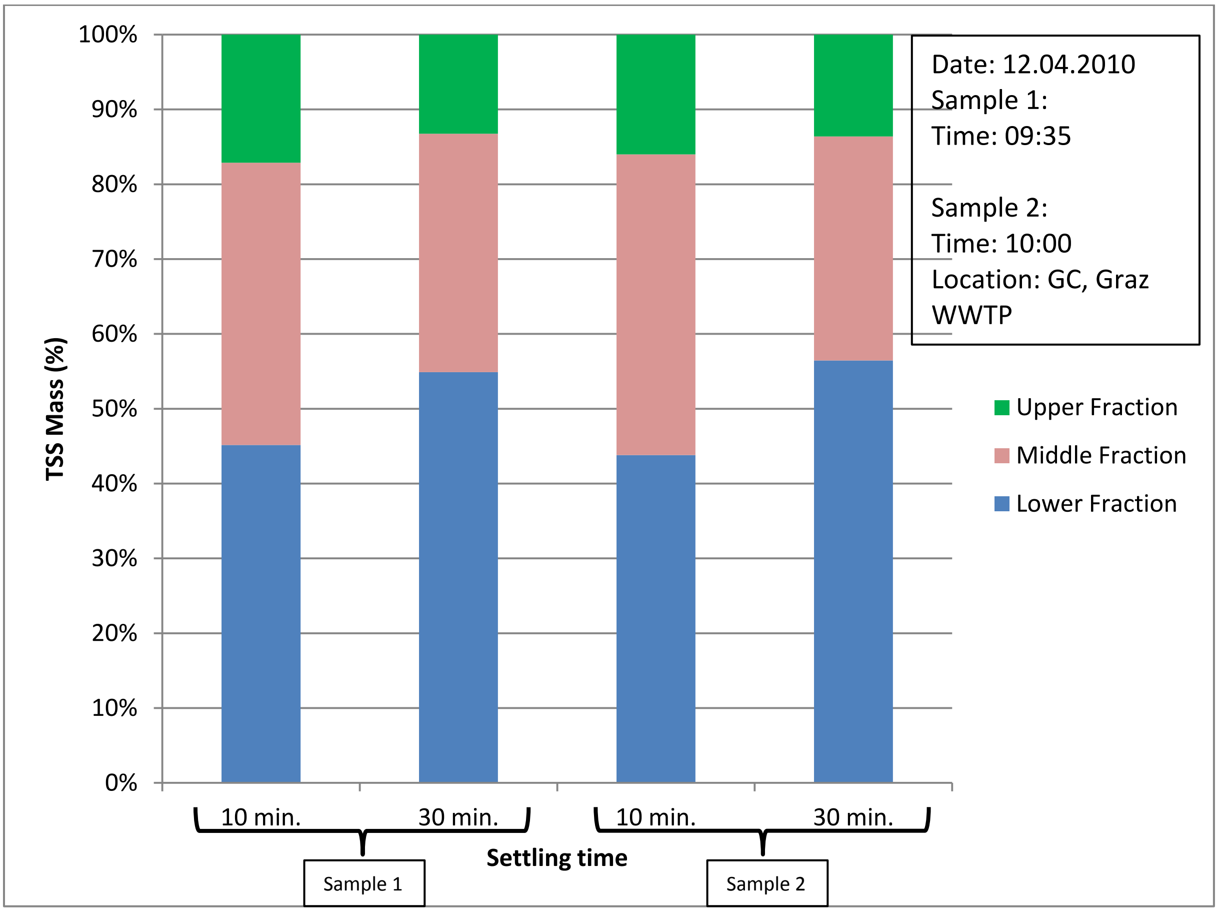



**Figure 5.36: TSS Mass at settling time of 10 & 30 min. for wet weather**

### *5.2.3.6 Mass Balance*

Table 5.1 (Aslam et al., 2011b) shows the resulting concentrations of total suspended solids and also the mass balances. The experiments are performed in duplicate and is shown as ‘a’ and ‘b’ in the table. In this table, the results of the TSS in three fractions are measured and compared with the overall sample’s concentration. This overall sample is the sample which is used for experimentation in settling column. It can be seen from Table that the overall mass balances fit quite well with the sum of the three part fractions. The differences are in a range of only 4 – 5%. When comparing the two different settling times of 10 and 30 minutes, an increase of 11% solids in lower fraction could be observed.

It was interesting to see that the concentrations in the upper fraction are almost equal to those in the middle fraction, or these two fractions have a difference of about 0 – 10% in the concentrations of TSS. This behaviour was also observed during the laboratory experiments.

The mass balance shows the high quality of analyses and sampling. It shows that the sampling is performed according to standards with minimal errors. After sampling, the laboratory analyses for TSS also show great accuracy.

**Table 5.1: Total suspended solids in 3 different fractions and Mass Balances (Aslam et al., 2011b)**

| | Sample ID | Fractions | TSS (mg/L) | | | Mass (mg) | Mass (%) |
|---|---|---|---|---|---|---|---|
| | | | a | b | Average | | |
| Settling time: 10min. | 1 | Lower | 1738 | 1794 | 1766 | 900.66 | 45 |
| | 2 | Middle | 288 | 302 | 295 | 752.25 | 38 |
| | 3 | Upper | 324 | 332 | 328 | 341.12 | 17 |
| | Total | | | | | 1994.03 | 100 |
| | **1+2+3** | **Over All Sample** | **504.67** | **505.33** | **505.00** | **2070.50** | **Δ = + 4%** |
| | **Sample ID** | **Fractions** | **TSS (mg/L)** | | | **Mass (mg)** | **Mass (%)** |
| | | | a | b | Average | | |
| Settling time: 30min. | 4 | Lower | 2158 | 2162 | 2160 | 1112.40 | 56 |
| | 5 | Middle | 236 | 236 | 236 | 590.00 | 30 |
| | 6 | Upper | 258 | 258 | 258 | 268.32 | 14 |
| | Total | | | | | 1970.72 | 100 |
| | **4+5+6** | **Over All Sample** | **504.67** | **505.33** | **505.00** | **2070.50** | **Δ = + 5%** |

### 5.2.4 Experimental Campaign – 3

This was the final experimental campaign performed in summer 2010. A comprehensive plan was made for measuring dry weather and wet weather event. The main focus was on dry weather. These experiments were undertaken according to the new improved method. A settling time of 10 and 30 minutes was used in this campaign. Period sampling was also introduced. Video were made to measure the visual settling velocity, size and shape of particle. In the end the results are also compared with the one other online instrument 'Solitax' (Figure 4.10 shown in Chapter 4).

#### *5.2.4.1 Periodic Sampling / Time Interval*

The experiments were done for four different timings of day depending on the flow of wastewater in the Graz WWTP. These timings were selected on the basis of the previous data of flow rate of wastewater from Graz WWTP authorities. The time interval categories were made to study the settling of solids in minimal flow rate, rising flow rate, peak flow rate and down/stable flow rate. These settling studies will help us to find out the settling behaviour of solids in all different flow patterns of the day. The details about time interval are given as below:

- Morning minimal flow (06:00 – 07:00)
    - The flow of wastewater during this time interval at the entrance of the Graz wastewater treatment plant is 400 l/s.
- Morning rising flow (09:00 – 09:30)
    - The average flow in this time period is 750 l/s.
- Daily Peak flow (10:30 – 11:00)
    - The flow of wastewater is highest from all the day in this time interval. This flow is stable for the time period of half to one hour. The average flow in this time period is more than 1000 l/s.
- Daily stable flow (16:00 – 16:30):
    - The flow of wastewater starts to drop down after the peak time and time interval is selected to have a representative sample of wastewater having stable decreasing flow rate at the entrance of the Graz WWTP. The wastewater has almost stable flow rate till night. The average flow in this time period is 800 l/s.

#### *5.2.4.2 Dry Weather experiments*

The experiments were performed for the 05 dry weather events ranging from June 2010 to August 2010. The results are shown in Figure 5.37.

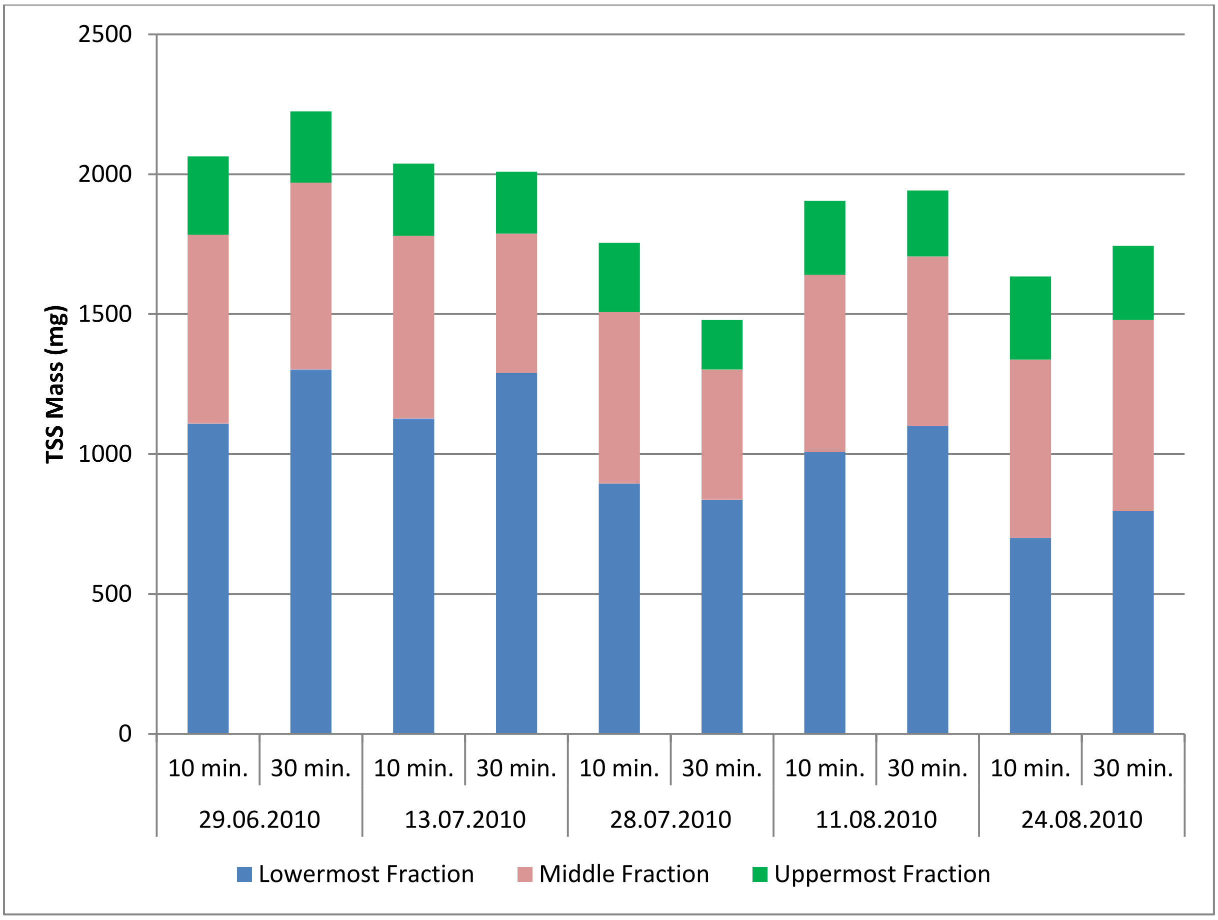



**Figure 5.37: TSS at Gravel Chamber - Comparison of 10 & 30 min. (10:30 – 11:00)**

The results shows that there is an about 5-10 % increase in the settling of solids with the increase in settling time from 10 to 30 minutes. In one case the increase is about to negligible. The results in Figure 5.37 are from the sampling site gravel chamber.

The results in Figure 5.38 show the settling to solids in Influent Primary Settling Tank with settling time of 10 and 30 minutes for 05 dry weather days. The results also showed the same pattern as of Gravel Chamber. The one difference is that in almost all the samples, the lowermost fraction has about 60% of the total solids.

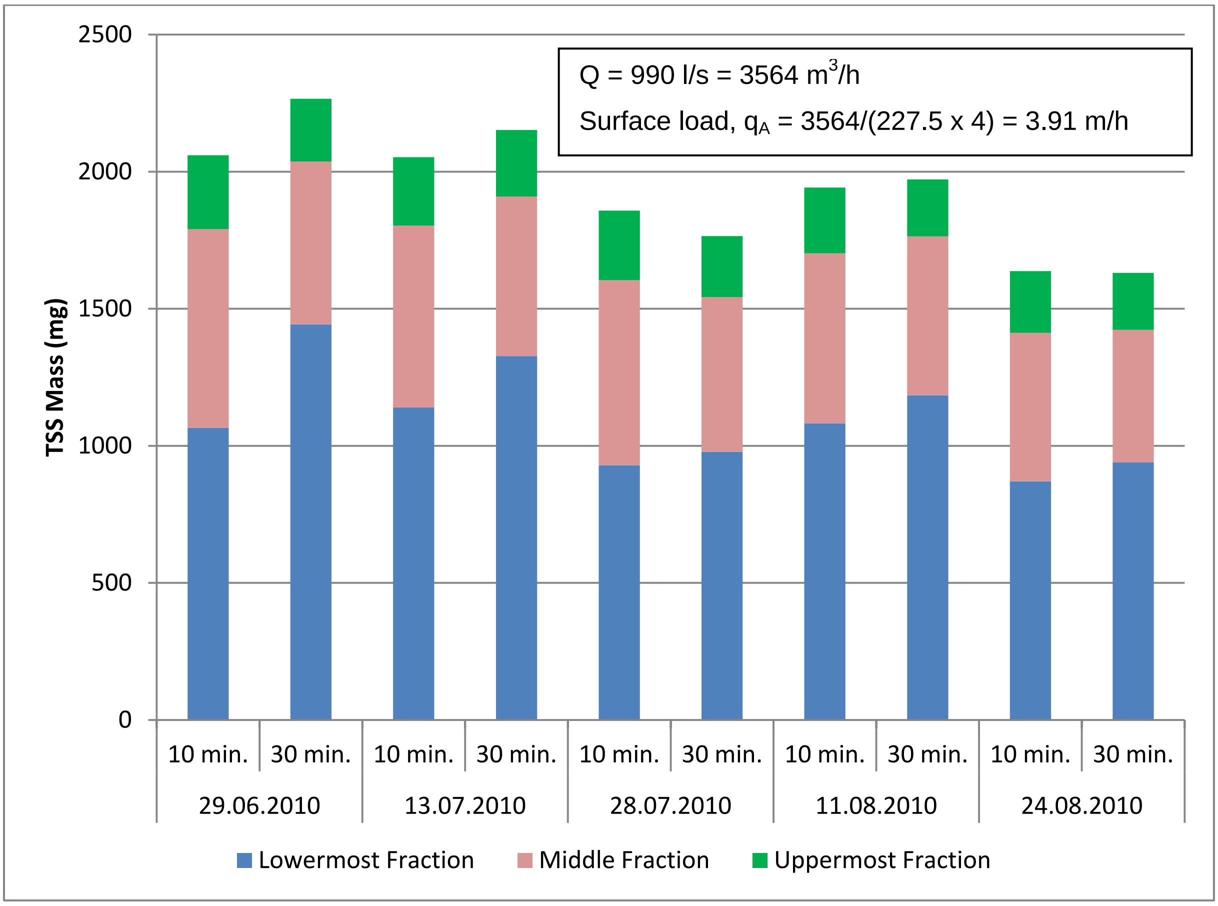



**Figure 5.38: TSS at Influent PST - Comparison of 10 & 30 min. (10:30 - 11:00)**

The results in Figure 5.39 show that there is about half of the TSS mass than that of Gravel Chamber and Influent Primary Settling Tank. The mass concentration in last three days shows higher trend while two initial days shows low reading of TSS mass. There are more solids in the higher fractions as it is the effluent, so it contains very less inorganic solids which settle very fast. The results show that there are about 10 – 30% solids settle in the lowermost fraction.

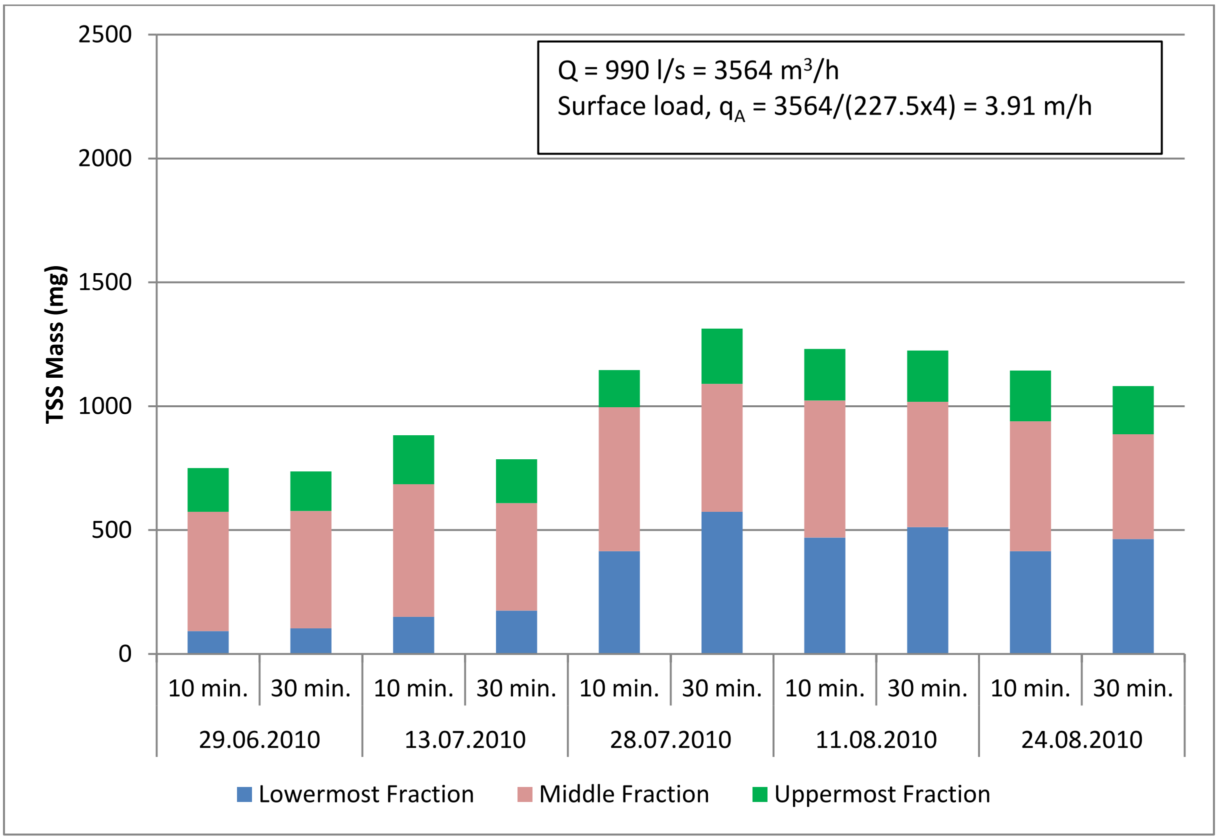



**Figure 5.39: TSS at Effluent PST - Comparison of 10 & 30 min. (10:30 – 11:00)**

### *5.2.4.3 Wet Weather experiments*

The wet weather events were also selected and experimented on the same protocols as mentioned in the previous step. The results in Figure 5.40 show that there is very less difference in the settling of solids in lowermost fraction, almost negligible. The difference is only due to the concentration of upper two fractions. The results show a small error in the total mass of fractions at Gravel Chamber and Influent Primary Settling Tank. These errors can be ignored when it is measured in percentages. The interesting thing is that the lowermost fraction have shown about same concentration of TSS mass in all the sampling points regardless of settling time of 10 and 30 minutes.

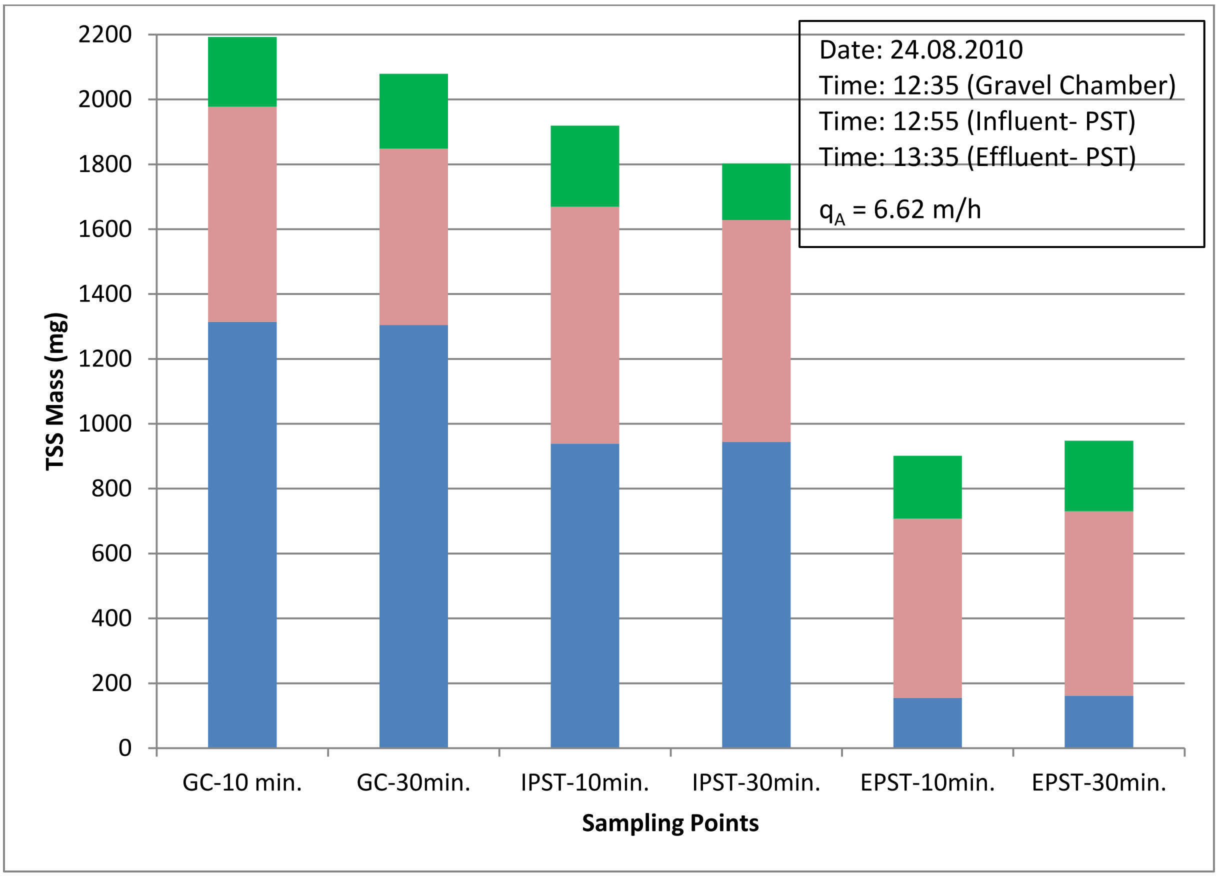



**Figure 5.40: TSS (mg) - Rain Weather 24-08-2010**

One other event of wet weather is reported in Figure 5.41. This event shows the ideal result. The overall mass is shown as same i.e. 1800mg.

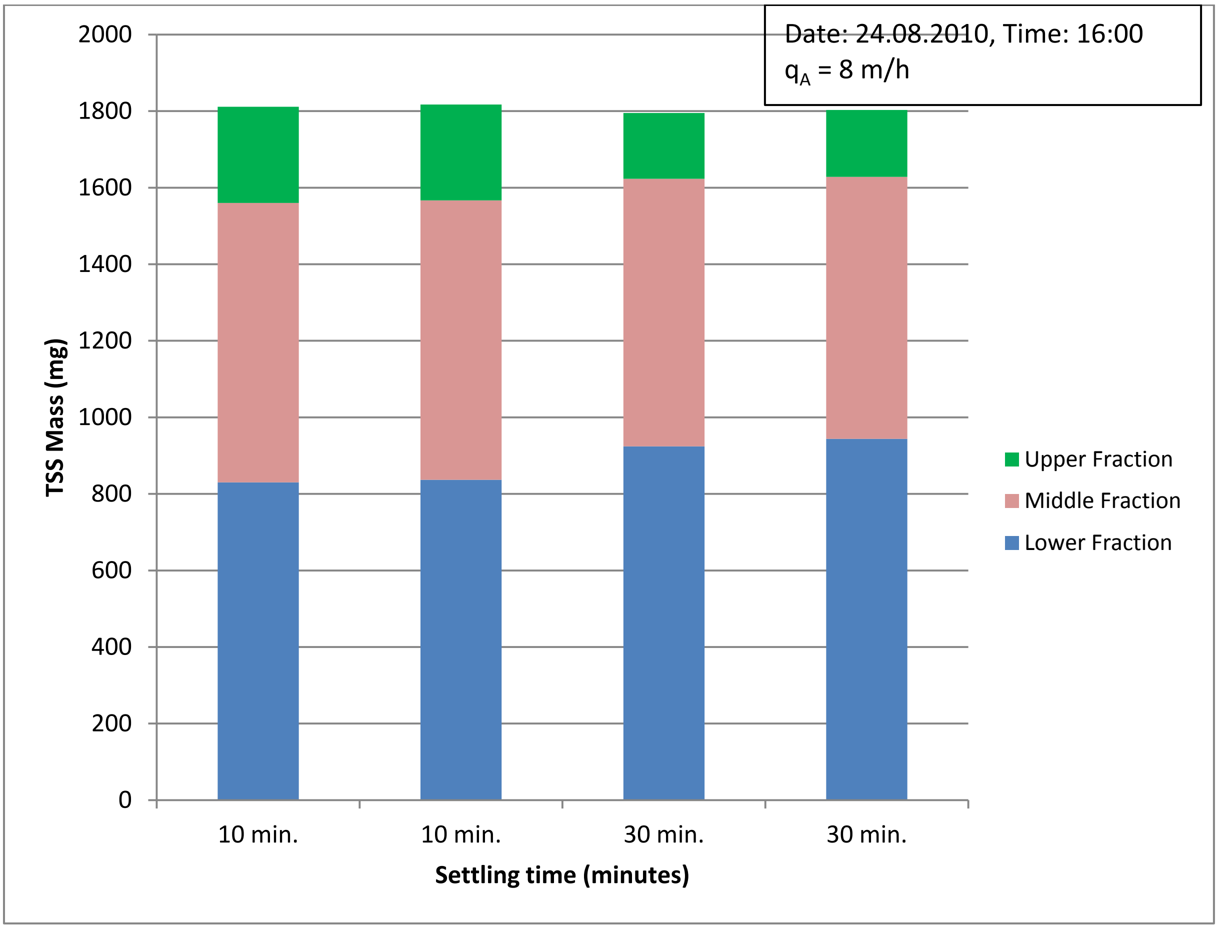



**Figure 5.41: TSS (mg) - Rain Weather Event**

The lowermost fraction shown an increase of about 5 % in the TSS mass with the increasing time of 20 minutes. But overall about 45 – 50 % solids settle in lowermost fraction with in first 10 and 30 minutes respectively.

### *5.2.4.4 Videos of settling processes*

The settling of solids in the settling apparatus was monitored by the video camera to observe and determine all the settling parameters without disturbing the flow of wastewater within the column. Hazzab (Hazzab et al., 2008) also reports that this method offers the advantage to not disturb the flow. The size and shape of particles are important parameters in settling of solids in wastewater. The settling velocity is also one of the most important parameter in settling studies. This video monitoring was done at the entrance point of the Graz WWTP to have a comprehensive orientation of solids in urban raw wastewater. The videos were made for all sampling locations mentioned in Experimental Campaign – 3. Video Analyses will be discussed in the next chapter.

### *5.2.4.5 Mass Balances*

Table 5.2 (Aslam et al., 2011a) shows the concentrations of total suspended solids and also the mass balances. It can be seen from Table that the overall mass balances fit quite well with the sum of the three part fractions.

The table shows that for the settling time of 10 minutes, lower fraction has an average TSS concentration of 2301 mg/L and middle fraction has an average TSS concentration of 258 mg/L. As the TSS concentration of lower fraction settle in the bottom of the lower fraction, so the remaining portion of that fraction is almost similar to that of the middle fraction. If it is assumed that this remaining portion of lower fraction has the TSS concentration (mg/L) equal to that of middle fraction, then the settled solids can be calculated.

**Table 5.2: Total suspended solids in 3 different fractions and Mass Balances (Aslam et al., 2011a)**

| | **Sample ID** | **Fractions** | **TSS (mg/L)** | | | **Mass (mg)** | **Mass (%)** |
|---|---|---|---|---|---|---|---|
| | | | a | b | Average | | |
| Settling time: 10min. | 1 | Lower | 2348 | 2254 | 2301 | 1127 | 63 |
| | 2 | Middle | 266 | 250 | 258 | 653 | 32 |
| | 3 | Upper | 244 | 248 | 246 | 258 | 13 |
| | Total | | | | | 2039 | |
| | **1+2+3** | **Over All Sample** | 496,00 | 506,00 | 501 | 2054 | ∆= **-0,76** |
| | **Sample ID** | **Fractions** | **TSS (mg/L)** | | | **Mass (mg)** | **Mass (%)** |
| | | | a | b | Average | | |
| Settling time: 30min. | 4 | Lower | 2658 | 2606 | 2632 | 1290 | 64 |
| | 5 | Middle | 194 | 204 | 199 | 498 | 25 |
| | 6 | Upper | 228 | 206 | 217 | 221 | 11 |
| | Total | | | | | 2009 | |
| | **4+5+6** | **Over All Sample** | 496,00 | 506,00 | 501 | 2054 | ∆= **-2,22** |

The differences are in a range of only 0.76 – 2.22%. When comparing the two different settling times of 10 and 30 minutes, an increase of 13% solids in lower fraction could be observed. It was interesting to see that the concentrations in the upper fraction are higher than those in the middle fraction with the settling time of 30 minutes. This behaviour was also observed during the laboratory experiments.

### *5.2.4.6 Comparison of settling apparatus experiments with Solitax*

The results of the final campaign were compared with the online tool of measuring TSS called 'Solitax', as shown in Figure 5.42. The experiments on solitax have been done in parallel to the experiments in settling apparatus. So for the validation or cross check and reliability of the results, the results of TSS concentration (mg/L) were compared.

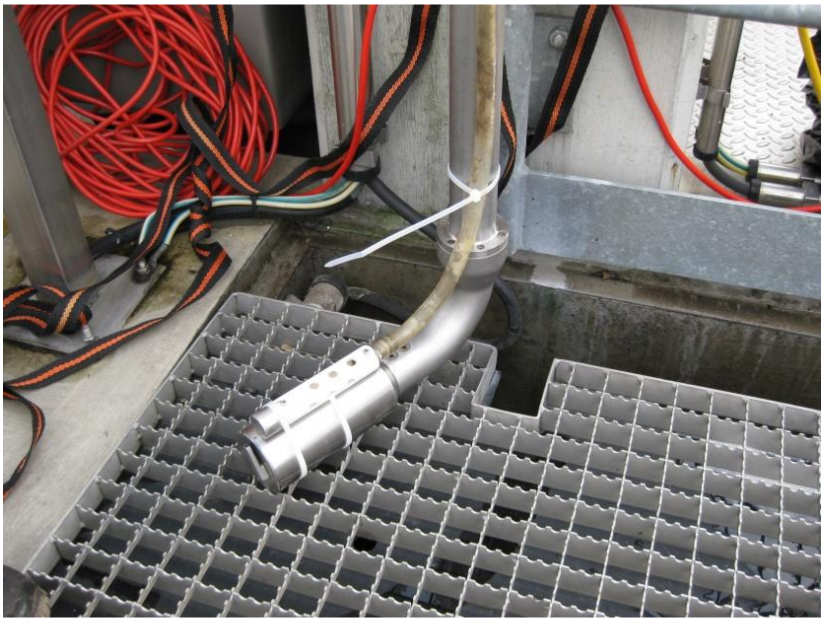


**Figure 5.42: Solitax with sampling probe (Vicuinik, 2012)**

### *5.2.4.6.1 Calibration of Solitax*

The Solitax instrument is calibrated with measurements of laboratory of Institute of Urban Water Management and Landscape Water Engineering at TU Graz. The results are shown in Figure 5.43 and Figure 5.44.

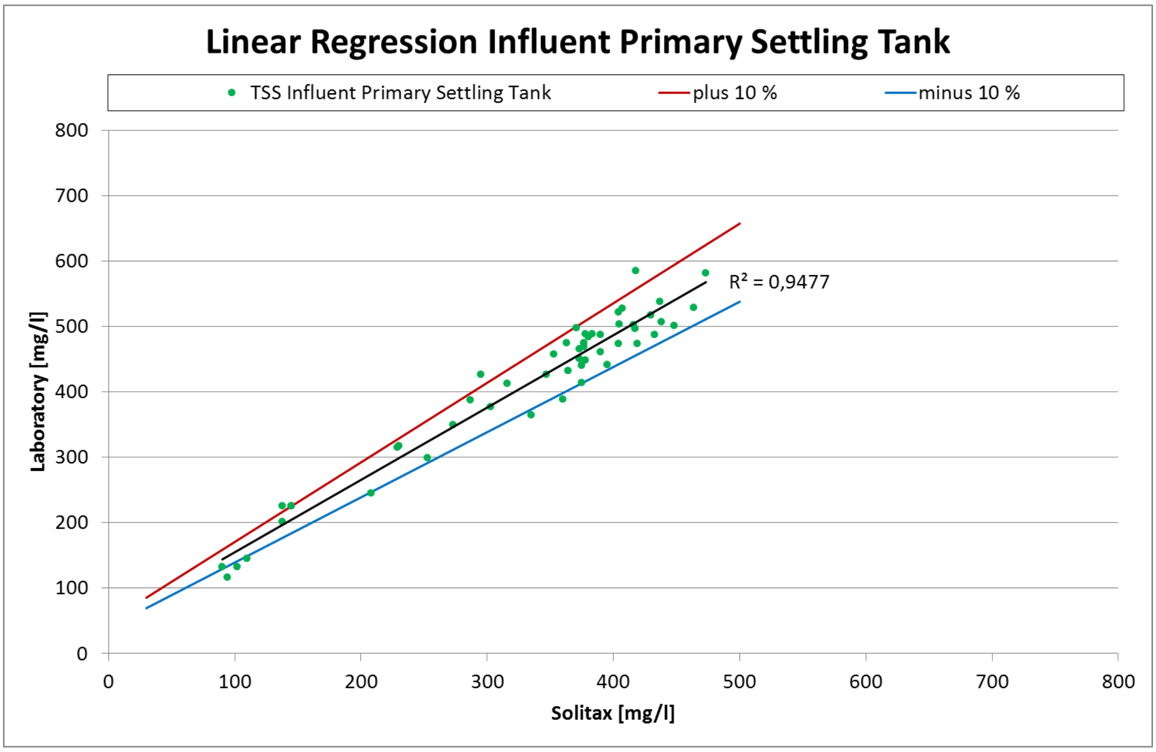



**Figure 5.43: Calibration of Solitax at Influent Primary Settling Tank (Vicuinik 2012)**

The linear regression shows that results of the solitax are reliable and calibrated. So the results of the settling apparatus were also compared with solitax.

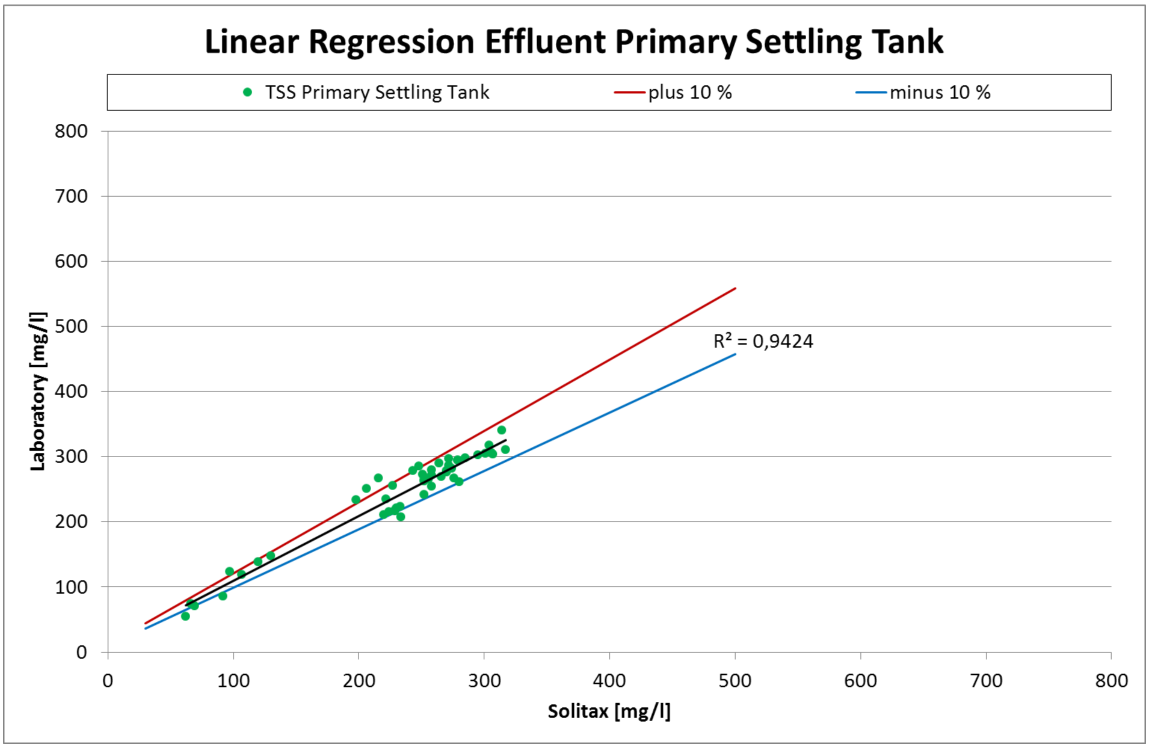



**Figure 5.44: Calibration of Solitax at Effluent Primary Settling Tank (Vicuinik 2012)**

### *5.2.4.6.2 Comparison of results with solitax*

Figure 5.45 shows the concentration of influent and effluent of primary settling tank, calculated by the both apparatuses (settling apparatus and solitax).

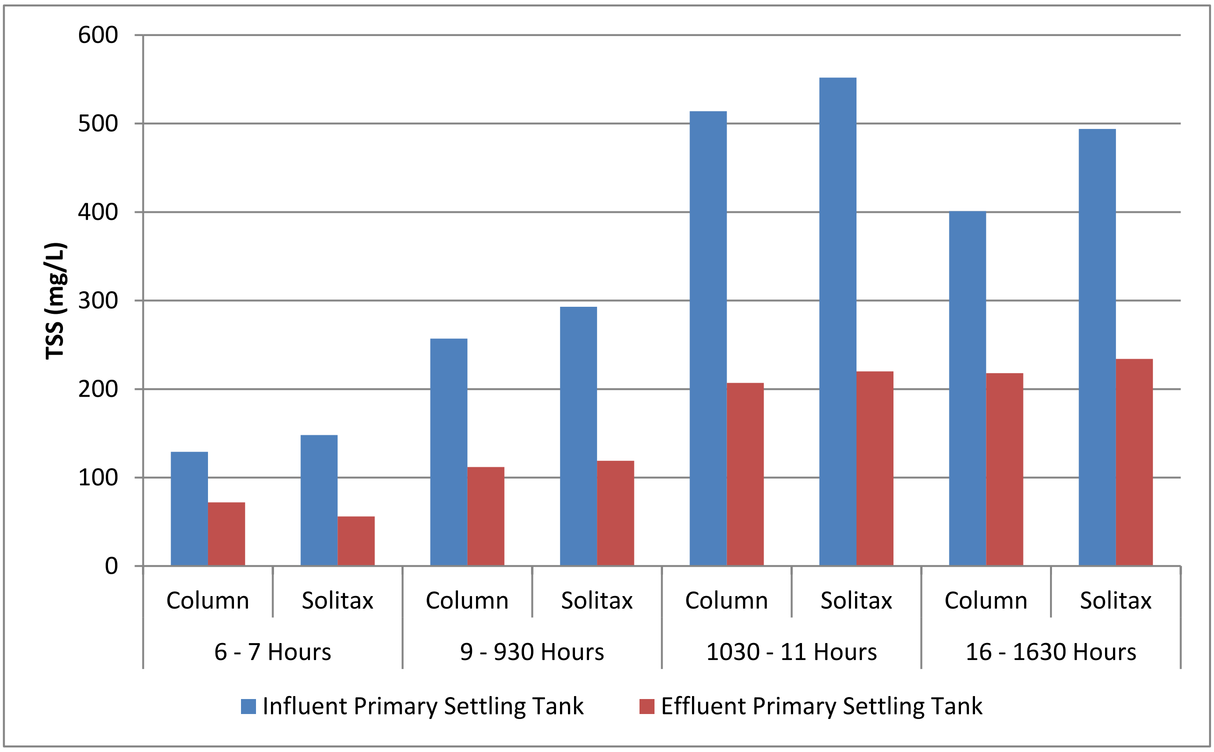



**Figure 5.45: Comparison of TSS Conc. (mg/L) - Dry Weather (13-07-2010)**

These results in Figure 5.45 show almost the same the concentration in different time intervals. The difference in the results from both methods is negligible.

One wet weather event was also compared with the Solitax to show the reliability of the results in both weather events. These results are shown in Figure 5.46. These results indicate that there is difference of about 15 – 20 % in the concentration of Influent Primary Settling Tank when compared the settling apparatus with Solitax. Solitax is an instrument and it has a higher resolution data. The results from this instrument were also calibrated. So there is marginal difference in the results of both methods then it can be said that how much reliable the results are and it can be published and referred anywhere.

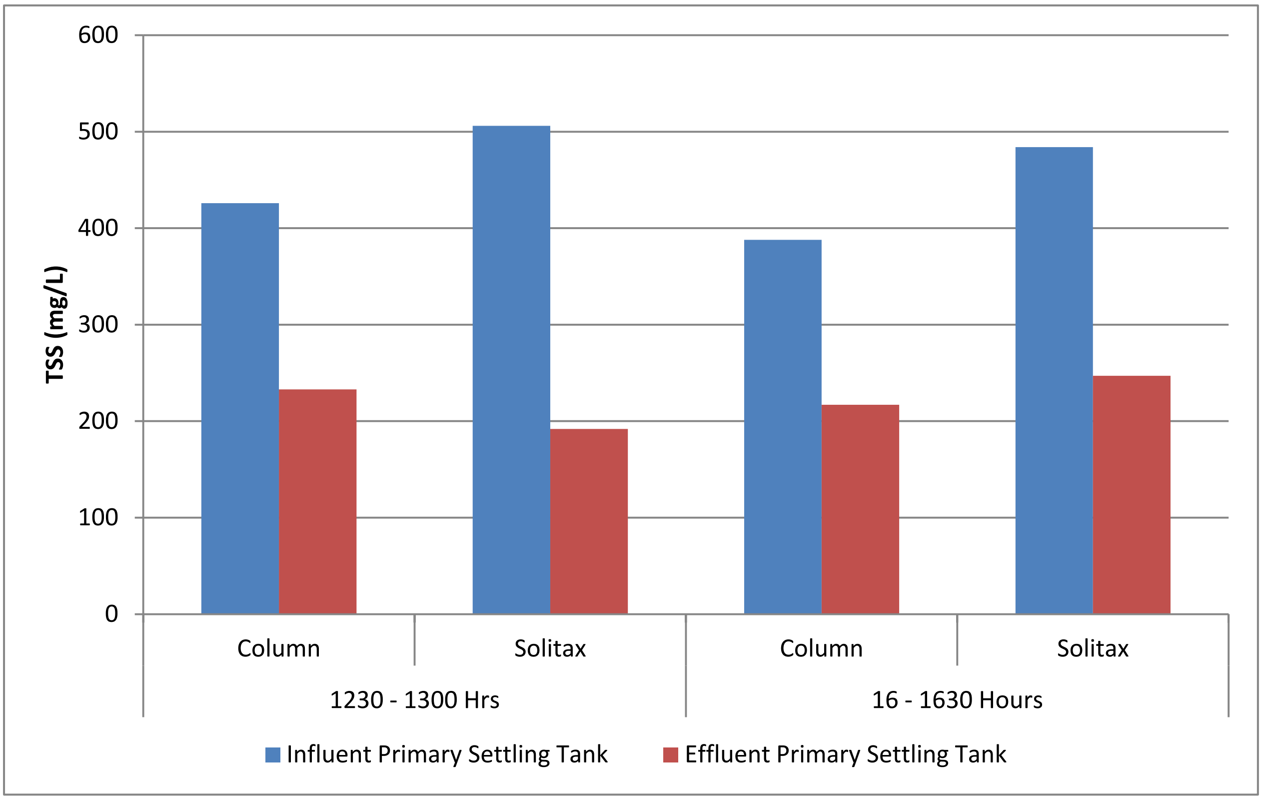



**Figure 5.46: Comparison of TSS Conc. (mg/L) - Wet Weather (24-08-2010)**

# 6 Chapter – 6 Results and Discussion – Video Analysis

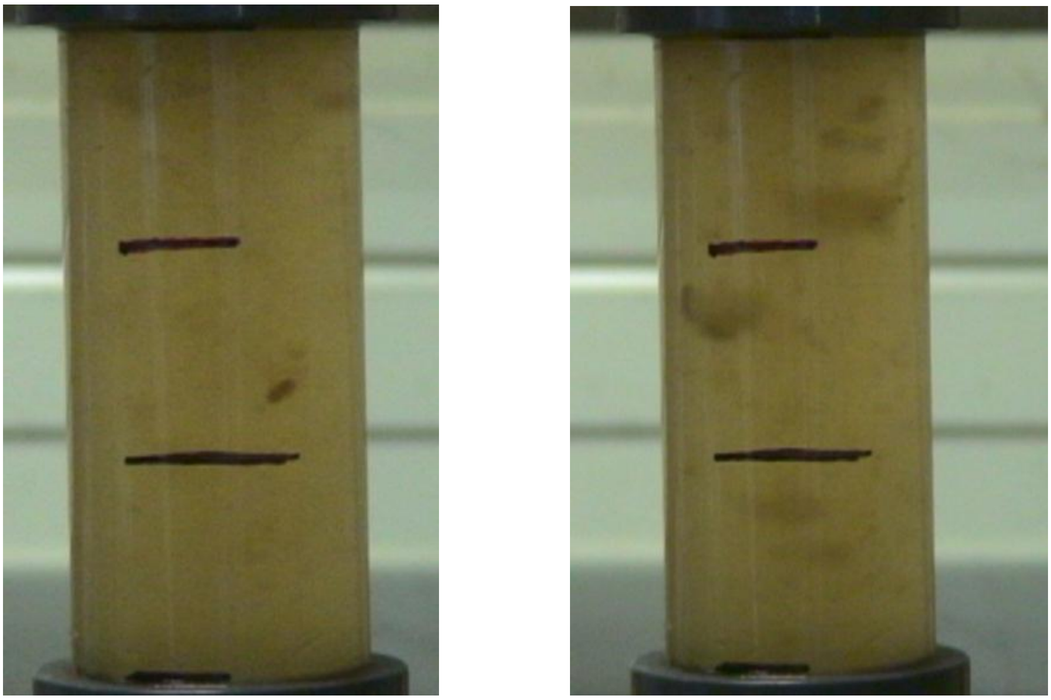
The videos were made to monitor the settling of solids in raw wastewater in settling apparatus. This chapter highlights the video analysis with the help of statistical graphs. The first section of the chapter discusses the time interval for which the experiments were undertaken and videos were made. The wastewater from all the sampling points were experimented and monitored by the video camera. The 2nd and last section of this chapter discusses the particle size and settling velocities and their correlation.

## 6.1 Video Monitoring

The settling of solids in the settling apparatus was monitored by the video camera to observe and determine all the settling parameters without disturbing the flow of wastewater within the column. Hazzab also reports that this method offers the advantage to not disturb the flow (Hazzab et al., 2008). The size and shape of particles are important parameters in settling of solids in wastewater. The settling velocity is also one of the most important parameter in settling studies. This video monitoring was done with wastewater of the entrance point of the Graz WWTP to have a comprehensive orientation of solids in urban raw wastewater.

## 6.2 Shape of Particles

The shape of particle is one of the most important parameter in settling of solids. Spherical particles settle easily while other takes time and settle slowly. The shape of the particles of raw wastewater from Graz WWTP can be seen in Figure 6.1. It is clear from the figure that particles do not have any regular shape. Some particles have regular shape while mostly have irregular shape. Some particles have filamentous shapes. These particles cause hindrances in the settling of other solids within the column. Sometimes these particles help in fast settling of other particles as they take the other particles with them down the column. Some solids are rectangular in shape, some are in square form.



Date: 29.06.2010, Time: 10:30 Date: 11.08.2010, Time: 10:30

**Figure 6.1: Real time shape of solids in the settling column (Aslam et al., 2011b)**

## 6.3 Particle size estimation and settling velocity measurement

The measurement of the particle size in this case was not any easy job. The measurements of the particle size in two dimensional (2D) are only possible from the video camera. The length and width of each particle is measured with the scale and cross-section was calculated in $mm^2$ (Aslam et al., 2011b). The exact procedure of the calculation of these both parameters is also shown in Figure 6.2. The settling velocity was measured by using the following formula:

$$Settling\ Velocity\ (S.V) = \frac{Distance\ covered}{Time\ elapsed} \qquad \text{[cm/sec.]}$$

The black line was marked on the column at some regular distance interval (at about 5 cm) to find out the distance covered by the specific particle. When the particle reached at marked line, the time was noted down and then allows that particle to settle down to other marked line at the distance of 5cm/10cm. The time was again noted at this point. In this way, the time and distance both are known. The settling velocity was calculated by using these values of distance and time in the above equation.

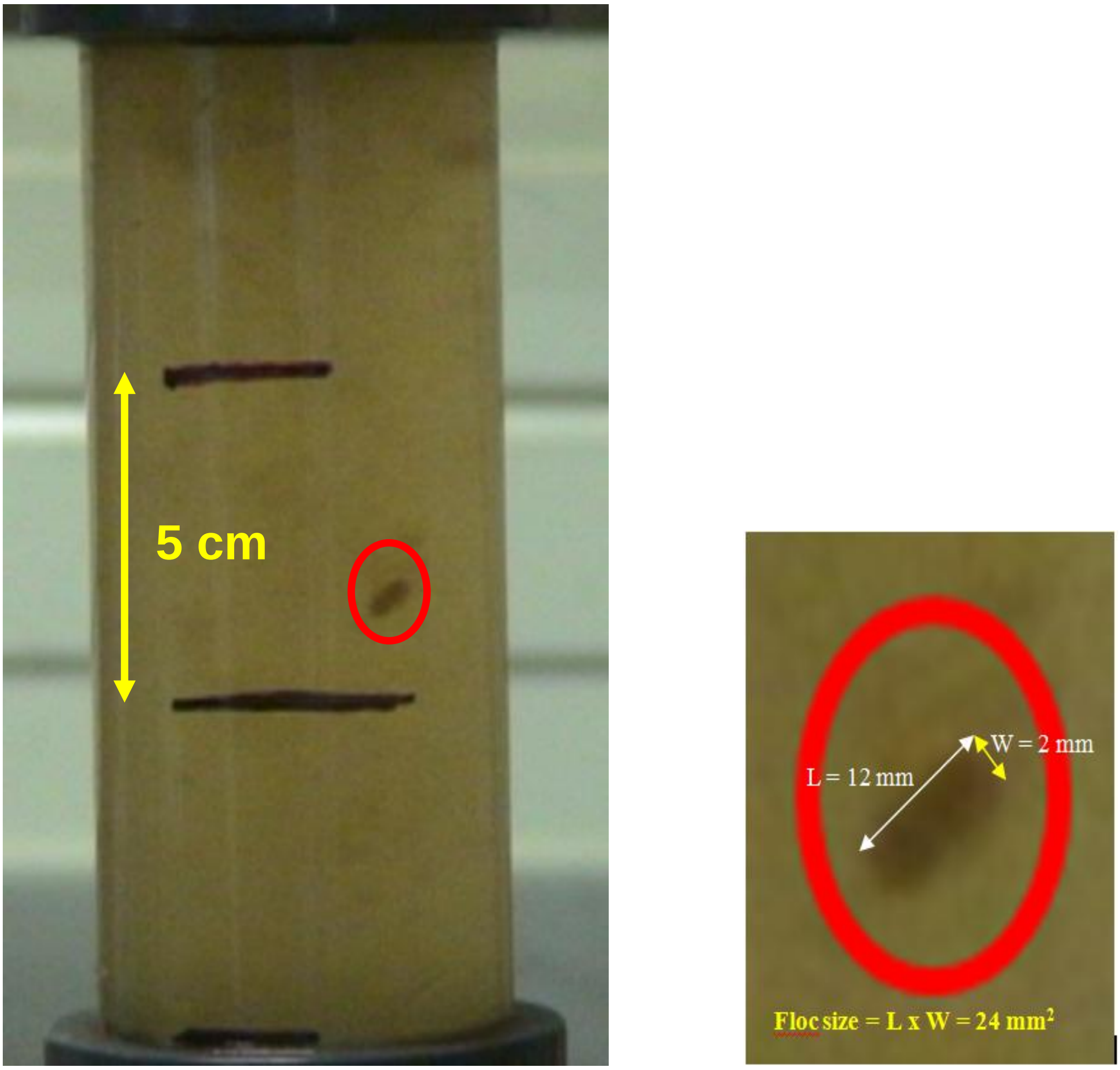



**Figure 6.2: Calculation of Particle size (cross-section) and settling velocity (Date: 29.06.2010, Time: 10:30)**

## 6.4 Experimental Campaign for Video Monitoring

The experiments were done for four different timings of the day depending on the flow of wastewater in the Graz WWTP (Aslam et al., 2011a). Four time periods / interval were selected on the basis of experiments of experimental campaign – 1 & 2 and previous data of flow rate of wastewater from Graz WWTP authorities. These time interval categories were made to study the settling of solids in minimal flow rate, rising flow rate, peak flow rate and down/stable flow rate. Settling studies of this kind, will help us to find out the settling behaviour of solids in all different flow patterns of the day.

These videos were made for each experiment. The timing of each video was 30 minutes so that it covers settling processes for both settling time of 10 and 30 minutes. The video monitoring is very comprehensive method to study the settling of solids as it does not disturb the settling of solids within the column and have complete picture of solids behaviour in wastewater.

### 6.4.1 Morning minimal flow (06:00 – 07:00)

The flow of wastewater during this time interval at the entrance of the Graz wastewater treatment plant was 400 l/s. The particles were very small in size in this time interval. The size of cross-section of particle during the early morning ranged from 0.1 $mm^2$ – 50 $mm^2$. It was very difficult to measure the exact size of the particles. Some particles were clearer while most of the particles are so small and light that these can easily disguise in the wastewater. The solids were mostly the filament type like organic solids. The wastewater in the column was not so turbid. The settling velocity of these particles ranged 0.1 cm/sec to 1.50 cm/sec (3.6 –54 m/h). Most of the solids settled in the column within first 10 minutes. The video was made for 30 minutes to see the settling of solids for more than 10 minutes. It is evident from the videos that there is no significant settling of solids after first 10 minutes (Aslam et al., 2011a).

### 6.4.2 Morning rising flow (09:00 – 09:30)

The average flow in this time period was 750 l/s. The particle settled in the form of little flocs. Some particles settled individually. These individual particles settled very fast as compared to the small flocs. But the speed of these individual particles was slowed down due to the traffic of these flocs. The size of cross-section particle/flocs ranged 3 – 250 $mm^2$. These flocs have different shapes; some of them have regular shapes but mostly have irregular shapes. The determination of the size of these irregular shaped flocs was very complex but it was measured successfully. The settling velocity of the flocs/particles was in the range of 0.5 – 2 cm/s (18 – 72 m/h). The wastewater was more turbid as compared to the earlier time interval of morning (Aslam et al., 2011a).

### 6.4.3 Daily Peak flow (10:30 – 11:00)

The flow of wastewater was highest from all the day in this time interval. This flow was stable for the time period of half to one hour. The average flow in this time period was more than about 1100 l/s. The wastewater was much turbid in this time period. The wastewater at this time was denser than in the morning timings. It was observed that the settling of the very small particles was hindered by the medium of the wastewater. The first visible particle reached in the lower fraction after 1 min. The size (cross-section) of this particle is about 9 $mm^2$. Some small particles were moving down along with the wall of the settling column avoiding the traffic of big particles/flocs. The size of cross-section of particles/flocs in this time interval ranges from 0.30 to 500 $mm^2$ with settling velocity in the range of 0.4 – 3.5 cm/s (14.4 – 126 m/h). The shape of particles/flocs was of both types i.e. regular and irregular. The movement of particles within the column is very much interesting. Some particles move in circular path. The small light particles during it downward movement starts to move suddenly in the upward direction due to the fast downward movement of heavy particles. Some bigger particles make different shapes during its movement down in the column. They don't have a single shape. The flocs break down into small particles and then again join with some other particles to make different shape (Aslam et al., 2011a).

### 6.4.4 Daily stable flow (16:00 – 16:30)

The flow of wastewater started to drop down after the peak time and these timings were selected to have a representative sample of wastewater having stable decreasing flow rate at the entrance of the Graz WWTP. The wastewater had almost stable flow rate till night. The average flow in this time period was 780 l/s. The wastewater was less turbid as compared to the previous time interval. The particles settled individually as well as in the form of flocs. The wastewater was not as dense as it was in the peak flow time. The smaller particles found very less hindrance in their downward movement in the settling column. The bigger particles/flocs were in different shapes i.e. filament, long threads type, regular and irregular. The size (cross-section) of particles/flocs ranges from 0.5 to 400 $mm^2$. The settling velocities of the particles/flocs are 0.5 – 3.0 cm/s (18 – 108 m/h) (Aslam et al., 2011a).

## 6.5 Dry Weather events

The particle size and settling velocity measured in the last step is plotted for different dry weather events. These dry weather events are from summer 2010 as a part of final experimental campaign. The dry weather experiments were performed on five different days consisting of 29.06.2010, 13.07.2010, 28.07.2010, 11.08.2010 and 24.08.2010. The graphs of all five days are shown from Figure 6.3 to Figure 6.7. Figure 6.3 shows the graph for first dry weather event. It shows that a mix relationship of particle size with settling velocity. The settling velocity is shown on x-axis with unit cm/sec while particle size is shown on Y-axis with the unit $mm^2$.

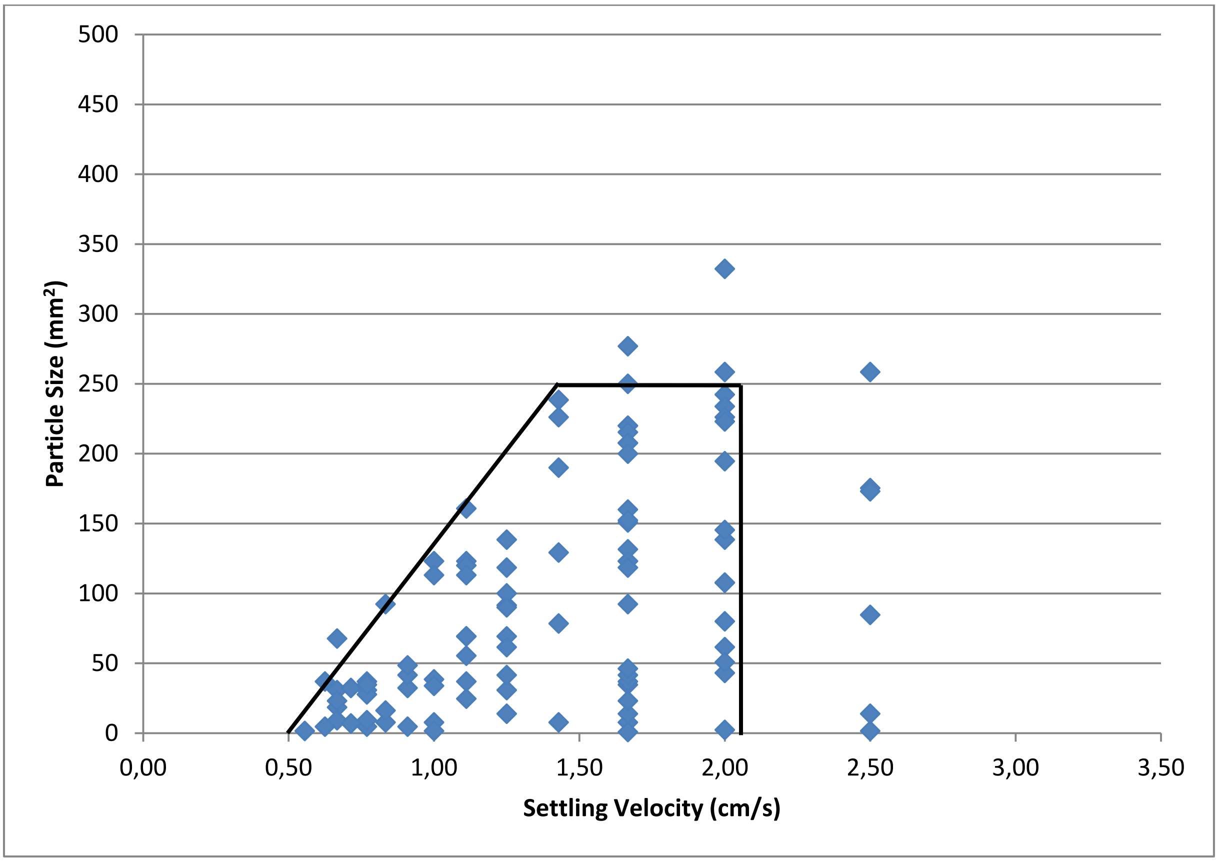



**Figure 6.3: Particle Size vs Settling Velocity, Location: Gravel Chamber - 29-06-2010 (Time: 10:30 – 11:00)**

The figure shows the clear function that more than 90% of the visible particles have a cross-section of ≤ 250 $mm^2$ and the settling velocity in the range of 0.5 – 2 cm/sec (18 – 72m/h). This function can be called settling function. It is clear from the above figure that settling velocity doesn't depend only on the particle size. There are particles which vary in size from 0.5 – 250 mm2 but they have the same settling velocity e.g. 1.67cm/sec, 2cm/sec. The particles which are smaller in cross-section size, have low settling velocities e.g. from figure 6.3, for the particle size ≤ 50 $mm^2$ the settling velocity lies in the range of 0.5 – 1 cm/sec.

It is very difficult to categorize the fractions of solids according to the particle size. It can be seen from the Figure 6.3 that some solids have same / similar sizes but they have different settling velocities. It cannot be a straightforward rule that solids of bigger size will settle faster than that of smaller size. Some particles have smaller sizes but they settle faster than that of bigger particles. The reverse case is also found correct.

Figure 6.4 shows the relationship of particle size and settling velocity for another dry weather event of 13.07.2010.

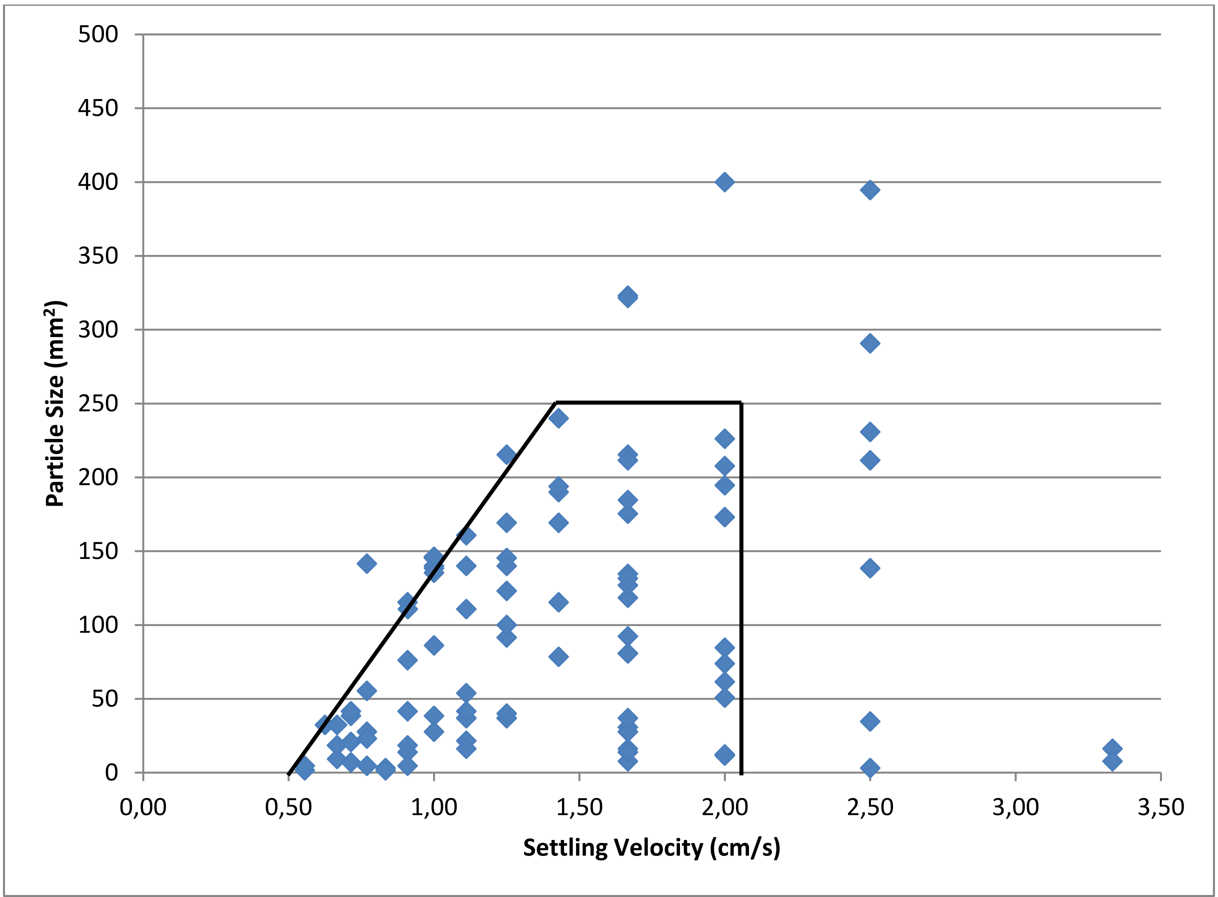



**Figure 6.4: Particle Size vs Settling Velocity, Location: Gravel Chamber - 13-07-2010 (Time: 10:30 – 11:00)**

This figure also shows the almost same behaviour of settling of solids. Both the parameters have almost the same relationship as for the previous event. In this graph, about 90% solids lies in the function i.e. cross-section particle size ranges from 0.1 – 250 $mm^2$ and settling velocity ranges 0.5 – 2 cm/sec. The settling velocity of two particles is showing some extreme readings i.e. about 3.50 cm/sec. Only few particles have a size of about 400 $mm^2$.

Figure 6.5 shows the graph between particle size and settling velocity for the third dry weather event i.e. 28.08.2010. This dry weather event shows that about 80% of the particles have cross-section particle size and settling velocity in the range of defined function as in last dry weather events. This weather event has a difference of about 10% from the previous dry weather events. The reliability of the function can be seen from all the three figures that mostly particle lie in this function. There are few particles which cross 2.5cm/s. Few particles have a maximum size of about 440 $mm^2$ while more than 80% particle sizes are less than 250 $mm^2$.

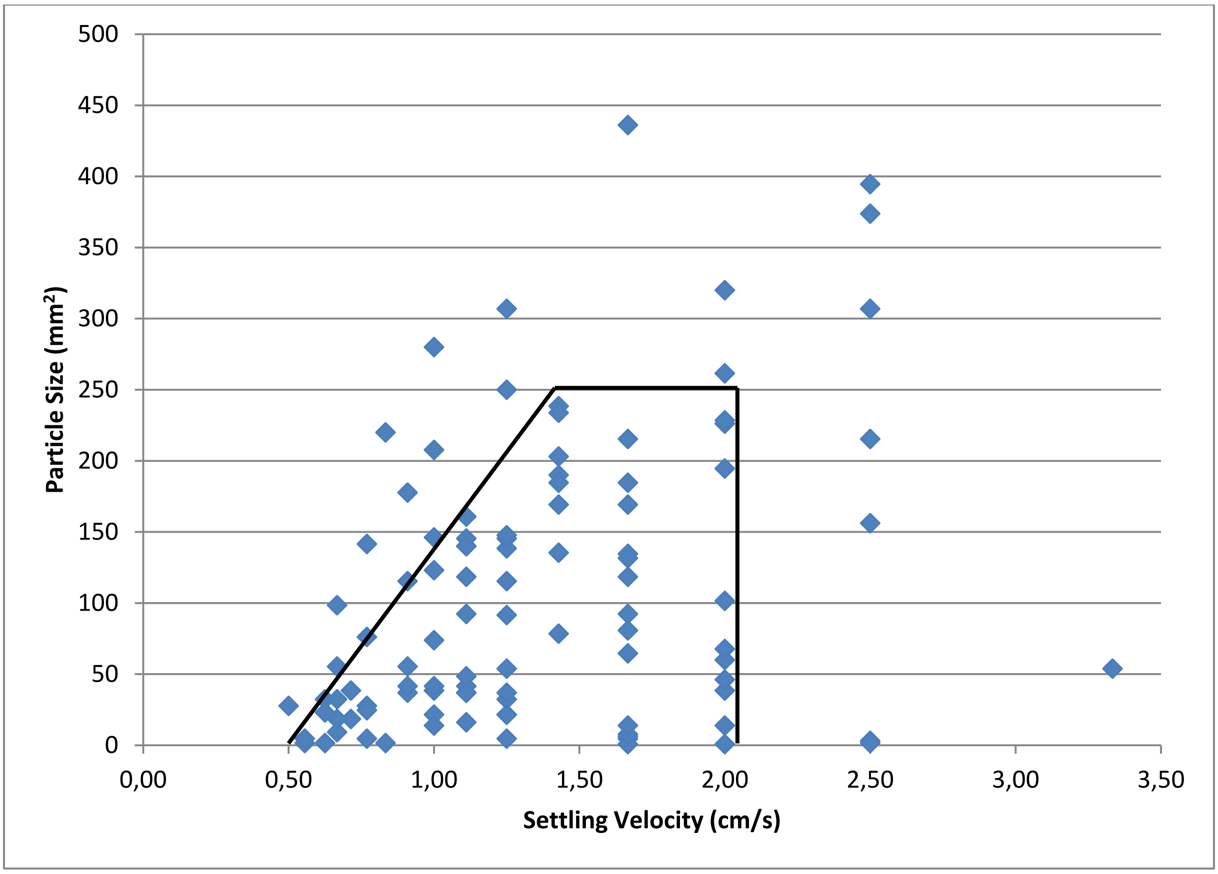



**Figure 6.5: Particle Size vs Settling Velocity, Location: Gravel Chamber - 28-07-2010 (Time: 10:30 – 11:00)**

Figure 6.6 shows the diagram of particle size versus settling velocity for the fourth dry weather event on 11.08.2010. This figure shows that few particle settle very fast while mostly lie in the range of 1 – 2 cm/sec. This event shows some higher speeds of the particles in the settling column. This shows the presence of some sand particles or inorganic particles which settles fast. The particle size is also in the lower range, about more than 90% of particles have size less than 250 $mm^2$. The relationship between particle size and settling velocity shows the same trend as in the previous event on 28.07.2010. About 76% particles lie in the function of particle size range 0.01 – 250 mm2 and settling velocity range 0.5 – 2 cm/sec.

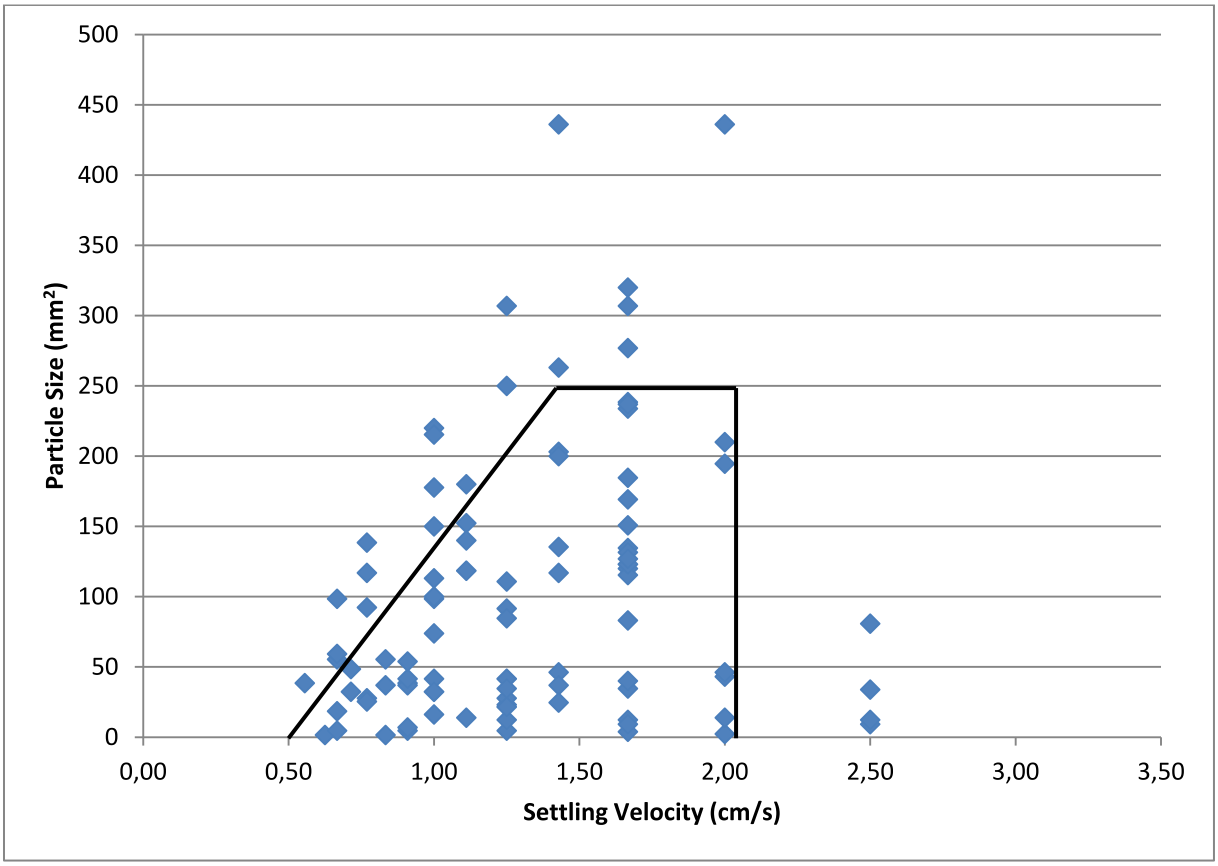



**Figure 6.6: Particle Size vs Settling Velocity, Location: Gravel Chamber - 11-08-2010 (Time: 10:30 – 11:00)**

The Figure 6.7 shows the graph having relationship between particle size and settling velocity both lie on y-axis and x-axis respectively. Few particles lie in the higher range of particle size i.e. above 400 mm$^2$. Very few particles have settling velocity higher than 2 cm/sec, while mostly particle have settling velocity less than 2 cm/sec. The strange thing is that in all the dry weather events there are no visible or measurable solids having settling velocity less than 0.5 cm/sec. The relationship which was developed as a function, in the previous dry weather events, also exists in this event.

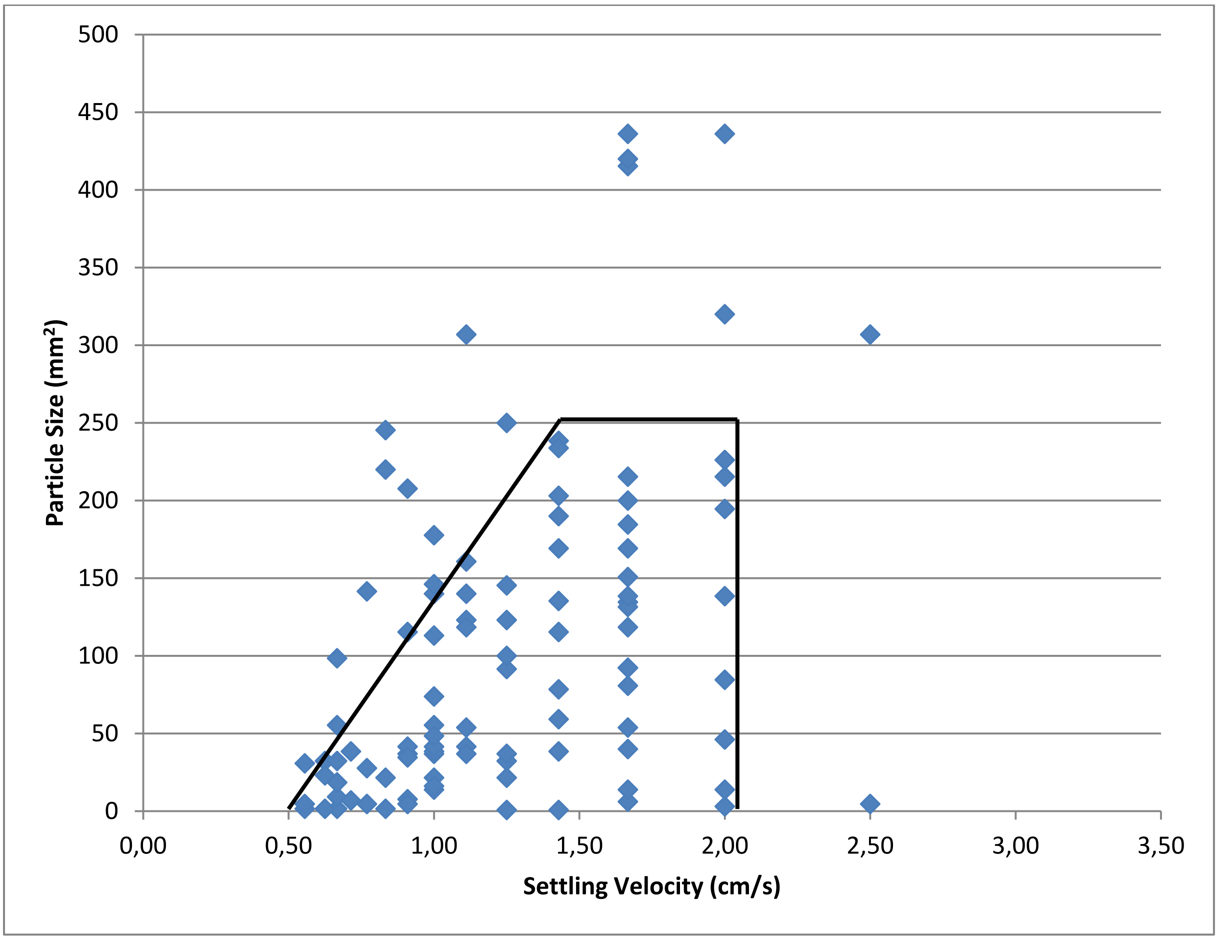



**Figure 6.7: Particle Size vs Settling Velocity, Location: Gravel Chamber - 24-08-2010 (Time: 10:30 – 11:00)**

The results from the dry weather events show good reproducibility. There is almost negligible difference in the behaviour, shape, size and settling velocity of the particles. The series of these dry weather experiments can be used in the effectiveness/efficiency of primary settling tanks and storm water tanks and also a better understanding about the settling of particles in raw wastewater. More than 80% particle sizes (cross-section) in all dry weather events are less than 250 $mm^2$. Few particles are above than 250 $mm^2$. The settling velocity lies in the range of 0.5 – 2 cm/s (18 – 72 m/h) while few particles have settling velocity greater than 2 cm/sec (72 m/h). The relationship between particle size and settling velocity was developed as a function in which the particle cross-section size ranges from 0.01 – 250$mm^2$ and settling velocity ranges from 0.5 – 2 cm/sec. This function was applied on all the dry weather events and it showed excellent results. About more than 80% solids/particles lie in this function.

The Figure 6.8 shows the a comprehensive graph in which all five days of dry weather from all above five figures (Figure 6.3 to Figure 6.7) are shown at glance. It can be seen from the figure that most of the particle size (cross-section) of solids lies in the range of 0.01 – 250 $mm^2$ and settling velocity lies in the range of 0.5 – 2.0 cm/sec. The function between particle size (cross-section) and settling velocity proved itself right in Figure 6.8.

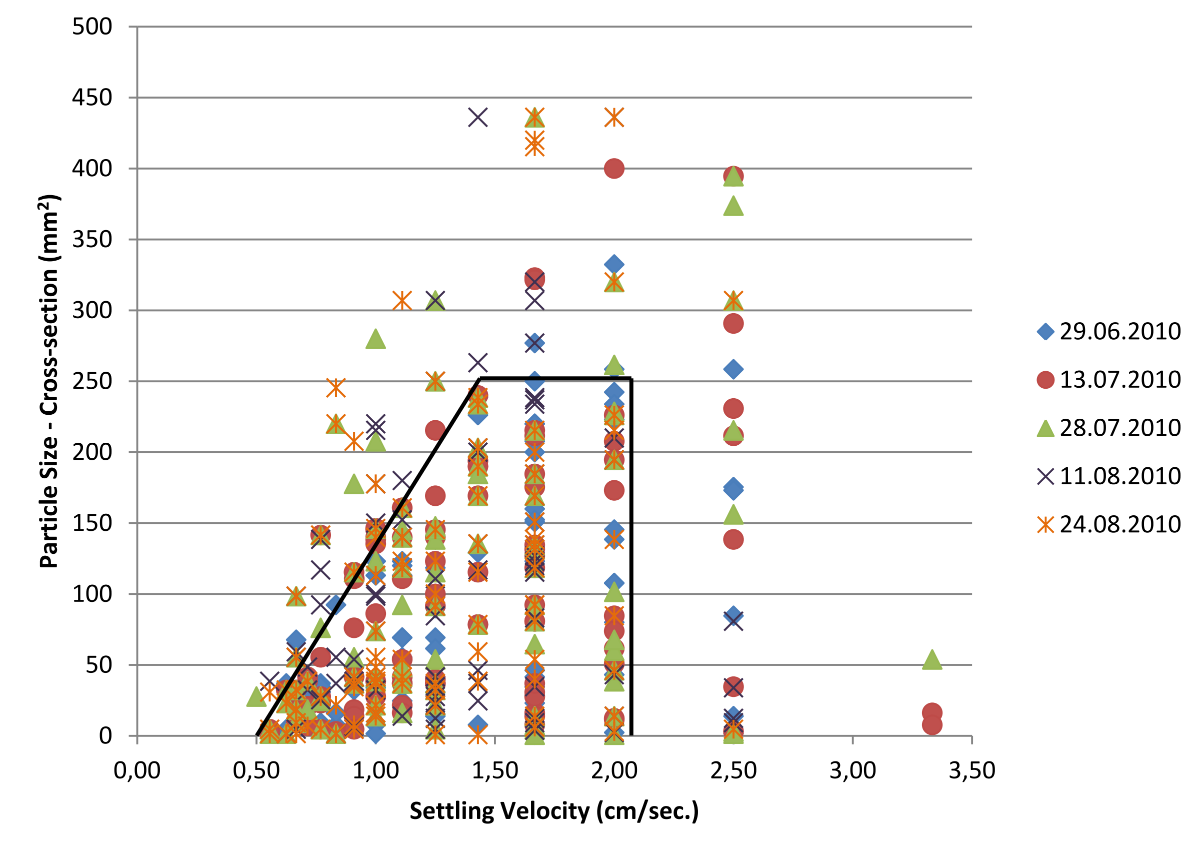



**Figure 6.8: Comparison of five days; Particle Size vs Settling Velocity, Location: Gravel Chamber (Time: 10:30 – 11:00)**

### 6.5.1 Comparison of three sampling locations

The settling experiments were performed in summer 2010 for three different locations at Graz WWTP i.e. Gravel Chamber, Influent Primary Settling Tank (IPST), Effluent Primary Settling Tank (EPST). These experiments were also monitored with Video Camera. This video analyses show that behaviour of solids at three different locations with almost same wastewater after few steps. It will be interesting to see the particle size and settling velocity at three different steps. The relationship of these two settling parameters will also be worth seeing.

Figure 6.9 shows the relationship of particle size and settling velocity for the location of gravel chamber. The Figure 6.10 shows particle size versus settling velocity for the sampling point of Inlet Primary Settling tank, while Figure 6.11 shows that relationship between the same parameters for the third and last experimental point of outlet of Primary settling tank. The difference in between three locations can be visible from the three diagrams.

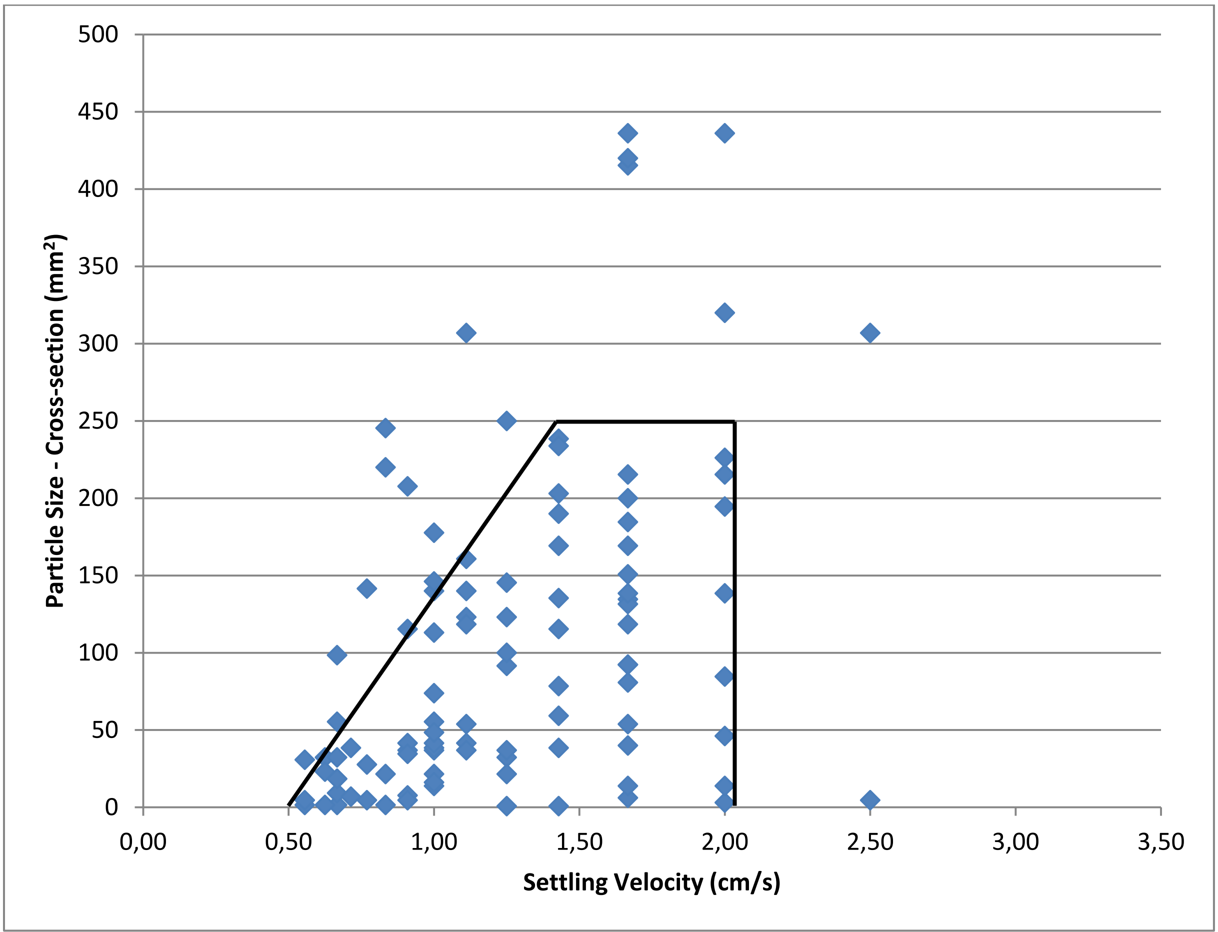



**Figure 6.9: Particle Size vs Settling Velocity, Location: Gravel Chamber - 24-08-2010 (Time: 10:30 – 11:00)**

The particle size (cross-section) at gravel chamber lies in the range of 0.1 – 440 $mm^2$. About 90% particles have size less than 250 $mm^2$. More than 80% of the particles have settling velocity less than or equal to 2 cm/s (72 m/h), as shown in Figure 6.9. The particle size (cross-section) reduces at Inlet Primary settling tank, mostly particle lie in the range 0.1 – 150 $mm^2$. This is due to the steps of screening and grit removal in between gravel chamber and primary sedimentation tank. The particle size reduces but the settling velocity is almost in the same range i.e. about more than 80% particles have settling velocity (SV) less than 2 cm/s (72 m/h). Only few particles have SV more than 3 cm/s (108 m/h).

The interesting thing to note down is that in IPST, the particle settling velocity is in the range of 0.67 – 1.67, while in wastewater of gravel chamber the SV starts from 0.5 cm/s.

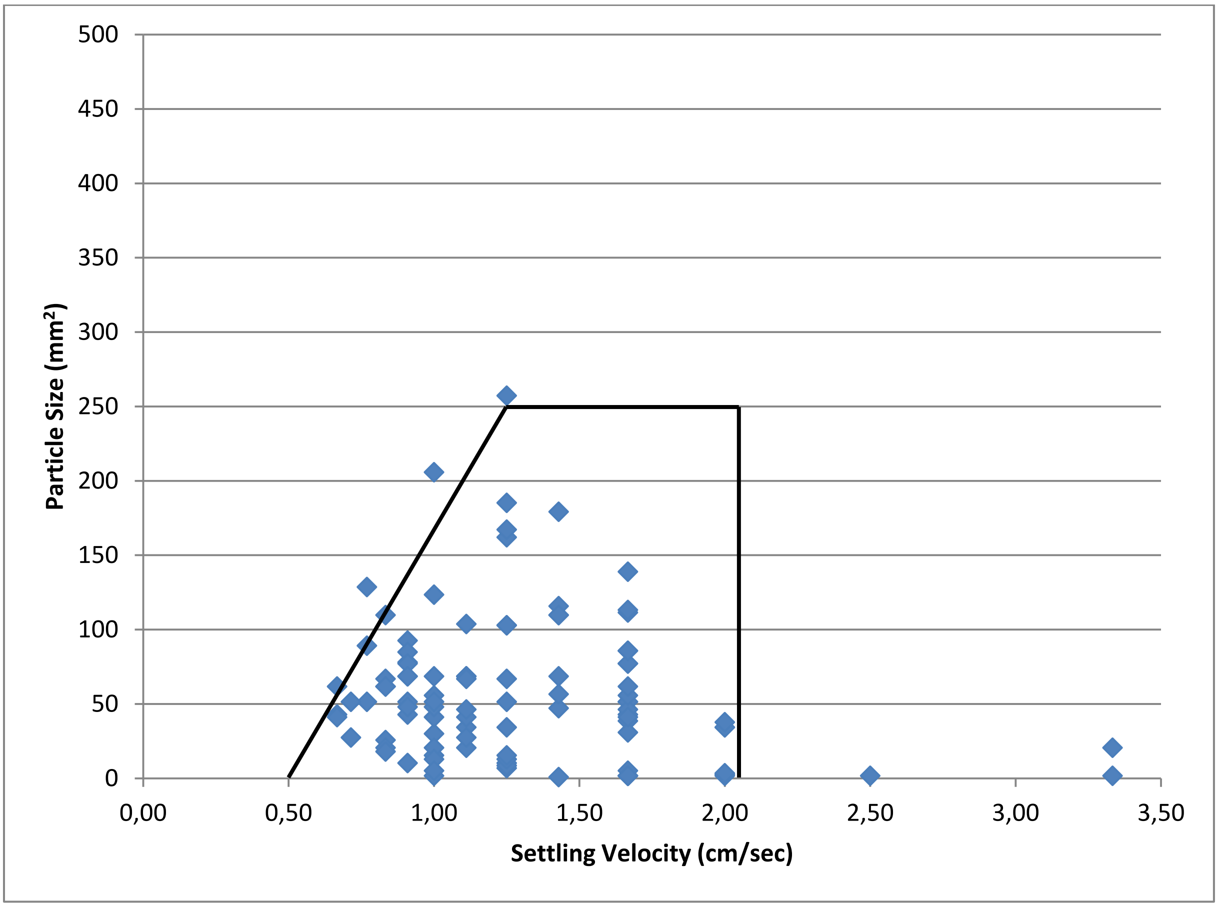



**Figure 6.10: Particle Size vs Settling Velocity, Location: Influent Primary Settling Tank - 24-08-2010 (Time: 10:30 – 11:00)**

There is a greater difference in both above figures (Figure 6.9 & Figure 6.10) and Figure 6.11 and it is obvious. The particle size reduces to less than 50 mm$^2$. The settling velocity is also reduced to less than 1 cm/s, only few particles have SV greater than 1 cm/sec. There are also few particles which have size above 50 mm$^2$. It shows that most of the particles settle in the primary sedimentation tank of Graz WWTP. The results will be very helpful for determining the efficiency of the primary settling tank.

The relationship between these two settling parameters is described as a function of particle size (cross-section) and settling velocity. In this function, the particle size lies in the range of 0.01 – 250mm$^2$ and settling velocity lies in the range of 0.5 – 2 cm/sec. It can be seen from the results mentioned in Figure 6.9 that about more than 80% solids/particles of the Gravel Chamber wastewater lie in this settling function, while in Figure 6.10, more than 90% particles of the Influent Primary Settling Tank wastewater lies in the range of abovementioned settling function.

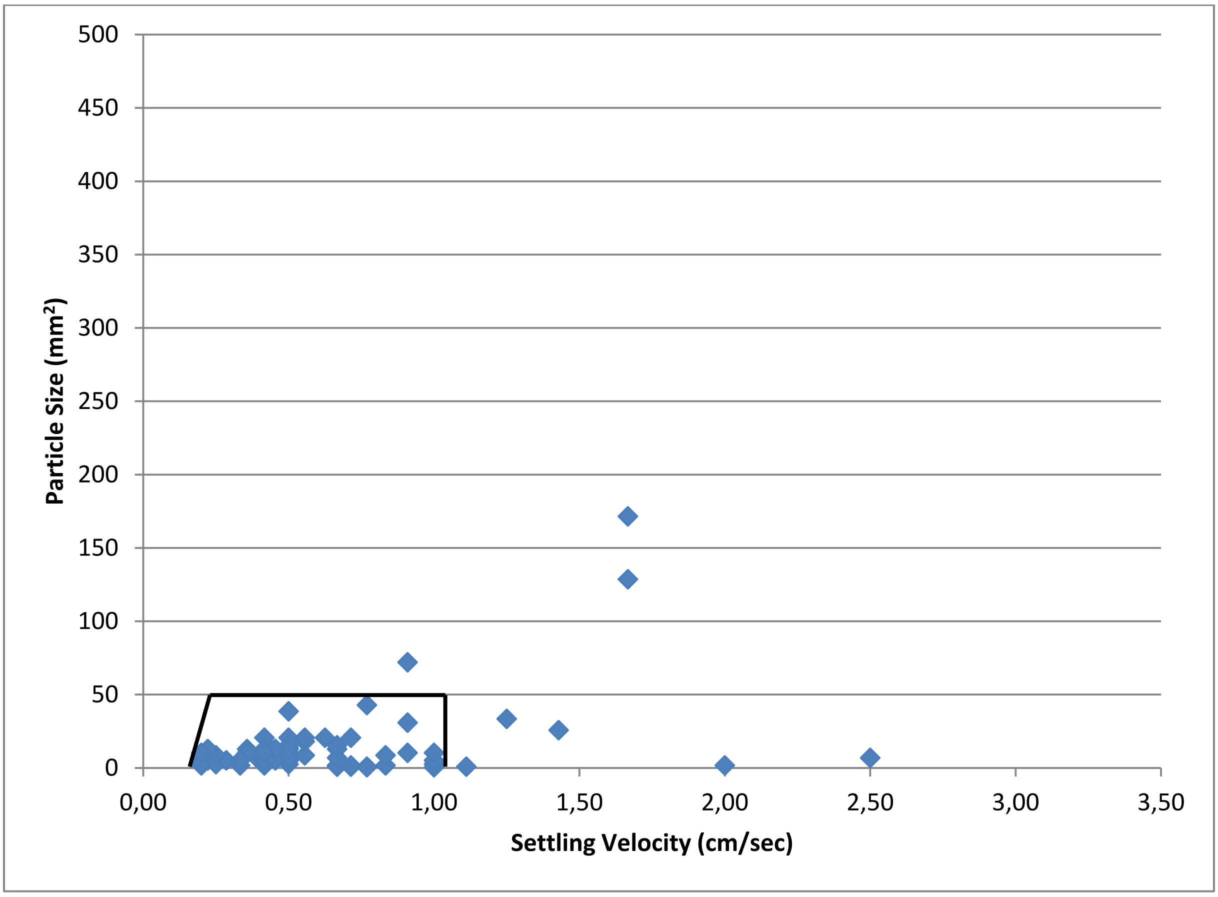



**Figure 6.11: Particle Size vs Settling Velocity, Location: Effluent - 24-08-2010 (Time: 10:30 – 11:00)**

The data from all the three sampling locations are compared in one figure i.e. Figure 6.12. It is clear from the figure that most of the particles are in the low particle size range with low settling velocities, at all three sampling points. About more than 80% of solids have particle size (cross-section) less than 250 $mm^2$ and settling velocity of less than 2 cm/sec (72m/h).

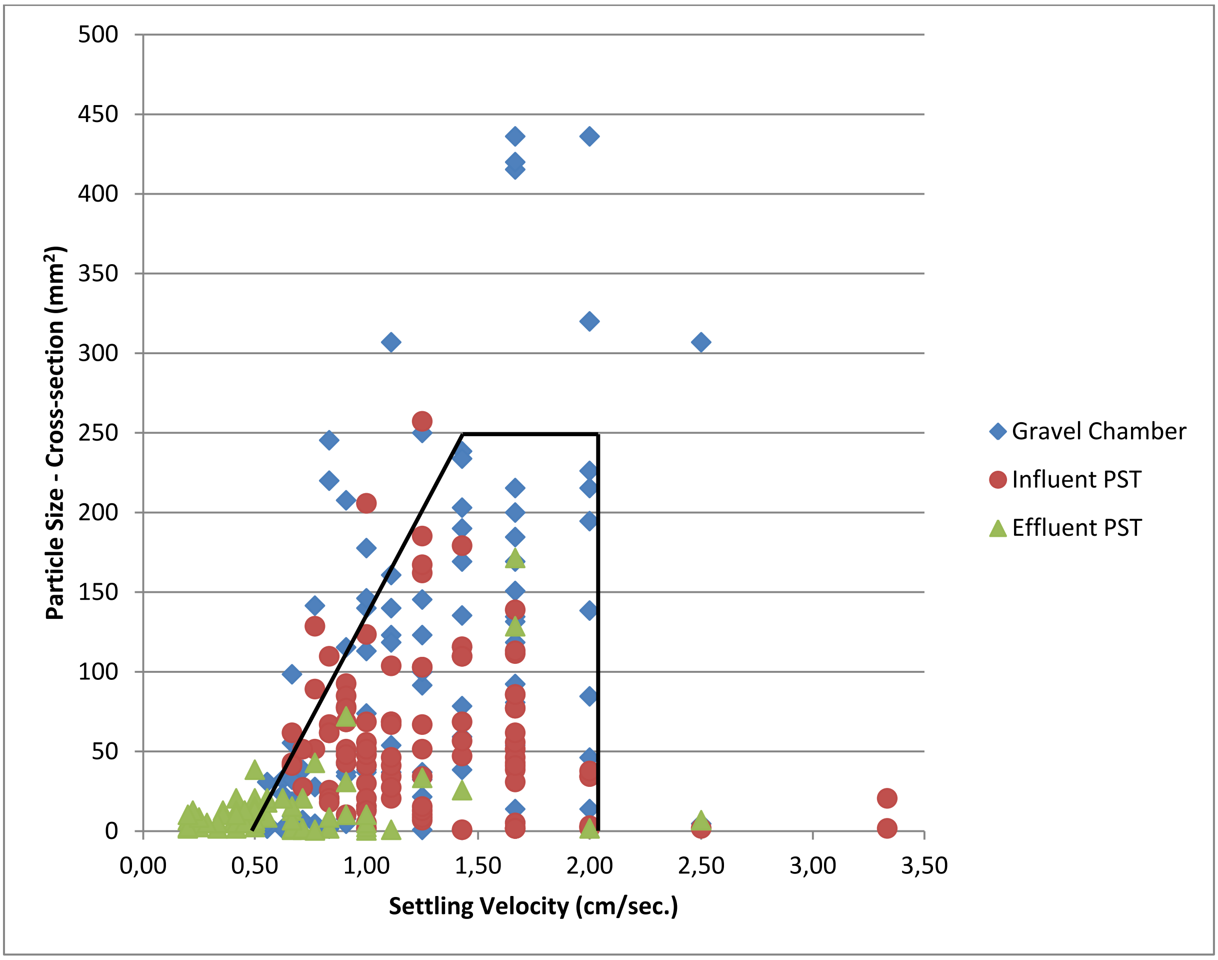



**Figure 6.12: Comparison of three sampling location: Particle Size vs Settling Velocity, Date: 24-08-2010, Time: 10:30 – 11:00**

## 6.6 Wet weather events

The wet weather event is observed in the afternoon on 24.08.2010. The morning experiments were performed on that day for the dry weather event. At about 12 noon, the rain started and it was a chance to get the data for the wet weather event also. The experiments were performed at about 12:30 – 13:00 when the flow was in the high range (more than 1500 l/s) at inlet of Graz WWTP, due to rain. These experiments were also monitored by the video camera to visualize the settling process of particles in wet weather. The video monitoring also helps in the determination of the particle size and settling velocity. There two parameters were calculated and shown against each other in Figure 6.13.

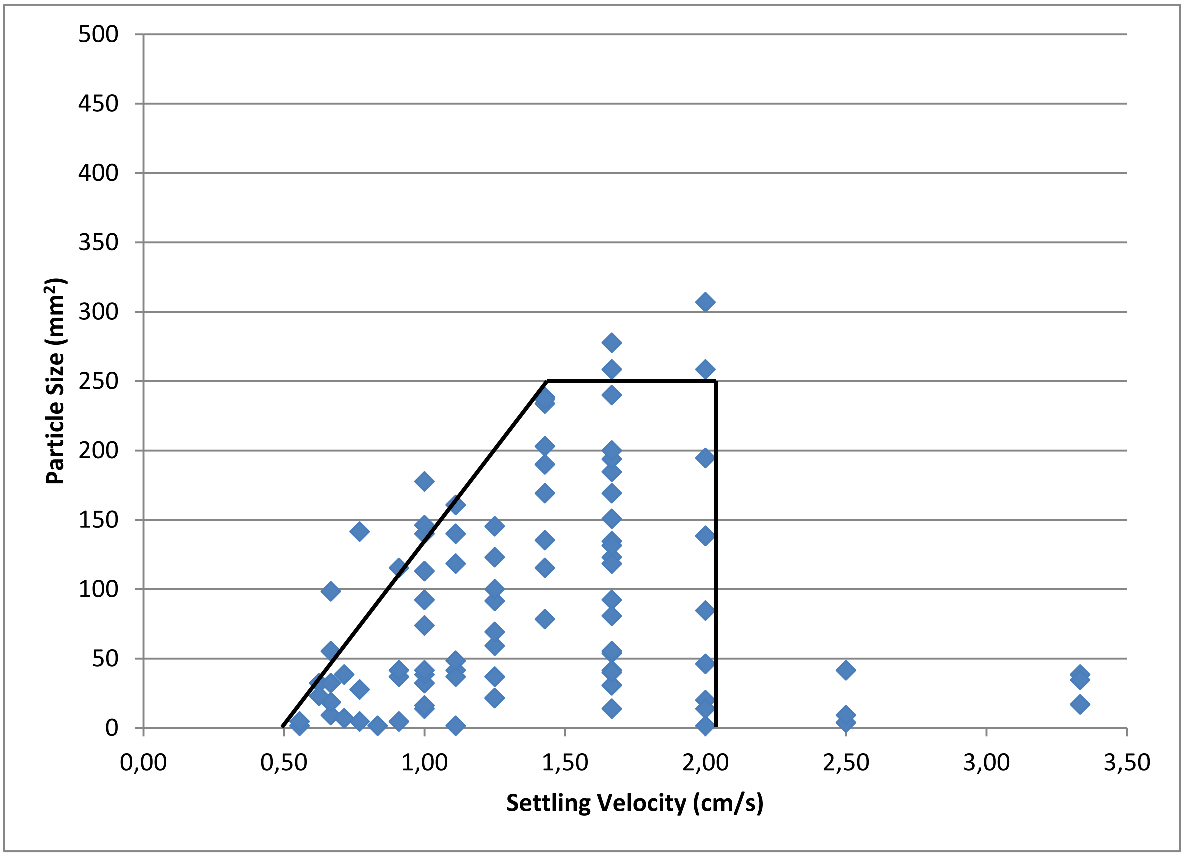



**Figure 6.13: Particle Size vs Settling Velocity, Location: Gravel Chamber - 24-08-2010 (Time: 12:30 – 13:00)**

Figure 6.13 shows that the particle size reduces from above 400 $mm^2$ to about 300 $mm^2$ (see Figure 6.7 for comparing the same locations in both weathers). The settling velocity however increased in wet weather as compared to dry weather, but the difference is not high. In dry weather the particle have settling velocity starting from less than 0.5 cm/s while in case of wet weather it starts from 0.67 cm/s and goes upto 3.40 cm/s. The particle size is scattered in case of dry weather, while in case of wet weather, particles are agglomerated and almost in group of same sizes. About more than 95% particles have size less than 250 $mm^2$. About more than 85% particles lie in the settling function of particle size and settling velocity.

Figure 6.14 shows the results of dry and wet weather. It is illustrated in the figure that the trend of the solids in wastewater in both weather conditions is the similar. The overall particle sizes during wet weather are lower as compared to that during dry weather conditions. But from the detailed analyses of the figure, it is clear that most of the particles in wet weather lie in the medium range of particle sizes (cross-section) i.e. 50 – 250 $mm^2$. While in dry weather the most of the particles lie in the lower range of particle sizes. The settling velocities are showing also the same trends in both weather conditions. The settling function of particle size and settling velocity, fit best in Figure 6.14, and mentioned as an area in between dark black lines.

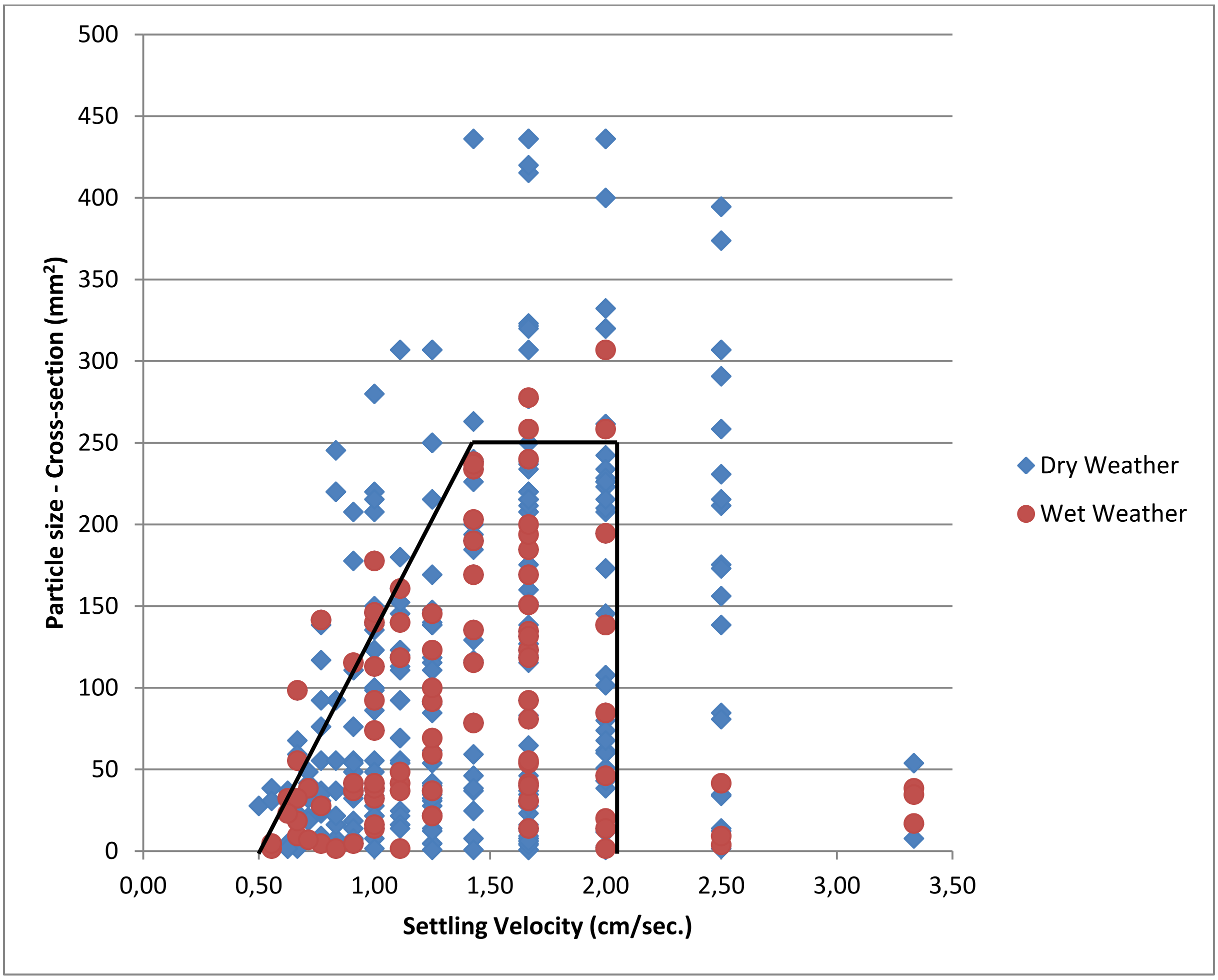



**Figure 6.14: Comparison of dry and wet weather; Particle Size vs Settling Velocity, Location: Gravel Chamber (Dry Weather: 29.06.2010, 13.07.2010, 28.07.2010, 11.08.2010, 24.08.2010, Wet Weather: 24.08.2010)**

# 7 Chapter 7 Results and Discussion – Prediction Model

## 7.1 Prediction Model

A model is prepared which can forecast the TSS mass of effluent of primary settling tank on the basis of TSS mass of influent primary settling tank. The benefit of the model is that if the concentration of TSS of influent primary settling tank is known, then TSS concentration of Effluent of primary settling tank can be determined without performing a separate test/experimentation. The model itself calculates the concentration of effluent (EPST). This model is tested on the final experimental campaign of summer 2010. The reproducibility is excellent. This model is tested for both dry as well as for wet weather. The results are perfect for both weather conditions.

### 7.1.1 Description of the model

Take the upper two fractions of the TSS mass of Influent primary settling tank. The TSS mass settled in the lower fraction lies at the bottom of the fraction. This fraction has a volume of 0.5 L. The remaining portion of this lower fraction is seen same like as a middle fraction. It can be said that remaining portion of the lower fraction have the same concentration as of middle fraction. Settleable solids in the column can be calculated in this way.

The model consists of two steps, first in the elimination step and other is to establish formula for the determination of concentration of TSS for effluent Primary Settling Tank.

#### *7.1.1.1 Step of elimination*

In this step, the solids which are eliminated or settled in the settling column will be determined.

a) Fast Settling solids (on bottom of lower fraction), $\eta_1$ = 45 – 55% ≈ 50%

b) Settling of suspended solids (SS) in Column, $\eta_2$

   a. For small hydraulic loads

      $\eta_2 = 25\% \times (1 - \eta_1)$

      $\eta_2 = 0.25 \times (1 – 0.50)$

      $\eta_2 = 0.13$

   b. For high hydraulic loads

      $\eta_2 = 15\% \times (1 - \eta_1)$

$\eta_2 = 0.15 \times (1 – 0.50)$

$\eta_2 = 0.08$

Total mass settled in column in dry weather is

$\eta_{total} = \eta_1 + (1 - \eta_1) \times \eta_2 = 0.5 + (1\text{-}0.5) \times 0.13 = 0.57 \approx 57\%$

Total mass settled in column in wet weather is

$\eta_{total} = \eta_1 + (1 - \eta_1) \times \eta_2 = 0.5 + (1\text{-}0.5) \times 0.08 = 0.54 \approx 54\%$

#### *7.1.1.2 Formula for calculation of TSS concentration of Effluent PST*

The concentration of the effluent primary settling tank is calculated from the concentration of the influent primary settling tank. A formula is developed in this regards and given below:

The three fractions of the wastewater of influent primary settling tank is given as under:

$x = x_1 + x_2 + x_3$ ………………………… Eq. 7.1

Where $x$ = TSS mass in Influent Primary Settling Tank (IPST) …………………….[mg]

$x_1$ = TSS mass in lower fraction (IPST) [mg], Volume: 0.5L

$x_2$ = TSS mass middle fraction (IPST) [mg], Volume: 2.5L

$x_3$ = TSS mass in upper fraction (IPST) [mg], Volume: 1.0L

The predicted concentration of the effluent of Primary Settling Tank is determined by the following equation.

$$C_{EPST} = \left(\frac{\left(\frac{x_2}{2.5}\right)+\left(\frac{x_3}{1}\right)}{2}\right) \times (1 - \eta_2)$$ ………………………… Eq. 7.2

Where $C_{EPST}$ = Predicted TSS Concentration in Effluent Primary Settling Tank [mg/L]

The predicted fractions of the effluent of Primary Settling Tank are elaborated as under:

$y = y_1 + y_2 + y_3$ ………………………… Eq. 7.3

Where $y$ = TSS mass in Effluent Primary Settling Tank (EPST) ………………….[mg]

$y_1$ = TSS mass in lower fraction (EPST) = $C_{EPST} \times 0.5L$…………………….[mg]

$y_2$ = TSS mass in middle fraction (EPST) = $C_{EPST} \times 2.5L$………………..….[mg]

$y_3$ = TSS mass in upper fraction (EPST) = $C_{EPST} \times 1.0L$ ………………..….[mg]

The above formula as in equation 7.1 and equation 7.2, can be used for both dry as well as for wet weather.

### 7.1.2 Dry Weather

This model is first used for the dry weather events. As the experiments in dry weather in final campaign of experiments in summer 2010 were performed on four different timings of the day depending on the flow rate. The model is applied on all the four timings, the results obtained were very good and can be applicable for future calculations.

Figure 7.1 shows the forecast model for the dry weather event on 29.06.2010 in the morning time interval 06:00 – 07:00. These experiments were tested for a settling time of 10 and 30 minutes. The total TSS mass in this time interval is about 750mg. The experiments were also performed for effluent primary settling tank (EPST), the values of TSS mass are also shown in figure as real values.

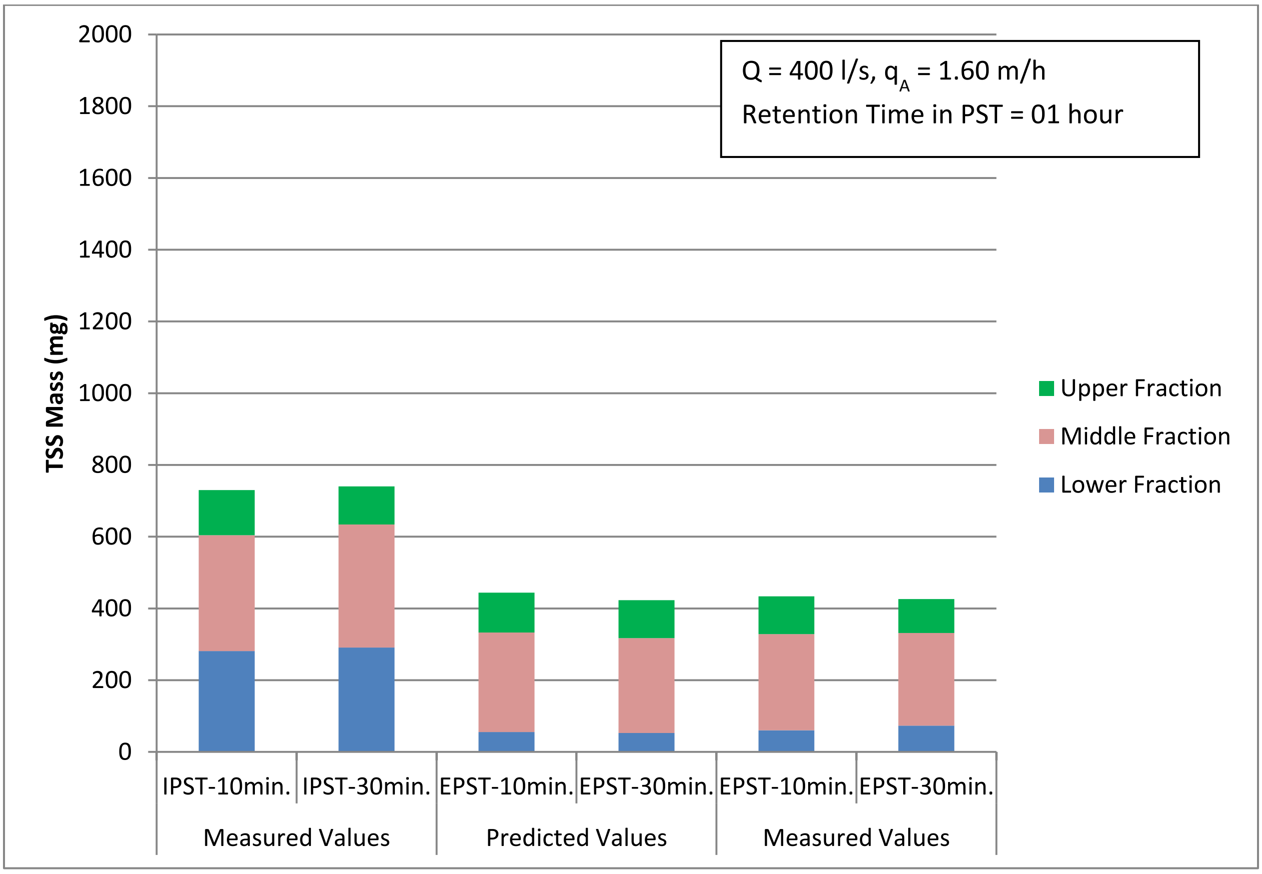



**Figure 7.1: Model for TSS Calculation of EPST from IPST - 29-06-2010 (Time: 07:10)**

The values calculated from the model are also shown in Figure 7.1 with the name of ‘Predicted Values’. The figure clearly shows that there is almost no difference in real values and predicted values. There is a negligible difference in both values of the effluent primary settling tank (EPST). These values are calculated for both settling times of 10 and 30 minutes.

Figure 7.2 shows the real and predicted values of EPST mass in each fraction for the dry weather event on 29.06.2010 for time interval 0900 – 0930. The results in the figure validate the model with minimal errors.

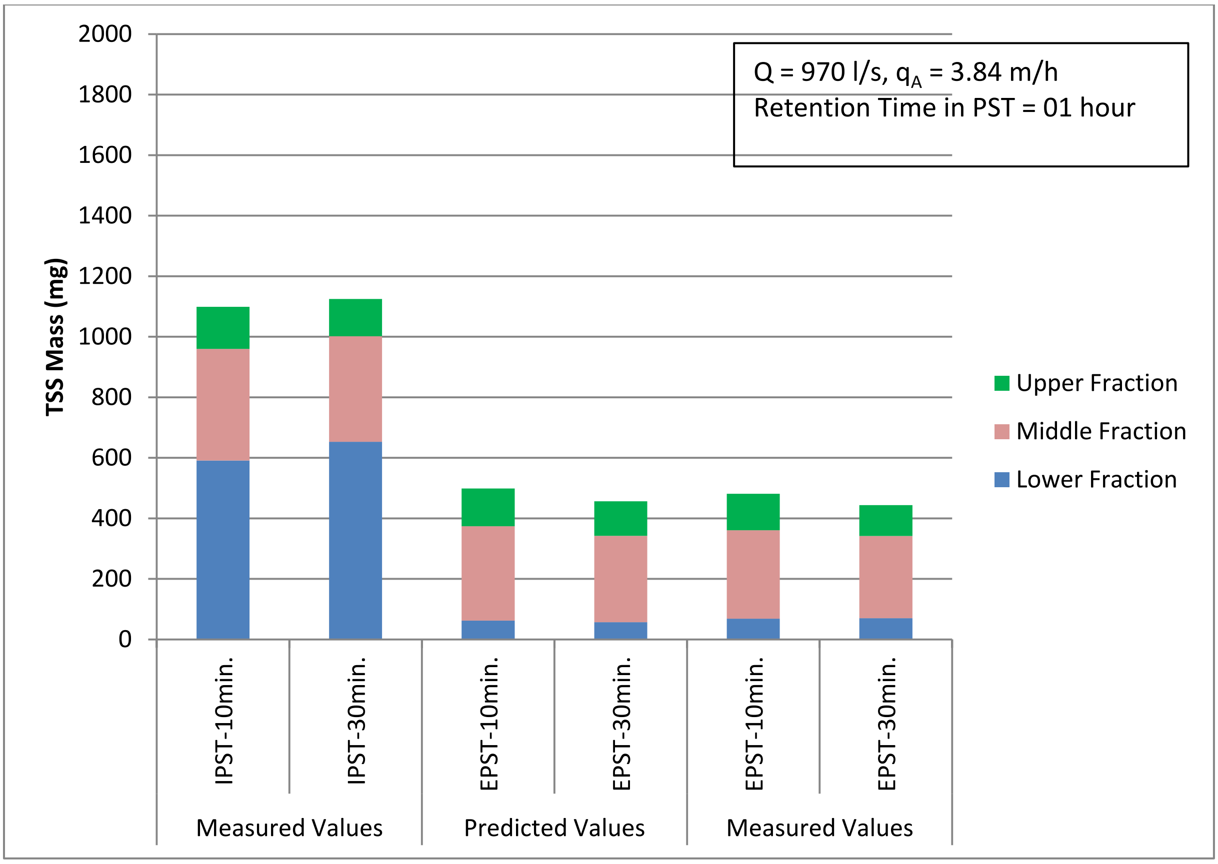



**Figure 7.2: Model for TSS Calculation of EPST from IPST - 29-06-2010 (Time: 09:20)**

The prediction model for the time interval (10:30 – 11:00), which has maximum flow throughout the day e.g 1450 l/s, is shown in Figure 7.3. This figure show good results and a complete compatibility of real and predicted values of EPST mass. The difference is negligible. The model has shown comprehensive results for the dry weather experiments.

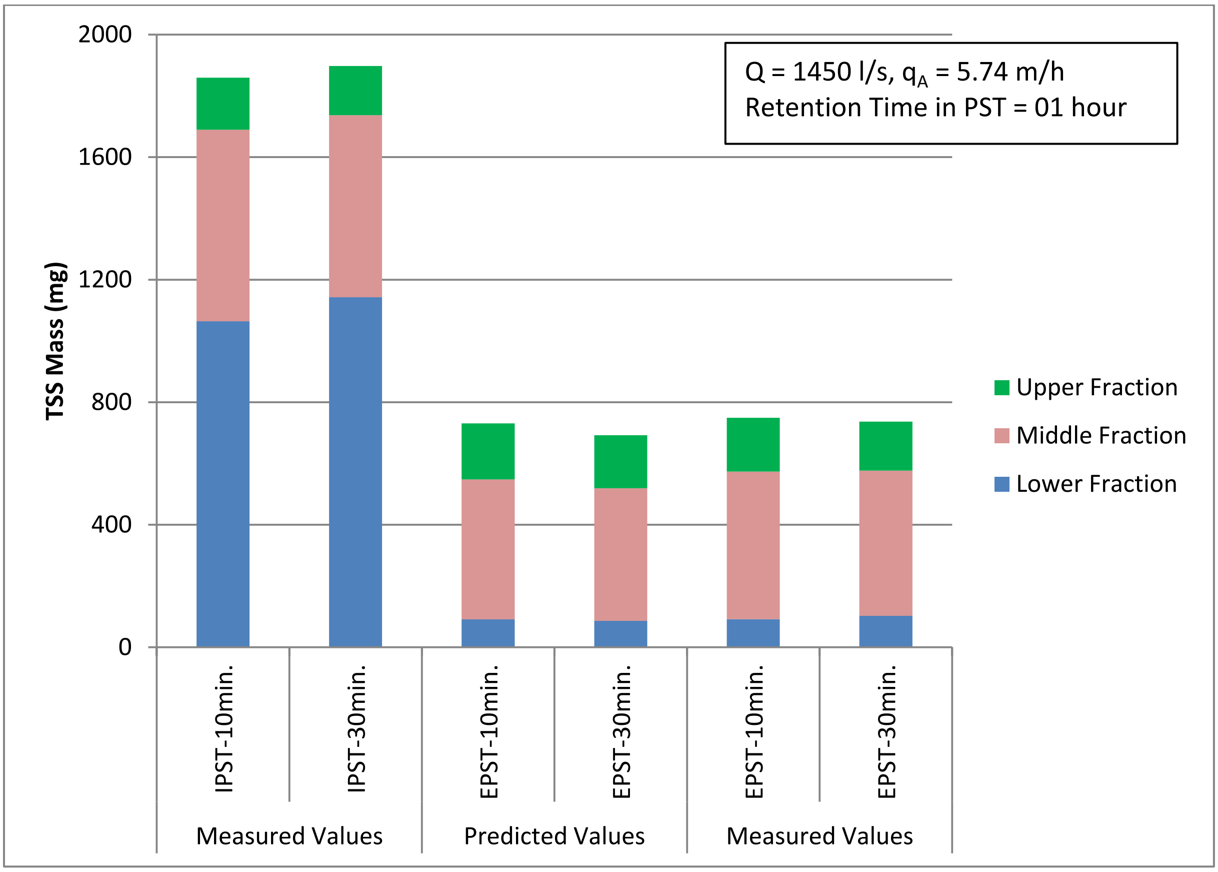



**Figure 7.3: Model for TSS Calculation of EPST from IPST - 29-06-2010 (Time: 10:50)**

**Table 7.1: Comparison of measured and predicted values for different timings of day (Dry Weather)**

| Date: 29.06.2010, Time: 07:10, Q= 400 l/s, Retention time: 01 hour | | | | | | |
|---|---|---|---|---|---|---|
| | Measured Values | | Predicted Values | | Measured Values | |
| | IPST-10min. | IPST-30min. | EPST-10min. | EPST-30min. | EPST-10min. | EPST-30min. |
| Lower Fraction | 281 | 291 | 56 | 53 | 61 | 74 |
| Middle Fraction | 323 | 343 | 278 | 264 | 268 | 258 |
| Upper Fraction | 126 | 106 | 111 | 106 | 105 | 95 |
| Total TSS | 730 | 740 | 444 | 423 | 434 | 426 |
| | | | | | | |
| Date: 29.06.2010, Time: 09:20, Q= 970 l/s, Retention time: 01 hour | | | | | | |
| | Measured Values | | Predicted Values | | Measured Values | |
| | IPST-10min. | IPST-30min. | EPST-10min. | EPST-30min. | EPST-10min. | EPST-30min. |
| Lower Fraction | 591 | 653 | 62 | 57 | 69 | 70 |
| Middle Fraction | 369 | 349 | 312 | 285 | 292 | 272 |
| Upper Fraction | 139 | 123 | 125 | 114 | 121 | 102 |
| Total TSS | 1099 | 1125 | 499 | 456 | 481 | 444 |
| | | | | | | |
| Date: 29.06.2010, Time: 10:50, Q= 1450 l/s, Retention time: 01 hour | | | | | | |
| | Measured Values | | Predicted Values | | Measured Values | |
| | IPST-10min. | IPST-30min. | EPST-10min. | EPST-30min. | EPST-10min. | EPST-30min. |
| Lower Fraction | 1065 | 1143 | 91 | 87 | 92 | 103 |
| Middle Fraction | 625 | 594 | 457 | 433 | 482 | 474 |
| Upper Fraction | 170 | 160 | 183 | 173 | 176 | 160 |
| Total TSS | 1860 | 1897 | 731 | 692 | 749 | 737 |
| | | | | | | |
| Date: 29.06.2010, Time: 16:20, Q= 900 l/s, Retention time: 01 hour | | | | | | |
| | Measured Values | | Predicted Values | | Measured Values | |
| | IPST-10min. | IPST-30min. | EPST-10min. | EPST-30min. | EPST-10min. | EPST-30min. |
| Lower Fraction | 922 | 1106 | 119 | 97 | 127 | 159 |
| Middle Fraction | 724 | 566 | 593 | 487 | 590 | 499 |
| Upper Fraction | 256 | 222 | 237 | 195 | 206 | 183 |
| Total TSS | 1902 | 1894 | 949 | 780 | 923 | 841 |

The measured and predicted values of effluent of primary settling tank can be best compared from the Table 7.1. The table highlight the actual values of each fraction of influent and effluent of primary settling tank. The results of the table show the effectiveness and accuracy of this model.

### 7.1.3 Wet weather

The prediction model is also tested and verified on the wastewater of Graz WWTP in wet weather. The formula used is same as mentioned in equation 7.2 and 7.3, but the value of $\eta_2$ is used as for high hydraulic loads, as mentioned in Heading 7.1.1.1 (value of $\eta_2$ is 0.08 in this case). The predicted values of EPST for wet weather is calculated and shown in Figure 7.4. It shows that real and predicted values have almost no difference in almost all the three fractions i.e. lower, middle and upper fraction.

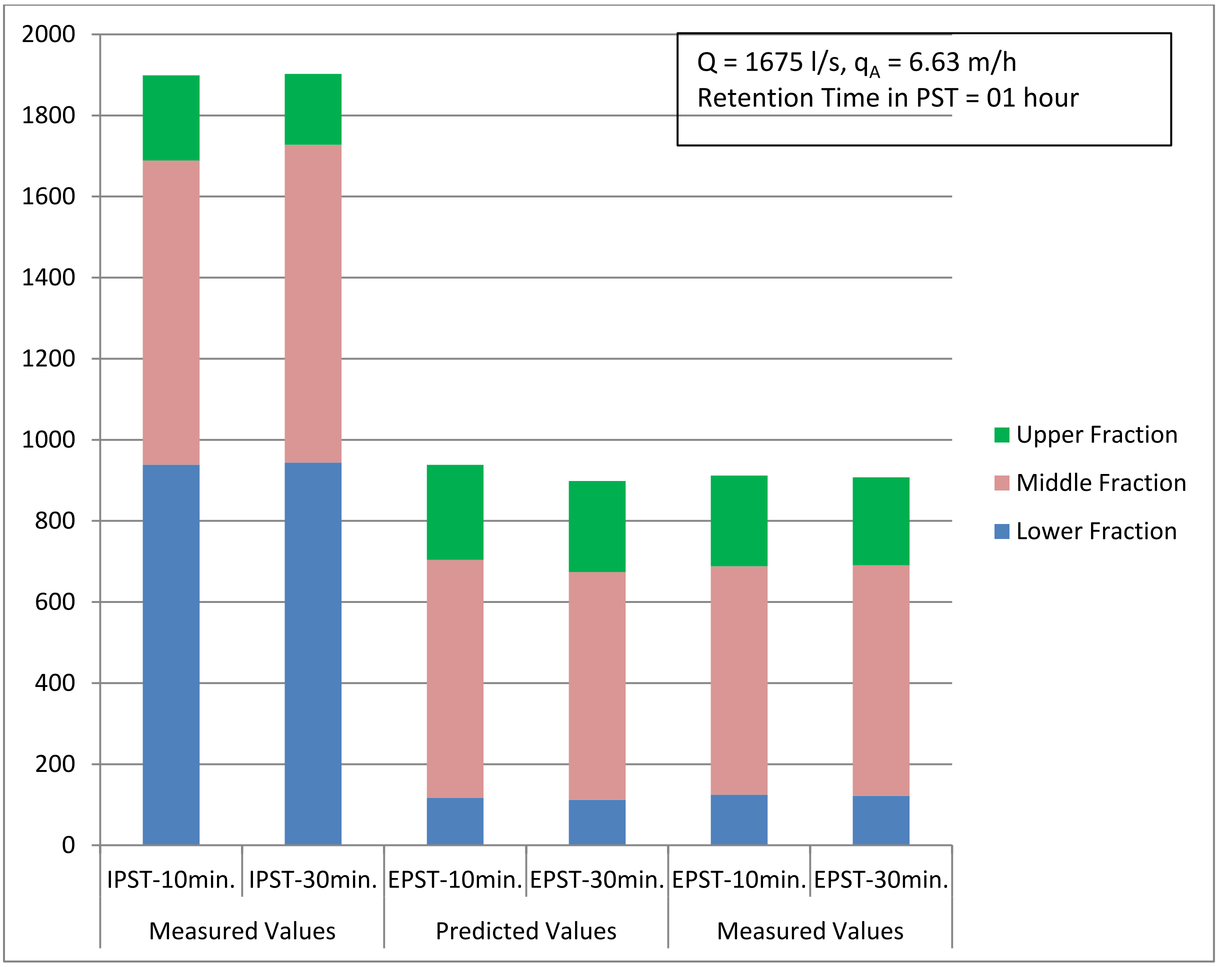



**Figure 7.4: Model for TSS Calculation of EPST from IPST - 24-08-2010 (Time: 12:55)**

This model can be used for forecasting the values of EPST on the basis of IPST for both weather conditions. This model is tried for all the experiments and it shows excellent reproducibility.

The prediction model could solve the problem of measuring the effluent of combined sewer overflow tanks. The concentration of effluent of CSO tanks / storm water tanks can be easily measured by knowing the concentration of influent of that tank, with the help of prediction model. In case of primary settling tank in any wastewater treatment plant, this model can be used for the determination of a) primary sludge, b) total solids to aeration/biological tanks.

# 8 Chapter – 8 Summary and Outlook

The aim of the thesis is to develop and innovate a comprehensive system for describing the settling of solids in raw wastewater prior to any treatment. The purpose of the study is to use its results/findings for improving the efficiency of primary settling tank and combine sewer overflow tank / storm water tanks.

Several objectives were defined on the basis of problems identified in this field (as discussed in Chapter 1) and to meet the above mentioned broader aim of research. This research was undertaken to address these objectives. This chapter overviews the study and objectives as mentioned in Chapter one and how those objectives are achieved. This chapter also discusses the major findings and outlook on further research.

## 8.1 Summary

There is very limited information available on the settling behaviour of solids in raw wastewater. There was a lot of research done on the secondary sludge in last 20 years. Many instruments were developed and used to study the settling behaviour of secondary sludge. These instruments / methods were used for measuring different settling parameters, mostly focused on settling velocity. There were very few instruments available which can measure or determine most of the settling parameters i.e. settling fractions of solids, settling behaviour of each fraction, types of solids (organic & inorganic solids), settling velocity, settleable solids, and pollution load by solids etc. Most of the instruments are very hectic to use i.e. some cannot be transportable from one place to another, some need more manpower, some need huge quantity of wastewater, and some need many hours of time for completion of experiment. One other important aspect is that there is a great difference between the nature of particles / solids in raw wastewater as compared to secondary sludge. The particles in raw wastewater varied in sizes, shapes, non-colloidal, non-homogeneous, so therefore complex to understand, as compared to secondary sludge.

In the view of above problems and shortcomings, this research was undertaken to develop and establish a settling apparatus / system by which a maximum of settling parameters can be measured at one time and that will be easy to use, requires less manpower and experimentation time. In short, this thesis will provide a comprehensive base knowledge to deal with problems of settling of solids in raw wastewater.

A settling apparatus was developed (Aslam et al., 2010; Aslam et al., 2011a; Aslam et al., 2011b) at Graz University of Technology to study the settling behaviour of solids in raw wastewater. A comprehensive literature survey was conducted to have a better understanding of the topic and to provide a base for the development of new apparatus. This study was conducted for the wastewater of Graz wastewater treatment plant. The experiments were performed initially in the laboratory of the Institute of Urban Water Management and Landscape Water Engineering at Graz University of Technology. On the basis of successful results these experiments were extended to the broader level on site at Graz WWTP.

The results / findings of the research were summarized and concluded in view of research objectives as under:

### 8.1.1 Fractions of solids

The first objective of the research was to determine the fraction of solids in raw wastewater. Considering the nature of solids in raw wastewater, it was very difficult to determine and measure the fraction of solids. The settling apparatus (Aslam et al 2010) was developed to find the fractions of solids. This settling apparatus was able to determine the five fractions of solids in wastewater. The results of the experiments at laboratory and On-Site show that there are three fractions present in raw wastewater. The above mentioned fractions can be defined as 1) fast settling solids, 2) suspended solids, 3) floating solids. These fractions ware measured on the basis of the concentration of solids in wastewater, TSS mass of three fraction, settling velocity of solids.

### 8.1.2 Settling behaviour of each fraction

The settling behaviour was observed and measured in the settling column for each fraction of solids in raw wastewater. Discrete settling was observed for these fractions. The hindered settling was also observed and measured in the middle fraction. The settling time was one of the most important parameters in the settling behaviour of solids. The experiments were performed initially for the settling time of 02 hours, and then start reducing it to achieve settling in less time. The best time for settling experiments, measured from both laboratory and field experiments, was 10 minutes. Most the solids got settled in settling column in the first 10 minutes. An increase of about 15 – 20% is measured in settling of solids in raw wastewater with the increase of settling time from 10 minutes to 120 minutes, as shown in Figure 8.1. The settling time of 10 – 30 minutes, is dependent on flow rate (Q), retention time and shape of the tank.

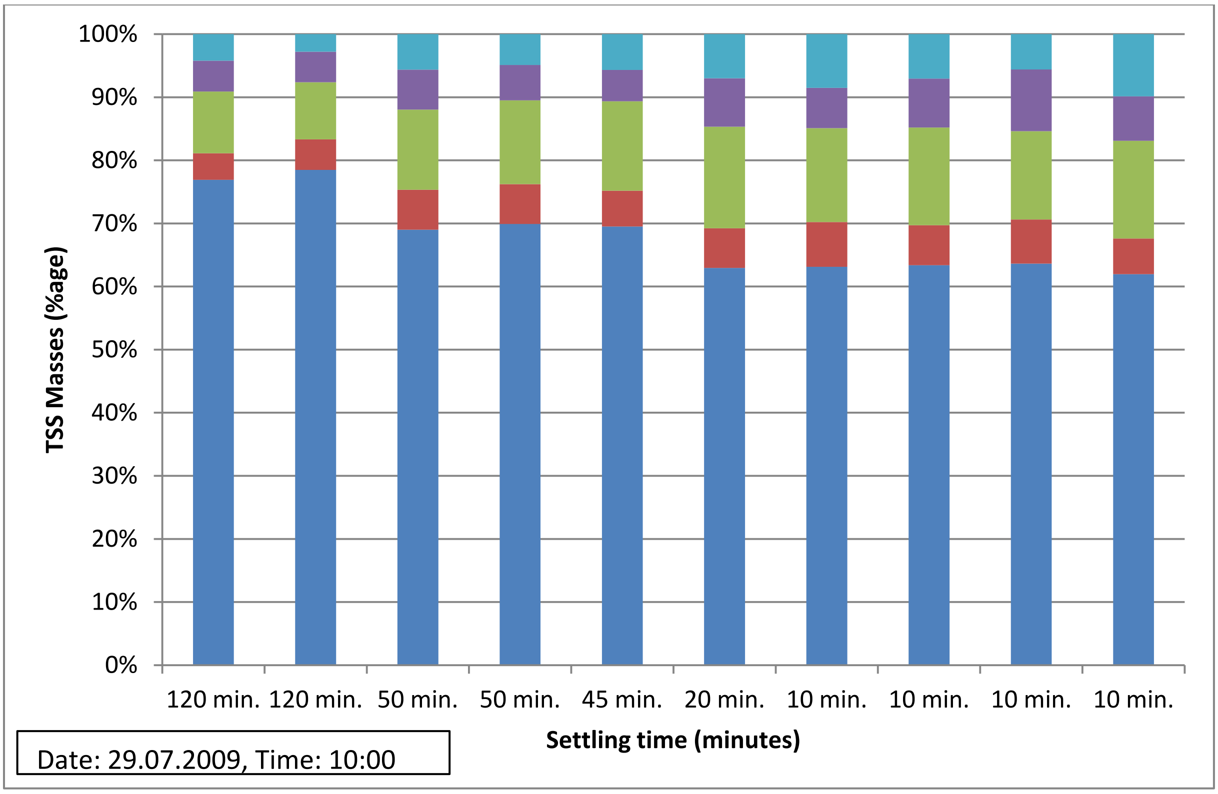



**Figure 8.1: TSS Mass (Percentage) in five fractions for different settling time**

The settling of solids in the column was also monitored by Video Camera. The purpose of making videos is to see the behaviour of solids in wastewater and to measure the size, shape and settling velocity of particles. The particles have both regular and irregular shapes but most of the particles have irregular shape. Some particles are like filamentous and haphazard shapes. The particle size (cross-section) ranges from 0.1 – 450 mm$^2$, as can be seen from Figure 8.2. The settling velocity of the particles was also measured and it ranges from 0.1 – 3.5 cm/sec (3.6 – 126 m/h), as shown in Figure 8.2. The results in the Figure 8.2 show the comparison of dry and weather with respect to particle size and settling velocity. It is concluded that in dry weather the some particles have higher settling velocities and larger particle size, as compared to wet weather. In wet weather about 90% particles lie in the range of settling function. A settling function was developed and shown as an area covered by black dark line in Figure 8.2. This settling function describes the relationship between particle size and settling velocity. In this function, the particle size (cross-section) ranges from 0.1 – 250 $mm^2$ and settling velocity ranges from 0.5 – 2 cm/sec (18 – 72 m/h). About 80% particles lie in this area of settling function.

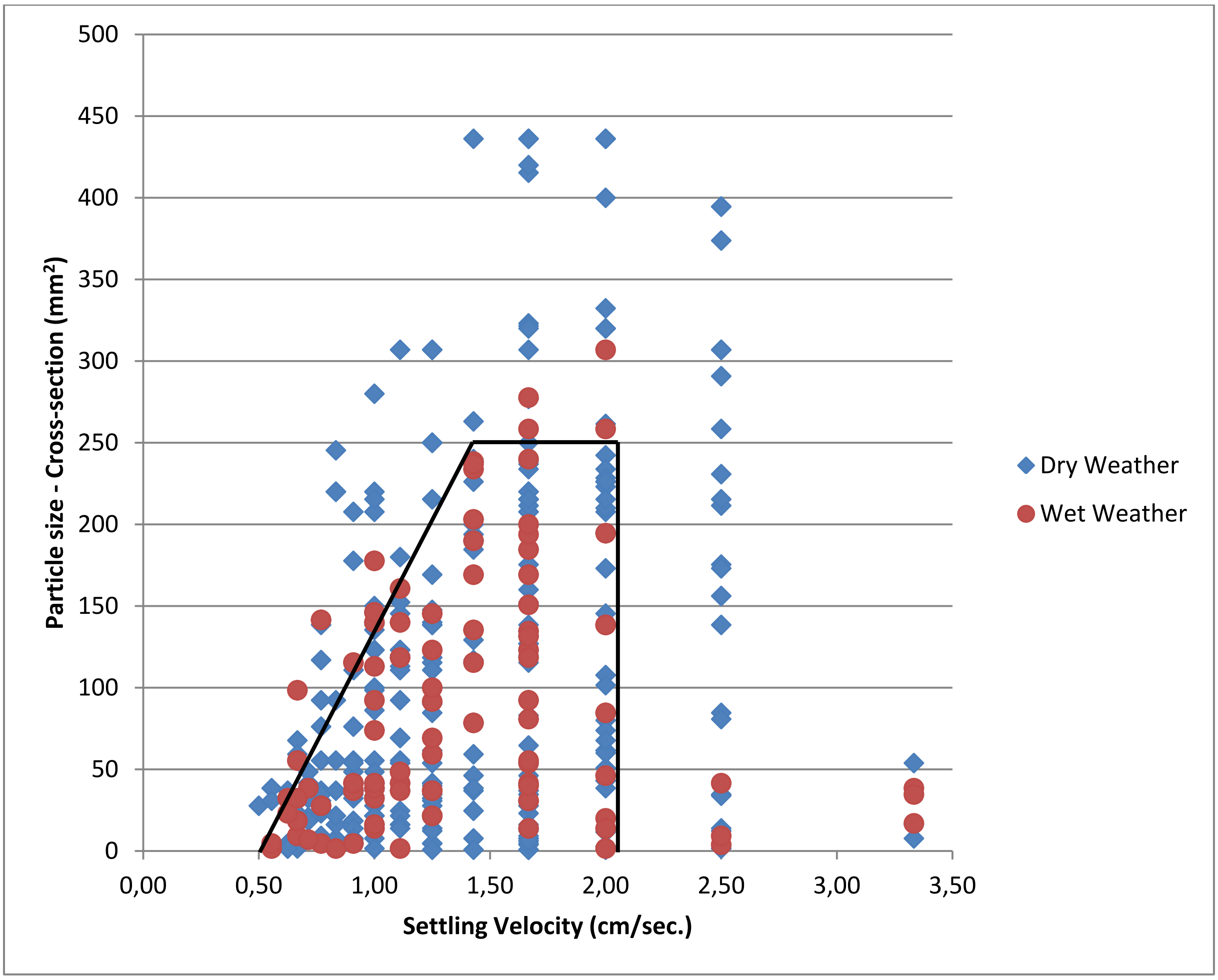



**Figure 8.2: Comparison of dry and wet weather; Particle Size vs Settling Velocity, Location: Gravel Chamber (Dry Weather: 29.06.2010, 13.07.2010, 28.07.2010, 11.08.2010, 24.08.2010, Wet Weather: 24.08.2010)**

### 8.1.3 Pollution load due to solids

Most water pollution is carried by the solids present in wastewater. The organic pollution associated with these solids is of greater concern. There are also some micro pollutants and heavy metals which go with solids if discharged in water bodies prior to any treatment. It is therefore very necessary to measure the pollution load of the solids present in raw wastewater.

The quality control parameters were tested for the obtained settling fractions of the solids from experiments on Settling apparatus at Laboratory and On-Site. These parameters include chemical oxygen demand, organic solids, inorganic solids, pH, conductivity, temperature. Chemical Oxygen Demand (COD) was the most important parameter to measure the organic strength of pollution associated with the particle. So the pollution load is also measured for these solids.

### 8.1.4 Better Understanding of the TSS fractions

The literature survey conducted gives us a comprehensive base knowledge and orientation about the previous research regarding settling of solids in raw wastewater. On the basis of this understanding from the literature, a new settling protocol has been developed for measuring the settling fractions and settling behaviour of these fractions. The huge quantity of experiments on this apparatus at both places (laboratory and On-Site) with a lot of variation in SOPs (Standard operating procedures), gives a better understanding about the settling processes in raw wastewater. The variation of sampling points (Gravel Chamber, Inlet Primary Settling Tank, Outlet Primary Settling Tank) also gives a broader look on the behaviour of solids at three different places. The primary settling tank is situated after screening and grit chamber, so wastewater from inlet and outlet of Primary Settling tank gave a better understanding about the settling processes in the settling tank and is ultimately helpful in the designing of the primary settling tank.

The results of experiments at primary settling tank were also compared with another TSS-measurement protocol (Solitax) and found reliable results with an error of ± 5%. The mass balances were also performed for all the experiments performed on the settling apparatus. It shows excellent reproducibility with a variation of ± 5%. The experiments were performed for the dry as well as for wet weather. The wet weather results give us the better understanding about the designing of combined sewer overflow tanks or storm water tanks.

### 8.1.5 Prediction/Estimation model

A model is an abstract description of reality, which is developed in order to understand better some defined aspects of the system to be analyzed or designed. It is a semantically closed abstraction of a system. It is a rational option to make predictions on the future behavior of real systems. It helps us to improve our understanding of the behavior of reality. Its analysis is more effective than direct observation of reality.

An estimation model was developed to predict the concentration and mass of TSS in each fraction of solids for the effluent of primary settling tank on the basis of values of TSS from Influent Primary Settling Tank. This model was applied to both dry weather

and weather conditions and was used for different time interval of the day. The results were excellent and reproducibility was perfect. It was compared with the real experimented values and it shows an uncertainty of ± 5%.
The estimation / prediction model can be used for the prediction of the primary sludge mass. This model can also be used for the determination of effluent of CSO tanks. The model can be used for sedimentation rate in CSO tanks.

## 8.2 Outlook

The results of this research will be helpful in determination of fractions of solids in urban raw wastewater. It can be utilized for estimating the primary sludge mass and effectiveness of primary settling tanks / combined sewer overflow tanks / storm water tanks. The estimation/prediction model can be best usable in the estimation of effluent of settling basins especially CSO tanks. The results will be utilized for further CFD modeling of primary settling tanks or combine sewer over flow tanks / storm water tanks. This settling apparatus should be used for the wastewater of some other treatment plants to authenticate its reliability.
The next steps after this research for new researchers are to follow up with additional experiments with modification in the procedure of experiments, design of settling apparatus, addition or subtraction of fractions, some online system to be developed and installed within the column to measure the particle size and settling velocity. The settling apparatus (Aslam et al., 2010) should also be used for the wastewater of the secondary settling tanks and find out the effectiveness of this apparatus for different types of wastewater. The future researchers should use the prediction model for the estimation of effluent of combined sewer overflow tanks / storm water tanks for different areas and check its reliability and reproducibility. This research will provide a platform to the young researchers to enhance their advanced research in describing and modeling the settling of solids in all type of settling basins (primary settling tanks, secondary settling tanks, combined sewer overflow tanks, storm water tanks).

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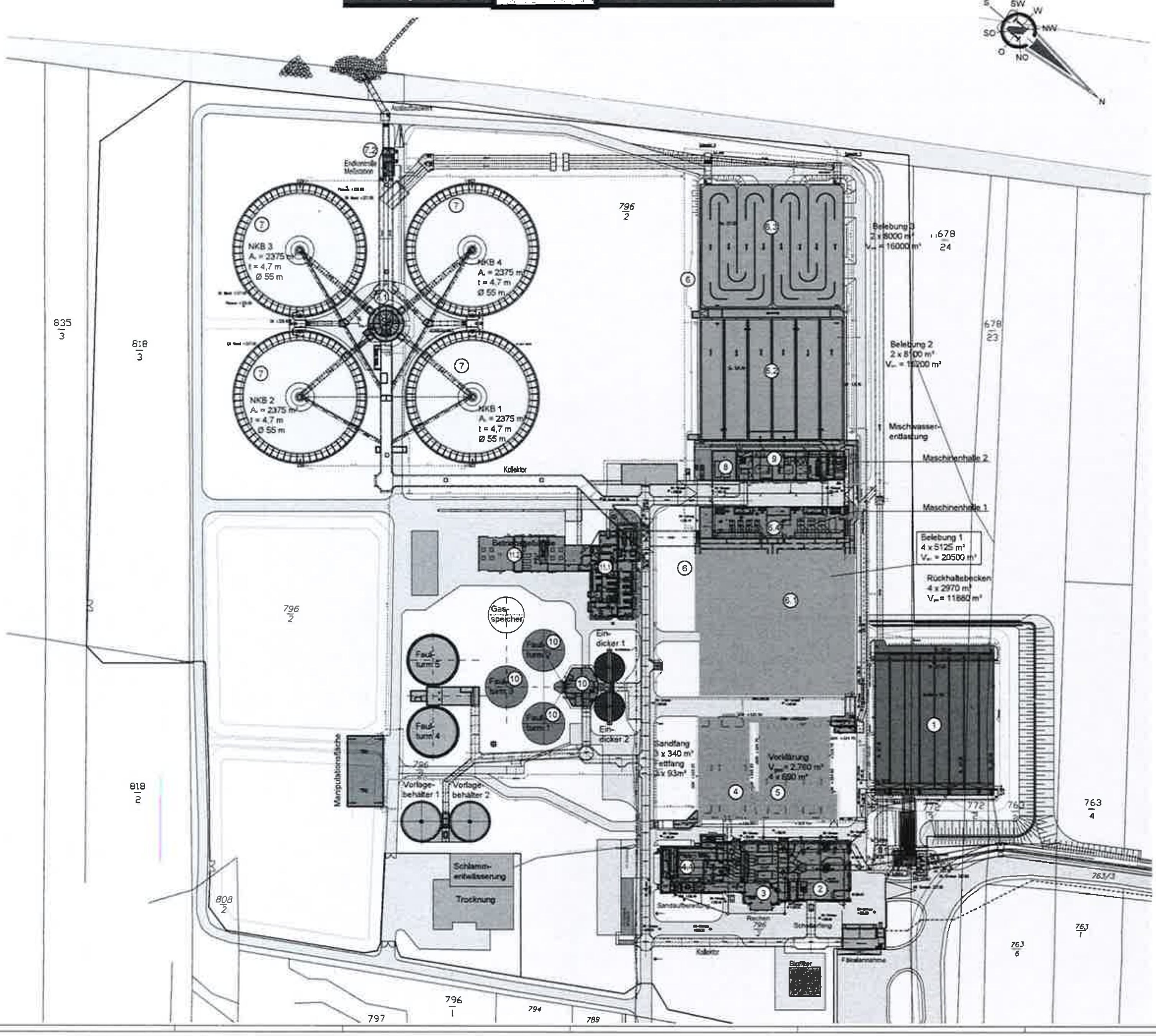
# List of Figures

# List of tables

# 10 Appendices

Kläranlage der Stadt **GRAZ** Kanalbauamt / Lageplan M. 1:500




## Legende

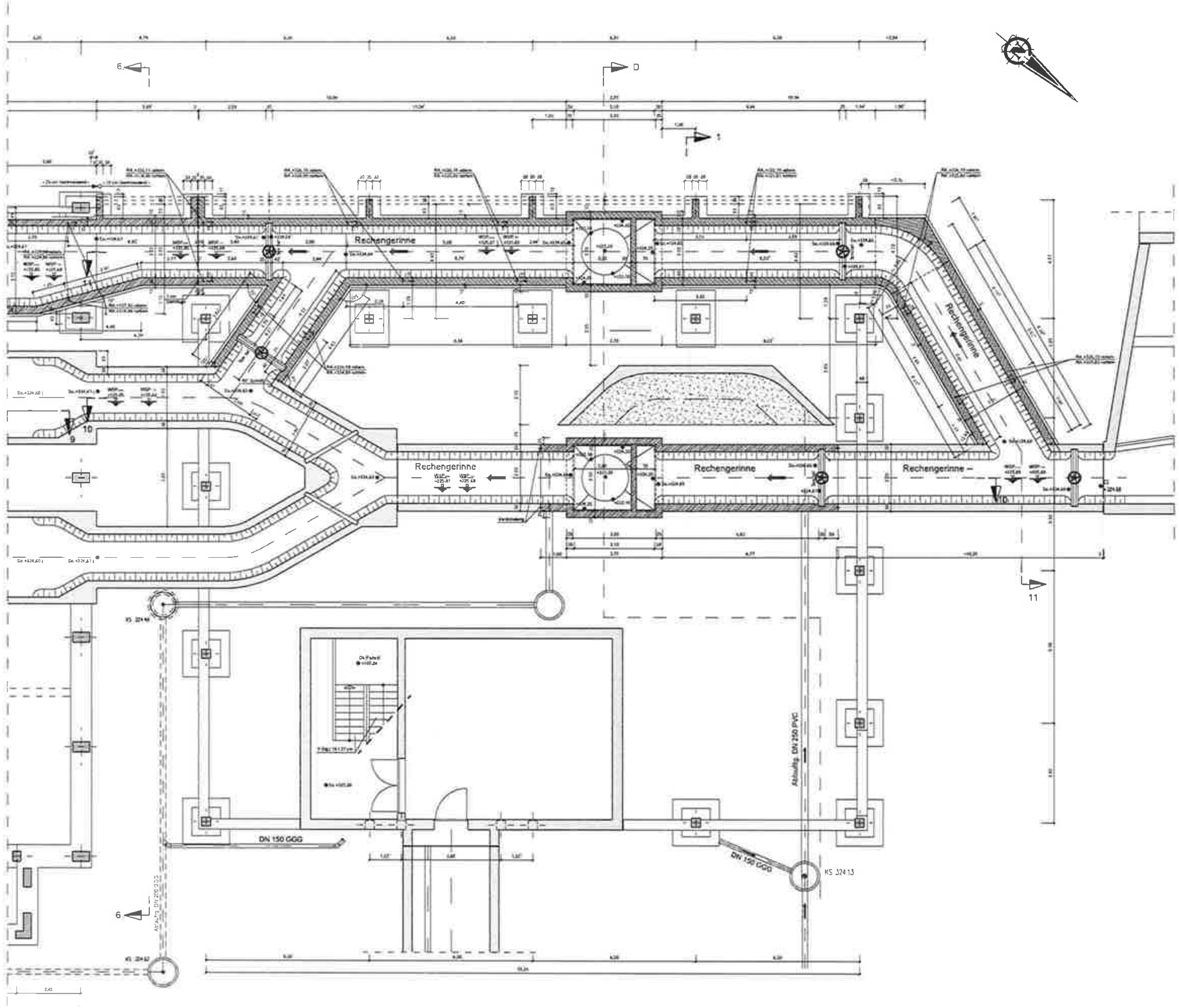
1 - Rückhaltebecken V = 11.880 m³ -
2 - Schotterfang -
3 - Rechenanlage -
4 - Sandfang V = 1.020 m³ -
4.1 - Sandaufbereitung -
5 - Vorklärung V = 2.760 m³ -
6 - Biologische Stufe V = 52.700 m³ -
6.1 - Belebungsbecken 1 / 4 x V= 5.125 m³ / $V_{ges}$=20.500 m³
6.2 - Belebungsbecken 2 / 2 x V= 8.100 m³ / $V_{ges}$=16.200 m³
6.3 - Belebungsbecken 3 / 2 x V= 8.000 m³ / $V_{ges}$=16.000 m³
6.4 - Maschinenhalle 1 -
7 - Nachklärung A = 9.500 m² -
7.1 - Endkontrolle Meßstation -
7.2 - Verteilbauwerk -
8 - Phosphatfällung -
9 - Maschinenhalle 2 ( BHKW-Anlage ) -
10 - Faultürme -
11.1 - Betriebsgebäude
11.2 - Werkstattgebäude -

Kläranlage der Stadt Graz

- Übersichtslageplan -

| | | |
|---|---|---|
| Jänner 2006 | Bestand | April 2016 |
| Fetz | Gelände | 1:500 |
| | Lageplan | |

# Grundriss Gerinneebene : Schotterfanggebäude M. 1:50

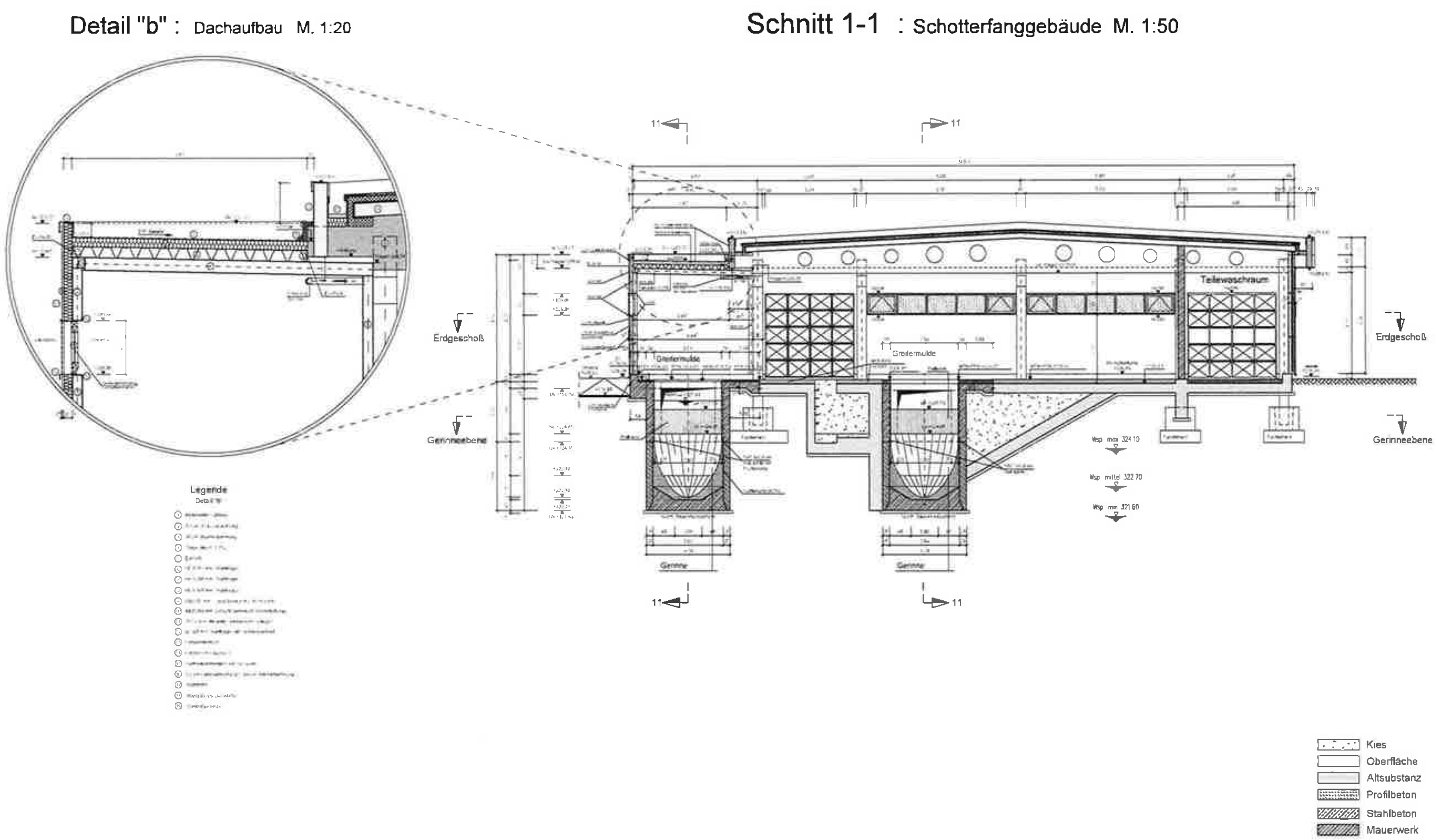



| | |
|---|---|
| | Kies |
| | Oberfläche |
| | Altsubstanz |
| | Profilbeton |
| | Stahlbeton |
| | Mauerwerk |

Kläranlage der Stadt Graz, BA 41

- Schotterfanggebäude -
Grundriss Gerinneebene

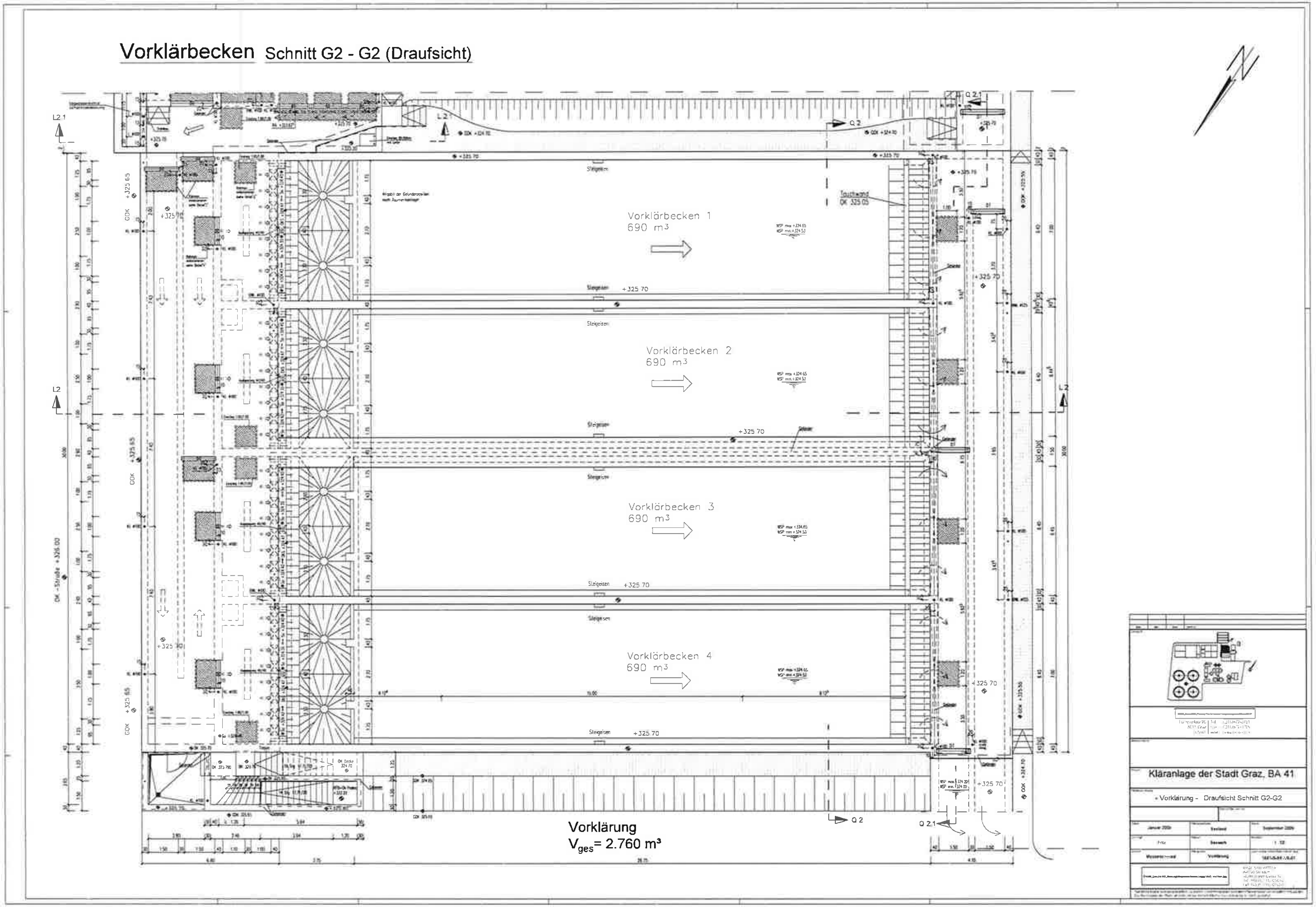
Jänner 2009 | Entwurf | September 2009
Fritz | Bauwerk | 1:50
Schotterfang



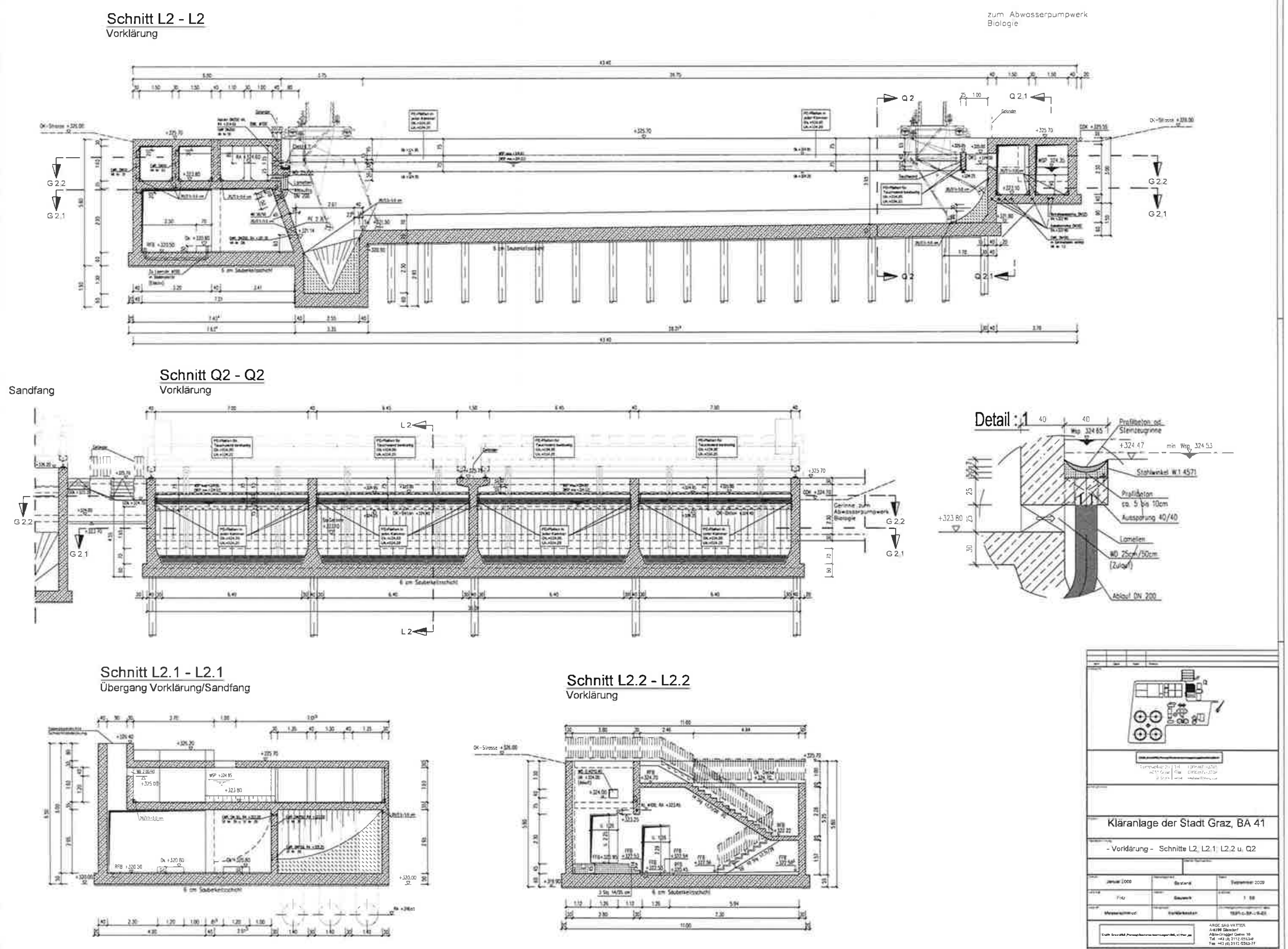

Kläranlage der Stadt Graz, BA 41

- Schotterfanggebäude -

Schnitt 1-1 und Detail "b"



Vorklärbecken Schnitt G2 - G2 (Draufsicht)
Vorklärbecken 1
690 m³
Vorklärbecken 2
690 m³
Vorklärbecken 3
690 m³
Vorklärbecken 4
690 m³
Vorklärung
Vges= 2.760 m³
Tauchwand
OK 325.05
Steigeisen
+325 70
+325 65
GOK
OK -Straße +326.00
L2
L2.1
Q 2
Q 2.1
Kläranlage der Stadt Graz, BA 41
• Vorklärung - Draufsicht Schnitt G2-G2




Kläranlage der Stadt Graz, BA 41

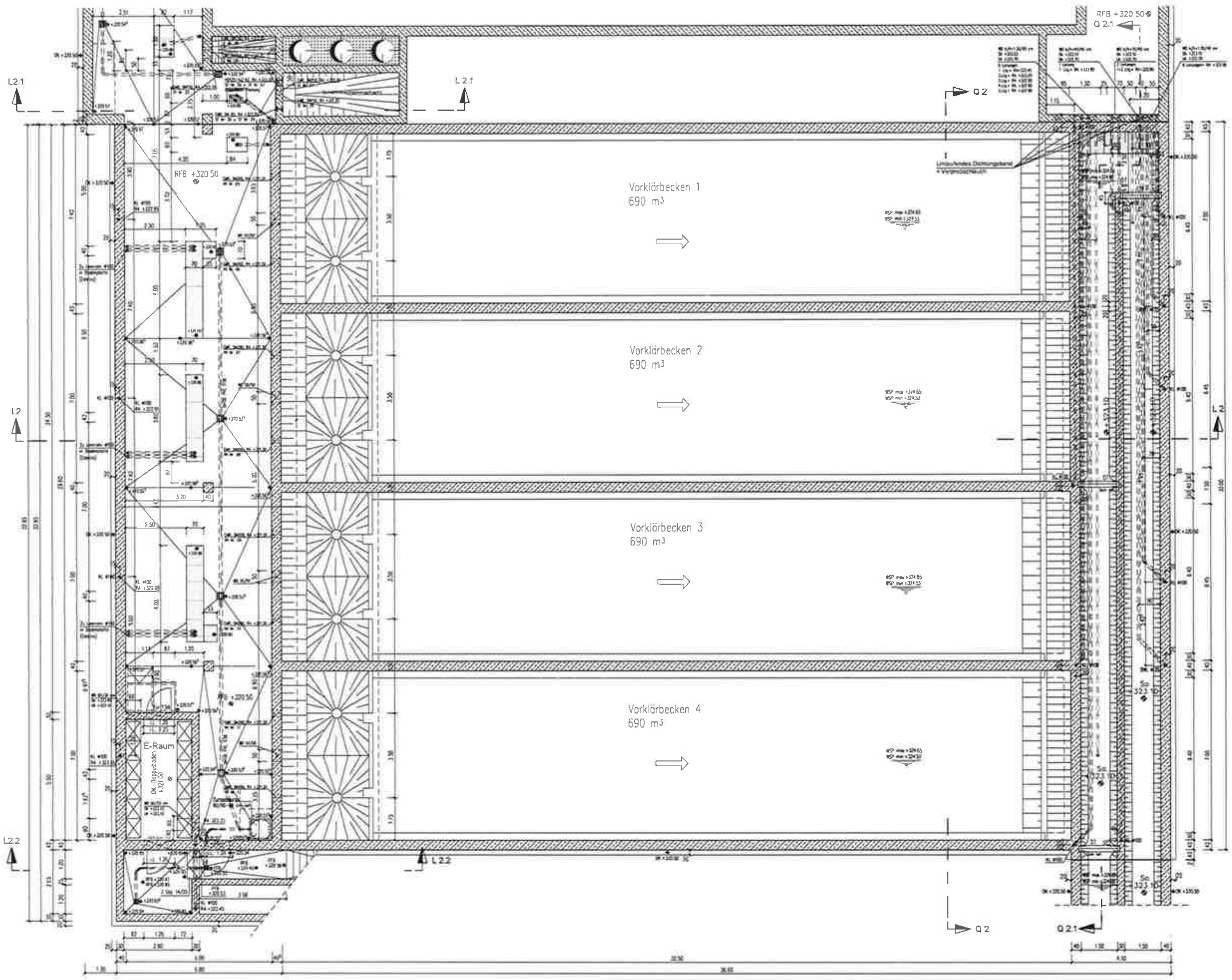
- Vorklärung - Schnitte L2, L2.1, L2.2 u. Q2

Januar 2000 | Bestand | September 2009

1:50

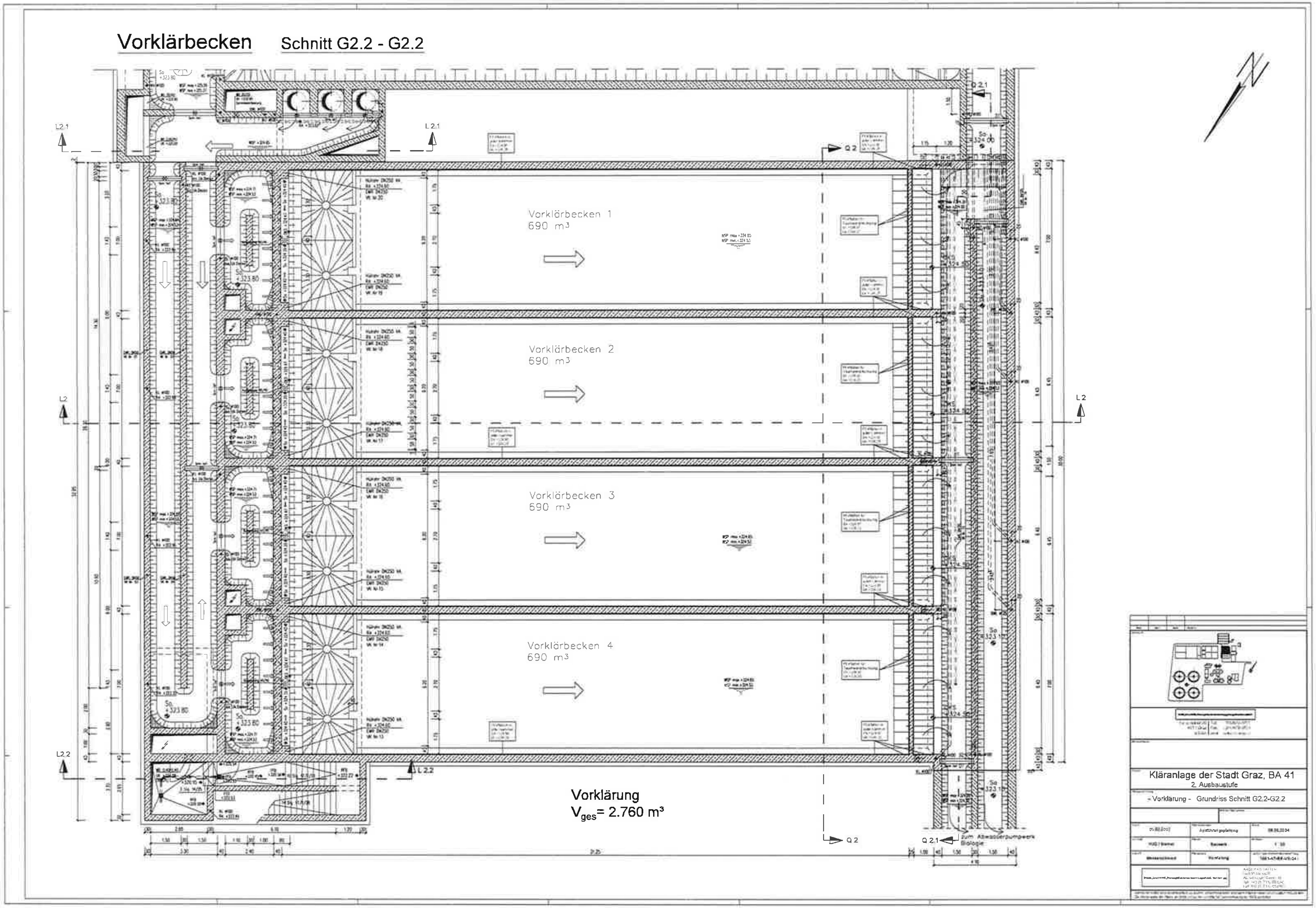
# Vorklärbecken

## Schnitt G2.1 - G2.1




Kläranlage der Stadt Graz, BA 41

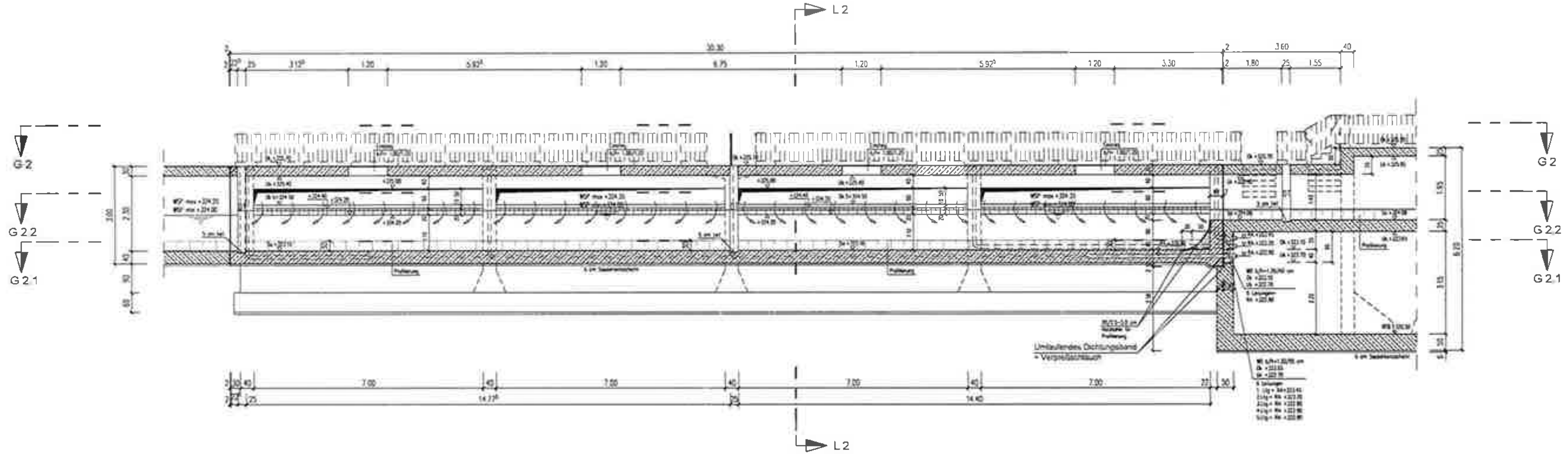
- Vorklarung - Grundriss Schnitt G2.1-G2.1



Vorklärbecken
Schnitt G2.2 - G2.2
Vorklärbecken 1
690 m³
Vorklärbecken 2
690 m³
Vorklärbecken 3
690 m³
Vorklärbecken 4
690 m³
Vorklärung
V$_{ges}$= 2.760 m³
zum Abwasserpumpwerk Biologie
Kläranlage der Stadt Graz, BA 41
2. Ausbaustufe
- Vorklärung - Grundriss Schnitt G2.2-G2.2

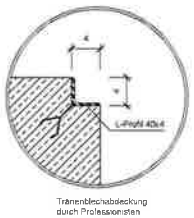
## Schnitt Q2.1 - Q2.1

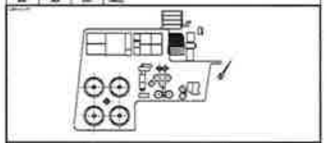
Vorklärung (Gerinne)




## Detail Zargen für Gitterrost

LV-Pos. 01.11.19.32 BZ
M 1: 2,5



| | | |
|---|---|---|
| Kläranlage der Stadt Graz, BA 41 | | |
| - Vorklärung - Schnitt Q2.1-Q2.1 und Detail | | |
| Jänner 2009 | Bestand | September 2009 |
| Fritz | Bauwerk | 1:50/2,5 |
| Messerschmied | Vorklärung | 1691-B-BK-VK-05 |

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