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Study of Particle Size Distribution in Activated Sludge Processes: Impacts of Solids Retention Time and Process Configurations

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Study of Particle Size Distribution in Activated Sludge Processes: Impacts of Solids Retention Time and Process Configurations

A dissertation submitted in partial satisfaction of the

requirements for the degree Doctor of Philosophy

in Civil Engineering

by

Zhongtian Li

2016

ABSTRACT OF THE DISSERTATION

Study of Particle Size Distribution in Activated Sludge Processes:

Impacts of Solids Retention Time and Process Configurations

Zhongtian Li

Doctor of Philosophy in Civil Engineering

University of California, Los Angeles, 2016

Professor Shaily Mahendra, co-chair

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Particle size distribution of the particulates is an essential characteristic of the wastewater quality. Particle size distribution has been used to predict COD, suspended solids, color, and turbidity. The understanding of particle size distribution contributed to the better understanding of soluble and particulate COD fractions and benefited the modeling of activated sludge process. Particle size distribution of wastewater particles was used to improve the understanding of both primary treatment and secondary treatment. Particle size of activated sludge flocs may affect key sludge handling processes including sedimentation, thickening, digestion, and dewatering. Particle size distribution of secondary effluent is also an important consideration for the design of tertiary treatment such as filtration and disinfection.

Several design and operational parameters, e.g. mixing, aeration, flocculation, and SRT, may affect particle size distribution of activated sludge. Previous results strongly suggest that

SRT is an important parameter affecting particle size distribution in activated sludge process. However, direct comparison of different wastewater treatment plants could not rule out possible confounders such as sheer force in aeration basin, doses of coagulants, and variation of organic loadings. The objective of this study is to investigate particle size distribution of activated sludge flocs under different SRTs and treatment processes. Particle size distribution of lab-scale MLE reactor and IFAS reactor were studied under various SRTs and carbon sources. Five full-scale wastewater treatment plants were surveyed for detailed understanding of the change of particle size distribution from raw wastewater to secondary effluent.

Chapter 2 investigates the impact of SRT on particle size distribution, sludge settleability, effluent turbidity, and removals of COD and NH_4^+-N. A MLE reactor is established with 16L of operational volume. Settling test, water quality analyses, and microscopic examination are applied to evaluate the impact of different SRTs. Particle size of activated sludge flocs are analyzed at different controlled SRTs. Particles with different size ranges were evaluated at various SRTs.

Chapter 3 focuses on the impact of SRT on particle size distribution, sludge settleability, effluent turbidity, and removals of COD, NH_4^+-N in a lab-scale Integrated Fixed Film Activated Sludge (IFAS) reactor. Chapter 3 further investigates the impact of difference carbon sources (Glucose vs. Sodium Acetate) on particle size distribution and reactor performance in the IFAS reactor. Settling test, water quality analyses, and microscopic examination are applied to evaluate the impact of different SRTs. Particle size distribution of

the mixed liquor in the IFAS reactor is compared with that in MLE reactor operated at similar SRTs for suspended solids.

Chapter 4 surveys particle size distribution in 5 full-scale WWTPs with different SRTs and treatment processes in the Los Angeles County. Particles size distribution profiles from primary influent to secondary effluent are fully evaluated. The relationship between SRT and particle size of activated sludge in biological process and sedimentation process are studied in detail.

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University of California, Los Angeles

2016

Dedication to my parents Fang Wei and Qian Li.

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I feel fortunate to meet friends and share the hobby of mountain hiking. Memories from High Sierra are mediating and will always be treasures of my life. There and back again from Mt. Whitney shaped my attitude towards many aspects of daily endeavor.

Finally, I would like to thank my family for their unconditional love and support. I am thankful for my parents being there with me during difficult time. I am grateful they always give me courage to follow my passion. “Home is behind and the world ahead.”

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2004 – 2008 B.S. in Environmental Science, Shandong Agricultural University, China

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- Li, Z.; Li, X. "Pyrosequencing Analyses of the Microbial Community in a Biologically Active Carbon (BAC) Reactor Treating 17β-Estradiol Contaminated Drinking Water" Under review.

- Li, Z.; Nandakumar, R.; Madayiputhiya, N.; Li, X., (2012) "Proteomic Analysis of 17beta-Estradiol Degradation by *Stenotrophomonas maltophilia*". Environmental Science & Technology 2012, 46, (11), 5947-5955.

- Li, Z.; Dvorak, B.; Li, X., (2012) "Removing 17beta-estradiol from drinking water in a biologically active carbon (BAC) reactor modified from a granular activated carbon (GAC) reactor". Water Research 2012, 46, (9), 2828-2836.

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Chapter 1 Introduction

1.1 Activated Sludge Process

In the middle of the 19th century, wastewater generated in the fast-growing regions and cities in Europe was discharged directly into rivers and canals, as well as into irrigation lands. The cleaning effect of irrigation fields had already been observed in the late 1870s, but in the first decade of operation, the scientific basis for the reduction of organics, which was indirectly monitored by smell and/or by taste, was largely unclear. Experiments designed to increase the specific wastewater loading rate compared to that of irrigation fields resulted in the development of intermittent soil filtration. The concept that microorganisms could naturally use organic and inorganic and inorganic carbon and nutrient sources for supporting growth and proliferation was gradually accepted in the end of the 19th century (Udo Wiesmann 2007).

The activated sludge process (ASP) was developed in 1913 at the Lawrence Experiment Station in Massachusetts by Clark and Gage (Metcalf 1930), and by Ardern and Lockett at the Manchester Sewage Works in Manchester, England (Ardern and Lockett 1914). Biomass collected from trickling filters were seeded to crude sewage and aerated in a tank. By repeatedly recycling deposited sludge and utilizing it as seeding biomass, the sludge became more capable of removing organics in sewage and termed as “activated sludge”. Upon since activated sludge process has been developed and modified to meet more stringent effluent standards and became the most common method of secondary municipal wastewater treatment technology. **Figure 1-1**

shows a schematic for activated sludge process used for primary and secondary wastewater treatment.

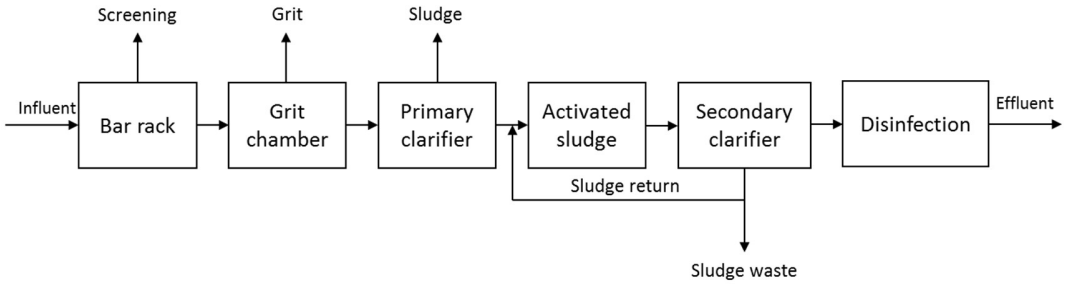

Figure 1-1. Schematic for activated sludge process used for wastewater treatment.

1.2 Activated Sludge Flocs

1.2.1 Formation of Activated Sludge Flocs

Floc-forming Bacteria. Study on the co-aggregation of nonflocculating bacteria shows that floc-forming bacteria, which offers specific cell-cell interactions and co-aggregation among pure cultures of nonflocculating sludge bacteria (Malik, Sakamoto et al. 2003, Katharios-Lanwermeyer, Xi et al. 2014). Cell surface hydrophobicity have dominant role in promoting bacterial adhesion (Olofsson, Zita et al. 1998, Muda, Aris et al. 2014). Co-aggregation pairings of bacteria belonging to the same genera share high degree of similarity, while the aggregation indices and patterns of co-aggregation are different (Malik, Sakamoto et al. 2003). *Acinetobacter* was found to function as bridging organism, similar to the bridging role by *Fusobacterium* and *Prevotella* in dental plaques (Kolenbrander, Andersen et al. 1985, Kolenbrander 1989). For instance, *Acinetobacter johnsonii* S35, *Acinetobacter junii* S33 function as bridging organisms in co-aggregates in activated sludge system (Tsuneda, Aikawa et al. 2003). Strains with specific surface interaction tend to

form activated sludge flocs. *Propioniferax*-like PG-02 and *Comamonas* sp. PG-08 are two phenol degradation bacteria strains. Adhesion protein on strain PG-02 and the complementary sugar receptor on strain PG-08 promote the formation of microbial flocs (Jiang, Tay et al. 2006). Floc-forming bacteria form bridges and connect nonflocculating bacteria in activated sludge flocs.

Extracellular Polymeric Substances. Activated sludge flocs consist of microorganisms, EPS, and organic and inorganic particles (Nielsen, Thomsen et al. 2004). EPS are the major colloidal constituents of the activated sludge flocs (Frolund, Palmgren et al. 1996). The flocs likely include a double-layered EPS structure of the loosely bound EPS (LB-EPS) derived from the tightly bound EPS (TB-EPS) (Poxon and Darby 1997, Li and Yang 2007). Microbial metabolism and extracellular lysis in activated sludge are influenced by operational and environmental conditions (Urbain, Block et al. 1993). EPS biopolymers on the surface of microorganisms, such as proteins, polysaccharides, and humic substances may have the effect of steric stabilization and steric destabilization (Tsuneda, Aikawa et al. 2003, Li and Yang 2007). A double-layered EPS structure of loosely bound EPS diffused from the tightly bound EPS that enclose microorganism may exist. The interaction brought by EPS may include hydrogen bonding between EPS molecules and entanglement between biopolymers, and facilitate cell attraction and attachments (Schmidt and Ahring 1994). The EPS are mainly responsible for the structure and functional integrity of the flocs and determine the physicochemical properties of the flocs. Previous works have shown that the concentration of EPS has an effect on settleability (Liao, Allen et al. 2001, Jin, Wilen et al. 2003, Ye, Ye et al. 2011) and dewaterability (Houghton, Quarmby et al. 2001, Li and

Yang 2007, Chen, Zhang et al. 2015). Previous studies indicate that EPS facilitate the formation of activated sludge flocs.

Recent research reveals that the importance of extracellular DNA (eDNA) in activated sludge floc formation. eDNA, as a substance of EPS, was found abundance in close proximity to living cells in activate sludge flocs. Activated sludge flocs disintegration of the microcolonies with high eDNA content is observed when activated sludge is digested by DNase. This observation indicates that eDNA might be an important structural component in activated sludge flocs (Dominiak, Nielsen et al. 2011). Release of eDNA occurs through lysis of a fraction of microorganisms in bacterial populations through both quorum-sensing (QS)-independent and -dependent mechanisms (Price-Whelan, Dietrich et al. 2006). eDNA binding with proteins, such as ß-toxin, may trigger refolding of protein, which make proteins more resistant to degradation. Meanwhile, eDNA is also responsible for building a skeletal framework for biofloc formation (Huseby, Kruse et al. 2010). Acid–base interactions between bacterial cells and between bacteria and surfaces can be promoted by eDNA binding (Das, Krom et al. 2011, Das, Sharma et al. 2011). The presence of eDNA on the cell surface of *Streptococcus mutans* enhances adhesion forces regardless of surface hydrophobicity and ionic strength of the surrounding medium (Das, Sharma et al. 2011).

1.2.2 Microbial Population of Activated sludge flocs

Early efforts of elucidating microbial population in activated sludge flocs are usually relied on morphological, cultural, and physiological methods. *Zoogloea* spp. was suggested to

constituent the majority of the bacteria in activated sludge flocs (Butterfield 1935). Other flocs-forming bacteria, including *Escherichia intermedium*, *Paracolobactrum aerogenoides*, *Nocardia actinomorpha*, *Bacillus cereus*, were further identified (Mckinney and Horwood 1952). Following study suggested that flocs formation was not a special property of certain group of bacteria. The chemical nature of wastewater determines the bacterial predomination and flocs formation is the resultant of metabolism of the organic matter in wastewater by the predominant bacteria (Mckinney and Weichlein 1953). Physical and chemical properties of bacteria surface were proposed to determine the activated sludge formation (Wilen, Lumley et al. 2008). A broader range of flocs-forming bacteria was discovered in ASP in later studies (McKinney and Edwards 1952, Kato, Izaki et al. 1971, Kakii, Kato et al. 1993).

Microbial communities of activated sludge flocs have been studied using a series of molecular techniques. It is estimated the number of bacteria in activated sludge is in the range of $1\text{-}10\times10^{12}$/g VSS (Nielsen, Mikkelsen et al. 2001). The active bacteria in flocs were assessed by DAPI staining, fluorescence in situ hybridization (FISH), and microautoradiography (MAR) (Nielsen, Juretschko et al. 2002, Wilen, Onuki et al. 2008). Confocal laser scanning microscopy (CLSM) provided improved resolution of the complexity of bio-aggregates in activated sludge flocs. The 3-D reconstructions of dye stained samples showed the spatial distribution of sugars, lipids and esterase producing bacteria (Szilveszter, Raduly et al. 2012). Many different functional bacterial groups were present in activated sludge systems, including Nitrate reducing bacteria, phosphorus accumulating organisms (PAO), glycogen accumulating organisms (GAO), Fe(III)-reducing bacteria, sulfate-reducing bacteria, methane-producing bacteria, ammonia oxidizing bacteria, nitrite

oxidizing bacteria, and Fe(II) oxidizing bacteria (Nielsen, Mikkelsen et al. 2001, Nielsen, Juretschko et al. 2002). Dominant filamentous bacteria were identified (Wagner and Loy 2002), the ammonium oxidizers (Purkhold, Pommerening-Roser et al. 2000) and PAOs (Crocetti, Hugenholtz et al. 2000).

1.2.3 Role of Activated Sludge Flocs in Activated Sludge Process

Activated sludge flocs are more accessible to carbon sources and nutrients in activated sludge system. Organic materials in raw wastewater exist in both soluble and colloidal or particulate forms (Andreasen and Nielsen 2000). In mixed liquor colloidal or particulate organic materials can absorb or adsorb to the microbial flocs. Degradation of colloidal or particulate organic materials by extracellular enzymes may increase the availability of soluble organic substrates for microbial growth. On the other hand, influent organic matters can influence the formation of extracellular polymeric substances (EPS) and the physicochemical properties of activated sludge. For instance, feed of acetate as the primary carbon source generate considerable more loosely bound EPS than that fed with starch (Ye, Peng et al. 2011). EPS and microorganisms from channel-rich conglomerates in activated sludge flocs. Microorganisms in such structure may experience higher substrate availability, up to a factor of 2, compared to free swimming cells(Logan and Hunt 1988). Activated sludge flocs provide a niche for microorganism with higher availability to energy and nutrients.

Activated sludge flocs provide shelter from adverse environmental conditions. Activated sludge flocs are physical barriers against predation by Protozoa (Bossier and Verstraete 1996).

Bacteria living in inner matrix of EPS are protected from shearing off by both Protozoa and turbulent flow. The actual finding is that predication by Protozoa is a natural selection process of the formation of activated sludge flocs(Li and Ganczarczyk 1990). It is observed that filamentous biotype disappeared in the absence of predation, indicating that bacteria might sense the presence of predication (Shikano, Luckinbill et al. 1990). Study on the co-aggregation of nonflocculating bacteria shows that floc-forming bacteria, which offers specific cell-cell interactions and co-aggregation among pure cultures of nonflocculating sludge bacteria (Malik, Sakamoto et al. 2003). Environmental factors such as substrate gradient, chemical and/or physical stress and predation are known to trigger bacterial aggregation in activated sludge systems(Bossier and Verstraete 1996). Investigation of micro-environment characteristics and microbial communities in activate sludge shows that bacterial compositions and distributions were heterogeneous and responded to micro-environment variation in flocs (Han, Liu et al. 2012). The formation of activated sludge flocs is the result of process selection of degrading microorganisms.

1.2.4 Importance of Particle Sizes in Activated Sludge Handling

Sedimentation of activated sludge is one of the most critical operations in activated sludge process. The performance of secondary sedimentation is crucial to overall effluent quality (Jin, Wilén et al. 2003). Different parameters have been developed to characterize sludge properties in terms of Sludge Volume Index (SVI), organic loading, sludge retention time, composition, and content of polymers, density, porosity, viscosity, and particle size distribution (Hilligardt and Hoffmann 1997). Most of modern secondary sedimentation tanks include thickening zone for

sludge concentration and sludge storage in case of a high hydraulic loading period (Plosz, De Clercq et al. 2011). Surprisingly very few studies have investigated the relationship between particle size distributions in regard of sludge satiability. It has been observed that the SVI is related to the median floc size for non-filamentous sludge (Barber and Veenstra 1986, Andreadakis 1993). Studies found that large flocs had a lower density and larger surface area. Higher SVI was observed with increasing floc size (Andreadakis 1993). However, the presence of filaments may influence the compressibility of sludge might be more profound (Wilén, Jin et al. 2003) flocs. Therefore, particle size analysis combined with morphology examination may be preferable to predict the settleability of activated sludge. Measurement of particle size can improve our knowledge of the settleability of activated sludge.

Particle size of activated sludge have significant effect on sludge dewaterability (Karr and Keinath 1978). Early studies show that among other physical properties of slurry, particle size profoundly affects suspension. The impact of particle size through specific surface term can be described by Kozeny–Carman equation, where q is filtrate flow, P is the pressure drop during filtration, S_0 is specific surface, μ is the viscosity of the fluid, ϵ is the porosity of the filter media, and L is the depth of the filter media.

$$q = \frac{5P}{\mu L} \cdot \frac{1}{S_0} \cdot \frac{\epsilon^3}{(1-\epsilon)^2}$$

Study of fractioned sludge samples into various size ranges showed that filterability decreased with decreasing particle size. Researchers also observed the relationship between particle size, filtration resistance, and solids retention time in both lab-scale reactors and full-scale

WWTPs (Knocke and Zentkovich 1986). The study suggests that solids retention time affects dewaterability of activated sludge by determining the size of sludge particles in the system. In a later study where particle size was purposely controlled by recirculation in a membrane bioreactor (MBR), initial hydraulic resistance obtained from three set of sludge samples with different mean particle size indicated that larger particles generated less resistance initially, but build up the resistance quicker than smaller particles (Wisniewski and Grasmick 1998). The study also revealed the contribution of soluble fraction of mixed liquor to total filtration resistance. 52% of filtration resistance generated from soluble fraction of supracolloidal-colloidal substances. This finding suggested that particle size, though important, is not the only factor that effect sludge dewaterability.

1.2.5 Impact of Particles in Secondary Effluent on Disinfection

Disinfection of secondary effluent is mandated by many water agencies for the discharge of secondary effluent (Bourgeous, Narayanan et al. 2003). The efficiencies of wastewater disinfection processes can be measured by evaluating coliform densities using the multiple tube fermentation (MTE) techniques (Parker and Darby 1995, Emerick, Loge et al. 1999). The MTE method works best for free-swimming bacteria. In secondary effluent bacteria are often attached with suspended particles and yield inaccurate reading by the MTE method. In addition, the association between bacteria and particles can shield both chemical and physical disinfection (Kollu and Ormeci 2012). Coliform bacteria, with typical size between 1 and 10 μm, have been shown to be protected during UV disinfection of wastewater by being enmeshed within particles

greater than 10 μm in diameter (Emerick, Loge et al. 2000). Improved method offers more accurate enumeration of the number of particles with associated coliform bacteria(Emerick, Loge et al. 1999). The inactivation of coliform can be modeled based on first-order decay expression. The presence of particle associated coliform reduced the efficacy of disinfection agent, increases operational cost, and impose compliance risk (Loge, Emerick et al. 2002). Scattering, adsorption, reflection and diffusion of incident UV light are common mechanisms of interference by particles (Vaezi, Nabizadeh et al. 2007). Scattered UV light is still capable of inactivating microorganisms. UV light that is adsorbed by particles is no longer effective for disinfection (Mamane 2008). Particles can also shield microorganisms from UV light by particle-microbe association that microbes are encapsulated in colloidal particles (Christensen and Linden 2003, Passantino 2004).

Two strategies could be used to reduce the concentration of particle associated coliform bacteria and consequently improve disinfection (Loge, Emerick et al. 2002). The first one is to remove particles prior disinfection process. For example, the adoption of MBR could efficiently removal particles larger than 0.2 μm in wastewater treatment. The second solution is to reduce the generation of particles that will not separate well by secondary sedimentation. For instance, study shows that an increase of SRT from 2.1 days to 6 days results 56% reduction of the fraction of particles which are associated (attached) with coliform (Loge, Emerick et al. 2002).

Recent study demonstrated that free-swimming bacteria that have full exposure to UV can be inactivated at UV doses lower than 9 mJ/cm^2. Free-swimming bacteria are much higher in number compared with particle associated bacteria. After the majority of free-swimming bacteria are disinfected, the inactivation of particle-associated bacteria determines the efficacy of overall

disinfection. Bioflocculation has statistically significant role of reducing log reduction of bacteria for particles with diameter lager than 25 μm (Kollu and Ormeci 2012).

1.3 Operational Parameters Affect Particle Size of Activated Sludge

The presence of polymer, sheer force, and flocculation are factors that control the flocculation of activated sludge. Many operational parameters could affect particle size of activated sludge by altering the presence and quantity of polymer, sheer force, and flocculation conditions. In addition, activated sludge process is a biological process where cell metabolisms ultimately control the physical, chemical, and biological characteristics of activated sludge flocs. Lab-scale tests showed clear trend of increase of particle size when inorganic polymer was dosed into mixed liquor with proper flocculation (Knocke and Zentkovich 1986). Extracellular polymeric substances with is biological origin also affect the flocculation, sedimentation and dewaterability of activated sludge (Li and Yang 2007). Variation of feed and operation conditions may provide different flocculation scenarios for activated sludge (Jin, Wilen et al. 2004). Well-established lab-scale test shows that the presence of cationic polymer and proper flocculation will increase particle size of activated sludge flocs with a dose-response relationship. In practice supplement of coagulant may significantly impact particle size, the use of coagulant are largely determined by the need of sludge handling process instead of secondary wastewater treatment. The actual amount of coagulant in the secondary treatment is not precisely controlled.

DO concentration is an important operating factor for controlling substrate utilization rate in activated sludge process. DO has been studied in regard to the effects on the structure, size and

size distribution of activated sludge flocs. An early study of two parallel and reactors operating at 1.5 mg/L, 5 mg/L, 15 mg/L showed slightly larger floc size with increased DO concentrations (Knudson, Williamson et al. 1982). This study suggested that the most important variable in determining the extent of oxygen limitation is the floc size distribution. Floc size distribution may help to explain the contradictory conclusion reported in literature regarding the effect of DO concentration on substrate removal or sludge production. Li and Ganczarczyk in another study concluded that DO and organic loading were the two most significant factors controlling the size distribution of activated sludge flocs (Li and Ganczarczyk 1993). However, the observation of the impact of DO on floc size distribution is not in consistent. The sufficiency of DO concentration in an activated sludge system may be impacted by many factors, with organic loading as the mostly important one. It a study of using stepwise regressions of major operating conditions with floc size distribution did not reveal recognizable correlation between DO and floc size distribution (Li and Ganczarczyk 1993). Previous study showed that moderate DO concentration in aerobic zone of activated sludge process may not have a direct impact on the particle size distribution of activated sludge flocs. With currently knowledge, it is reasonable to assume DO only will not significantly affect particle size of activated sludge given at sufficient level of higher than 2 mg/L.

Solids retention time (SRT) has been observed to be a parameter associated with mean particle size (Leu, Chan et al. 2012). Early work observed the decrease of small activated sludge flocs with increase SRT (Bisogni and Lawrence 1971, Chao and Keinath 1979). Settling test with activated sludge with sludge ages ranging from 0.25 days to 12 days shows that percent dispersion (nonflocculent or pin point floc) decreased exponentially with increased SRTs. Recent survey of

particle size distribution at the end of treatment chain in conventional activated sludge process, high purity oxygen process, Modified Ludzak-Ettinger (MLE) process, step-anoxic process, and oxidation ditch process shows that mean particle size of activated sludge flocs increased with increasing SRT, and the number of particles in the sedimentation supernatant decreased with longer SRT (Leu, Chan et al. 2012). Those results strongly suggest that SRT is an important parameter affecting particle size distribution in activated sludge process. However, direct comparison of different wastewater treatment plants could not rule out possible confounders such as sheer force in aeration basin, doses of coagulants, and variation of organic loadings.

1.4 Objectives and Organization of the Thesis

The objectives of this study are to systematically evaluate the impact of SRT on particle size distribution in different types of activated sludge systems. To achieve the objectives, a MLE reactor and an Integrated Fixed-film Activated Sludge (IFAS) reactor were established ad model reactors. Different SRTs and other operational conditions were tested their impacts on particle size distribution and sludge settleability were evaluated. Particle size distributions from primary influent to final secondary effluent in five full-scale wastewater treatment plants were surveyed at both wet-weather condition and dry-weather condition.

Chapter 2 investigates the impact of SRT on particle size distribution, sludge settleability, effluent turbidity, and removals of COD and NH_4^+-N. A MLE reactor is established with 16L of operational volume. Settling test, water quality analyses, and microscopic examination are applied to evaluate the impact of different SRTs. Particle size of activated sludge flocs are

analyzed at different controlled SRTs. Particles with different size ranges were evaluated at various SRTs.

Chapter 3 studies the impact of SRT on particle size distribution, sludge settleability, effluent turbidity, and removals of COD, $NH4^{+}$-N, in a lab-scale Integrated Fixed Film Activated Sludge (IFAS) reactor. Chapter 3 further investigates the impact of difference carbon sources (Glucose vs. Sodium Acetate) on particle size distribution and reactor performance in the IFAS reactor. Settling test, water quality analyses, and microscopic examination are applied to evaluate the impact of different SRTs. Particle size distribution of the mixed liquor in the IFAS reactor is compared with that in MLE reactor operated at similar SRTs for suspended solids.

Chapter 4 surveys particle size distribution in 5 full-scale WWTPs with different SRTs and treatment processes in the Los Angeles County. Particles size distribution profiles from primary influent to secondary effluent are fully evaluated. The relationship between SRT and particle size of activated sludge in biological process and sedimentation process are studied in detail.

Chapter 2 Impact of SRT on Particle Size Distribution and Reactor Performance in a Modified Ludzack-Ettinger (MLE) Reactor

2.1 Introduction

Particle removal is a critical consideration for wastewater treatment. Particle removal in primary sedimentation tank is achieved primarily through gravity in wastewater treatment plants. Primary sedimentation tank usually has good removal efficiency for the particles (>50 μm) (Neis and Tiehm 1997). Chemically enhanced primary treatment and the chemical-biological flocculation can improve small particle removal greatly (Odegaard 1998, Jimenez, Chavez et al. 2000, Zhang, Zhao et al. 2007, Zamalloa, Boon et al. 2013). Particle size in the primary effluent has impact on the efficiency of biodegradation of organic particles in biological secondary treatment. Increased microbial hydrolysis rate were observed for smaller particles due to increased surface area (Dimock and Morgenroth 2006, Puigagut, Salvado et al. 2007).

Activated sludge process (ASP) is one of the most important secondary wastewater treatment technologies. Activated sludge floc is the major form of particles in ASP. Activated sludge floc consists of bacteria, extracellular polymeric substances (EPS), and organic and inorganic particles (Nielsen, Thomsen et al. 2004). EPS are the major colloidal constituents of the activated sludge flocs (Frolund, Palmgren et al. 1996). The flocs likely include a double-layered EPS structure of the loosely bound EPS (LB-EPS) derived from the tightly bound EPS (TB-EPS) (Poxon and Darby 1997, Li and Yang 2007). EPS biopolymers on the surface of microorganisms, such as proteins, polysaccharides, and humic substances may have the effect of steric stabilization

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Sedimentation of activated sludge is one of the most critical operations in activated sludge process. The performance of secondary sedimentation is crucial to overall effluent quality (Jin, Wilén et al. 2003). Different parameters have been developed to characterize sludge properties in terms of Sludge Volume Index (SVI), organic loading, sludge retention time, composition, and content of polymers, density, porosity, viscosity, and particle size distribution (Hilligardt and Hoffmann 1997). Most of modern secondary sedimentation tanks include thickening zone for sludge concentration and sludge storage in case of a high hydraulic loading period (Plosz, De Clercq et al. 2011). Surprisingly very few studies have investigated the relationship between particle size distributions in regard of sludge satiability.

Solids retention time (SRT) has been observed to be a parameter associated with mean particle size. Early work observed the decrease of small activated sludge flocs with increase SRT (Bisogni and Lawrence 1971, Chao and Keinath 1979). Settling test with activated sludge with sludge ages ranging from 0.25 days to 12 days shows that percent dispersion decreased exponentially with increased SRTs. Recent survey of particle size distribution at the end of

treatment chain in conventional activated sludge process, high purity oxygen process, Modified Ludzak-Ettinger (MLE) process, step-anoxic process, and oxidation ditch process shows that mean particle size of activated sludge flocs increased with increasing SRT, and the number of particles in the sedimentation supernatant decreased with longer SRT (Leu, Chan et al. 2012). Those results strongly suggest that SRT is an important parameter affecting particle size distribution in activated sludge process. However, direct comparison of different wastewater treatment plants could not rule out possible confounders such as sheer force in aeration basin, doses of coagulants, and variation of organic loadings.

2.2 Materials and Methods

2.2.1 Reactor Set-up

A lab-scale MLE reactor was established. The working volume of the reactor is 16.0 L with 12.0 L of aeration zone and 4.0L of anoxic zone, as illustrated in **Figure 2-1** and **Figure 2-2**. Operational condition of the reactor is summarized in **Table 2-1**. Receipt of the synthetic wastewater was adopted and modified from a previous study with modifications (Babcock, Chen et al. 1993). The influent COD and NH_4-N were 250 mg/L and 40 mg/L, respectively. Synthetic influent was prepared using the following receipt: 350mg/L Glucose, 150 mg/L NH_4Cl, 55 mg/L K_2HPO_4, 20 mg/L $CaCl_2 \cdot 2H_2O$, 20 mg/L$MgSO_4 \cdot 7H_2O$, 10 mg/L $FeSO_4 \cdot 7H_2O$, 20 mg/L $MnSO_4 \cdot H2O$, and 20 mg/L KCl. Information about trace elements is available elsewhere. The DO was maintained at 6.3± 0.7 mg/L by supplying filtered air (0.45 μm filter) through two fine

bubble air diffusers. Feed was delivered to the anoxic zone, and solids were continuously recycled from the aerobic zone to the anoxic zone at a recycle rate of 100%. SRT was controlled by wasting appropriate amount of activated sludge from the aerobic zone. Temperature, pH and DO were recorded using oxygen and pH meters. Concentrations of COD, ammonium, nitrite and nitrate were measured using HACH® kits and electrodes in compliance with the US Environmental Protection Administration (US EPA) Standard Methods. pH of the mixed liquor was maintained approximately at 7.6 by adding NaHCO3 buffer. The reactor was aerated using filtered ambient air. The dissolved oxygen (DO) concentration in mixed liquor was maintained 3.5 ± 0.5 mg/L. Seeding activated sludge sample was collected from the Joint Water Pollutant Control Plant. 50 mL activated sludge from the Donald C. Tillman Water Reclamation Plant was seeded on Day 10 as source of nitrification microorganisms.

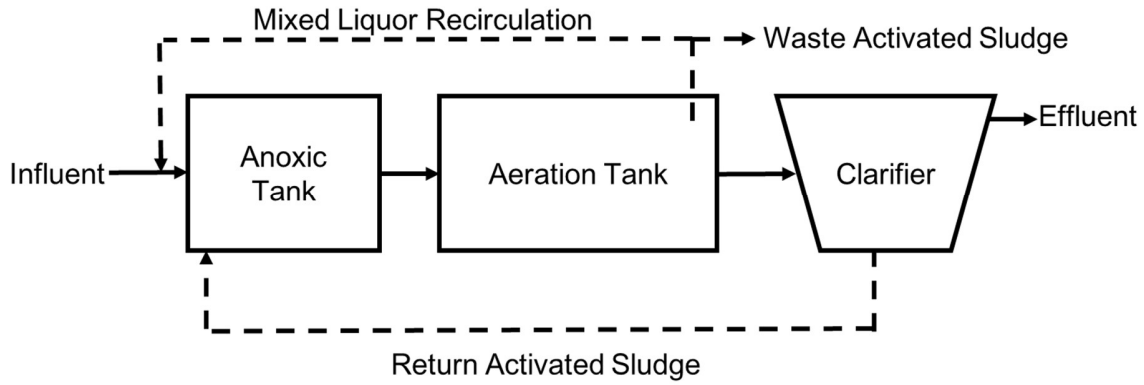

Figure 2-1. Schematics of the lab-scale MLE reactor

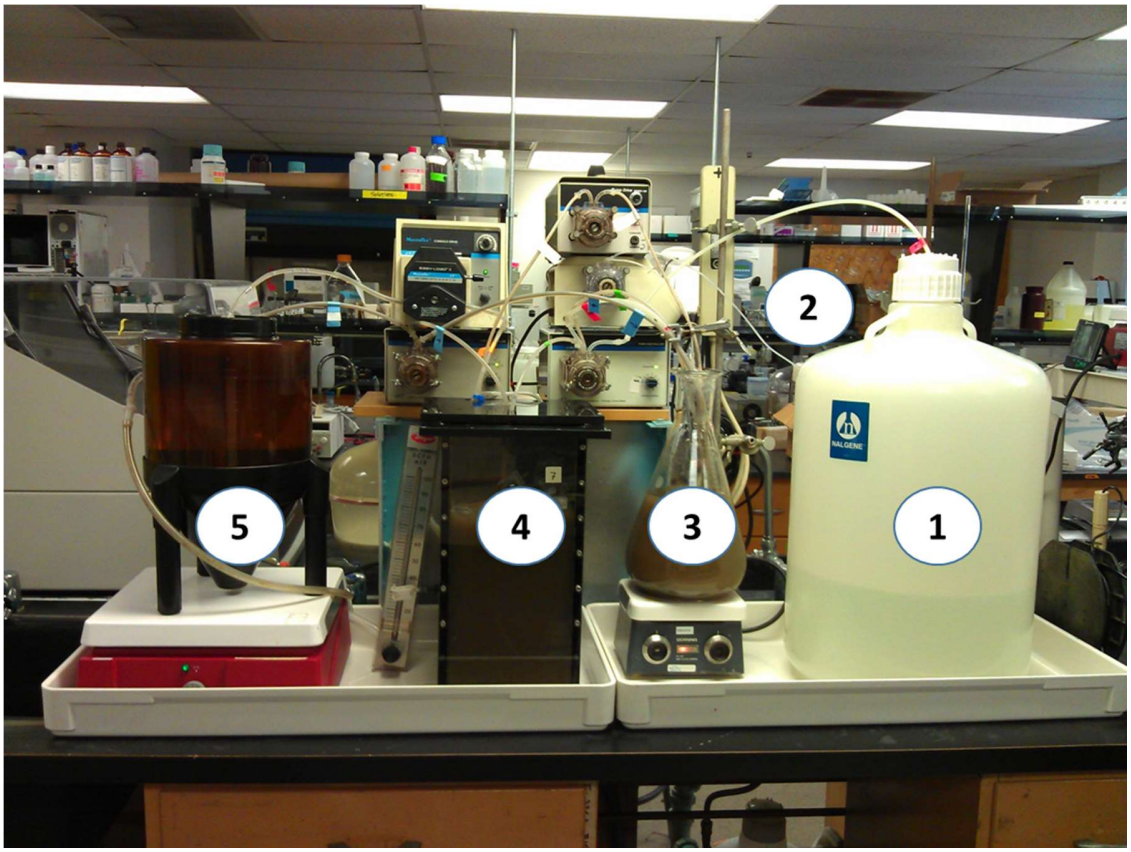

Figure 2-2. Illustration of the lab-scale MLE reactor. 1) Inorganic solution storage tank, 2) organic solution storage tank, 3) anoxic tank, 4) aeration tank, 5) sedimentation tank.

2.2.2 Sample Collection

Influent sample were collected at the combined inlet tube with 50 mL sample volume. Ammonia concentration and pH of influent samples were analyzed immediately after sample collection. Influent DO was not measure using the 50 mL sample. Rather, DO concentrations in the storage tanks of inorganic and organic solutions (**Figure 2-2**) were measured directly using a DO probe. The influent DO concentration were calculated based on pump rate of inorganic and organic solutions and their representative DO concentrations.

Effluent samples were collected at the top layer of supernatant in the sedimentation tank.

Care was taken to prevent disturbing the sludge blanket at the bottom of the sedimentation tank. Occasionally, a thin layer of floating activated sludge was observed at the top of the supernatant in the sedimentation tank. In this case, a pipette was used to collect the supernatant and minimize the inclusion of the floating activated sludge. Concentrations of ammonia, pH, turbidity and DO in effluent samples were measured immediately after sample collection. Samples reserved for COD analysis were acidified to pH of 2 and preserved at 4˚C in amber glass bottles.

2.2.3 Analysis of Particle Size Distribution

The particle size analysis was performed using an AccuSizer 780 optical particle sizer module (model LE400-0.5SE; Nicomp Particle Sizing Systems, Santa Barbra, California). The technique of single-particle optical sensing is used to detect individual particles in a certain size range as each particle passes through a thin optical detection channel. The wavelength of the light source of AccuSizer 780 was 700 nm. Light Extinction (LE) method and Light Scattering (LS) method were used and provide a range of detection of particles with diameters ranging from 0.5 μm to 500 μm. To prevent interference between particles, samples were auto-diluted by the AccuSizer 780. For each experiment, 0.5 mL of liquid sample was delivered to the system by a customized wide-bore pipette (Chan, Leu et al. 2011). Between each particle size test, three auto-flush cycles were performed to ensure clean dilution chamber, system tubing, and sensor. Blank sample (reverse osmosis water) was used to check system baseline after every 15 sample injections. A detailed description of the particle detection by AccuSizer 780 is available in Appendix A.

Representative particle size was calculated a method adopted from previous studies (Li,

Lau et al. 2006, Chan, Li et al. 2008, Leu, Chan et al. 2012), as follows:

$$\text{Total Particles} = \int_{0.5}^{M} Nds$$

$$\text{First Moment} = \int_{0.5}^{M} S \bullet Nds$$

$$\text{Particle Size} = \frac{\int_{0.5}^{M} S \bullet Nds}{\int_{0.5}^{M} Nds}$$

Where M is the upper limit of particle size cut-off values for calculation; N is the particle number count; S is the particle size measured from the AccuSizer 780 optical particle sizer. The calculated particle size is the centroid of the selected particle size range and independent of the total number of particles. The selected particle size cut-off values in this study are 0.5 μm – 50 μm, 0.5μm – 100 μm, and 0.5 μm – 500 μm.

2.2.4 Morphological analysis

Activated sludge floc was visually examined by Leitz Dialux 20 microscope. Images were captured by a digital camera system with image processing software. Morphological flocs were analyzed using wet mount, phase contrast microscopy, with digital photographs taken at 100× and 250× magnification. Five representative fields were analyzed per sample. Filament content was characterized by the filament index (FI) scale (0: none, 1: few, 2: some, 3: common, 4: very common, 5: abundant, and 6: excessive) as described by David Jenkins (David Jenkins 2003).

2.3 Results

The reactor was operated for 120 days in four phases. Prior of phase 1 stable operation of

the reactor with the same parameter as in Phase 1 was achieved. The operational parameters are summarized in **Table 2-1**. Influent DO, COD, NH_4^+-N and pH were kept stable. **Figure 2-3** shows the change of MPS, COD and NH_4^+-N removals, effluent turbidity, and sludge SVI during Phase 1 and Phase 2. As SRT of the MLE reactor increases from 4 days to 13.3 days, mean particle size (MPS) at 50 μm, 100 μm, and 500 μm cut-off values increased from 7.9±0.5 μm, 25.1±2.8 μm, and 34.3±1.2 μm to 26.9±7.8 μm, 50.0±10.0 μm, and 71.8±14.7 μm, respectively. With the increased SRT, NH_4^+-N removal increased from less than 5.0% to 79.6%. Meanwhile, the COD removal of the reactor was maintained higher than an average of 89%. Activated sludge showed a moderate and consistent decrease of SVI form an average of 106±13 mL/g to 89±9 mL/g.

To further test the impact of SRT on reactor performance, SRT of the MLE reactor was changed from 13.3 days back to 4 days in Phase 3. **Figure 2-4** shows the change of MPS, COD and NH_4^+-N removals, effluent turbidity, and sludge SVI during Phase 3. MPS of the reactor at 50 μm, 100 μm, and 500 μm cut-off values gradually decreased from 26.9±7.8 μm, 50.0±10.0 μm, and 71.8±14.7 μm to 11.8±7.6 μm, 30.5±5.6 μm, and 45.2±8.8 μm. As expected, the NH_4^+-N removal decreased sharply from an average of 79.6% to 8.6%. An immediate effluent turbidity jump on Day 81 was observed after SRT was decreased from 13.3 days to 4.0 days by waste appropriate amount of biomass from the aeration tank. A higher SVI of 111±5 mL/g was observed in Phased 3 compared with that in Phase 1 when the reactor was operated at the same SRT of 4 days.

To evaluate the impact of SRT on the particle size distribution in the reactor effluent, supernatant samples of mixed liquor after 90 min of sedimentation were analyzed when the reactor was operated at the most stable condition based on reactor performances, namely Day 1-Day 10 for

Phase 1, Day 47-Day 61 for Phase 2, and Day 106-Day 120 for Phase 3. This sedimentation time is equal to the retention time of the sedimentation tank for the reactor at HRT of 12 hours. Use the supernatant instead of reactor effluent minimized the impact of potential confounders such flow pattern in sedimentation tank. Each phase contained at least three sampling events. The average value of particle count for samples collected from each phase were shown in **Figure 2-5**. MPS of those supernatant samples were reported in **Table 2-2**. Particle size distribution in mixed liquor supernatant samples was shifted from smaller to larger particles from Phase 1 to Phase, when SRT increased from 4 days to 13.3 days.

Table 2-1. The operating condition and performance of the MLE reactor.

Reactor Operation and Performance	Phase (Duration in days)		
	Phase 1 (1-10)	Phase 2 (11-80)	Phase 3 (81-120)
Influent			
DO (mg/L)	6.9±0.6	6.7±0.3	6.6±0.1
COD (mg/L)	250 mg/L in synthetic wastewater using glucose as carbon source		
NH_4^+-N (mg/L)	40.8±1.5	40.5±1.7	42.0±1.2
pH	7.0±0.4	7.2±0.1	7.2±0.1
Mixed Liquor			
MLSS (mg/L)	2246±210	2967±361	2048±134
SVI (mL/g)	106±13	89±9	111±5
SRT (days)	4	13.3	4
Effluent			
COD (mg/L)	37.3±9.0	26.9±5.7	22.6±6.3
NH_4^+-N (mg/L)	20.9±2.1	6.9±4.8	18.5±1.6
DO (mg/L)	6.5±0.1	6.5±0.1	6.6±0.1
pH	7.0±0.4	7.2±0.1	7.2±0.1
Turbidity (NTU)	22.3±2.3	7.5±4.3	17.7±2.5

Table 2-2. MPS in mixed liquor supernatant samples after 90 min sedimentation in Phases 1, 2 and 3.

Phase \ Cut-off Values	50 μm	100 μm	200 μm	300 μm	500 μm
1	10.0±0.8	12.8±0.7	17.6±0.7	18.3±0.9	18.3±0.9
2	14.0±1.1	23.5±0.8	41.7±1.0	44.2±1.3	46.6±1.2
3	10.9±1.8	16.7±1.7	22.0±1.8	22.0±1.8	22.0±1.8

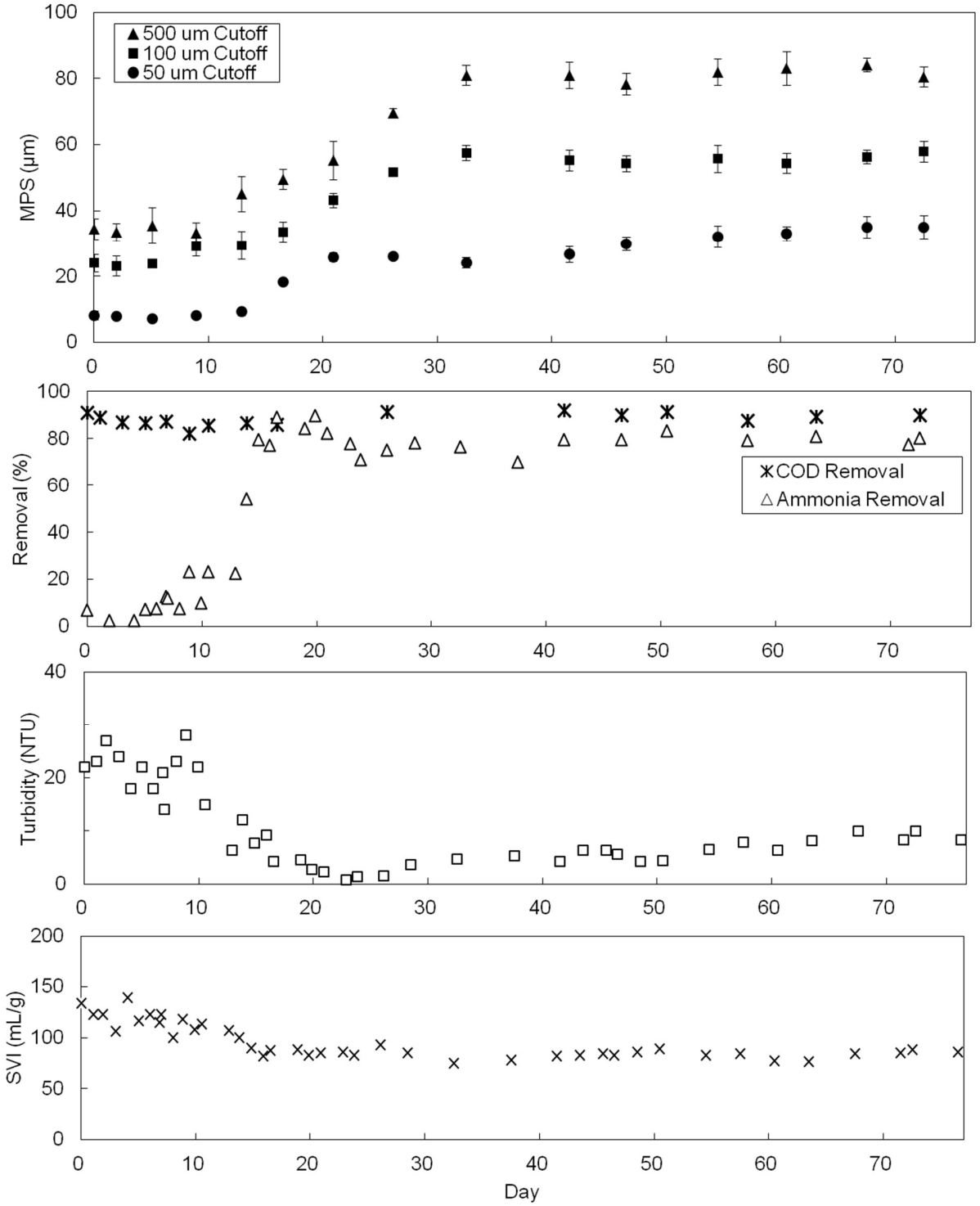

Figure 2-3. MPS, COD and NH_4^+-N removals, effluent turbidity, and sludge SVI by the MLE reactor in Phase 1 and Phase 2.

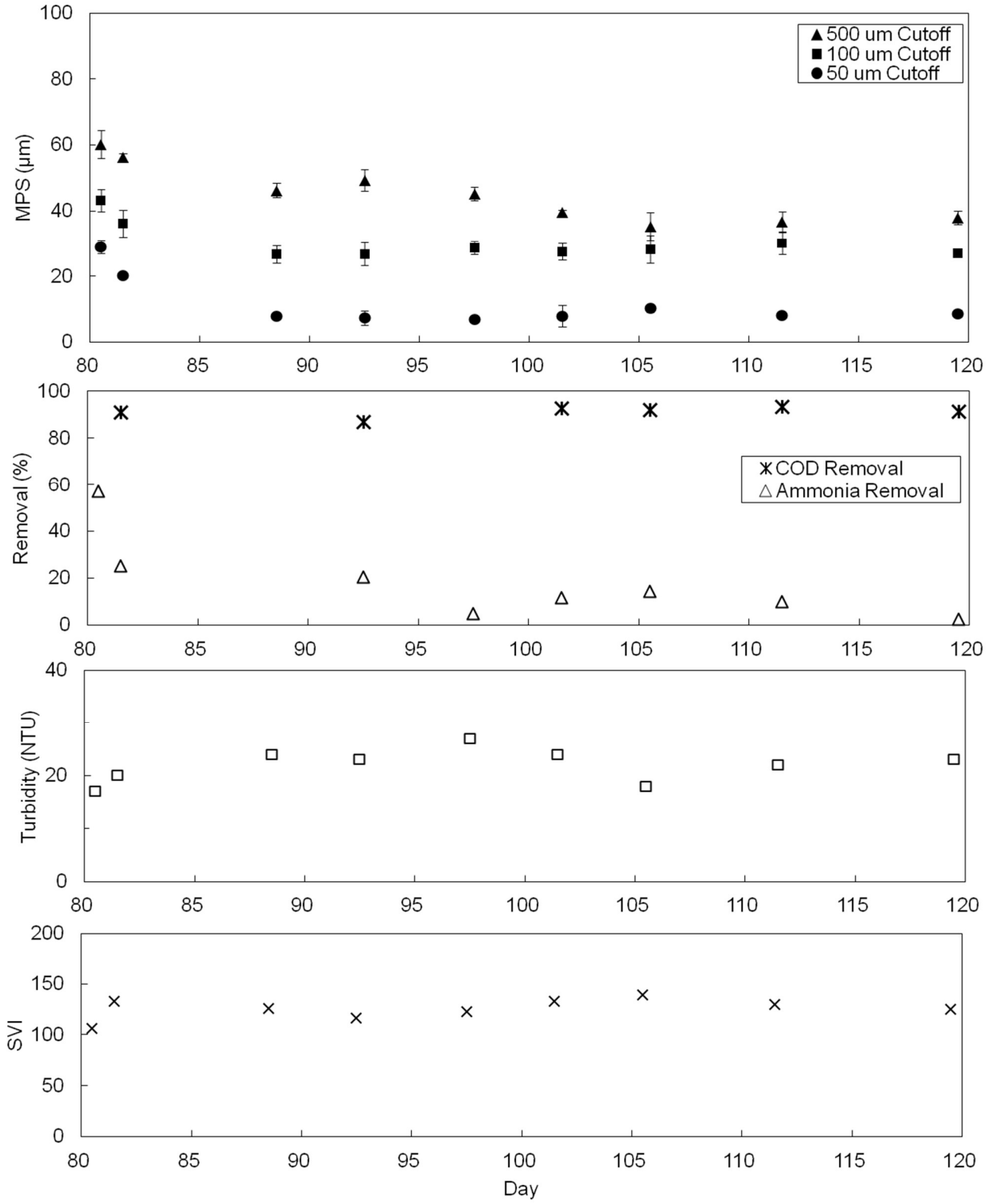

Figure 2-4. MPS, COD and ammonia removals, effluent turbidity, and sludge SVI by the MLE reactor in Phase 3.

Further analysis of the accumulative particle mass percentage shows distinct patterns for Phase 1 to Phase 3. 99% of the accumulated particle mass in supernatant were reached at 138 μm, 422 μm, and 224 μm, in Phase 1, Phase 2, and Phase 3, respectively. Accumulated particle mass calculation was sensitive to the number of particles with larger diameters, making the calculation a sensitive tool to evaluate the presence of larger activated sludge flocs at longer SRT. In regard to particle number in mixed liquor, however, Figure 2-7 showed at least 99.5% of flocs in all phases were smaller than 100 μm and at least 91.7% of flocs in all phases were smaller than 10 μm. It was noticed that at SRT of 13.3 days in Phase 2, the number of small particles less than 2 μm are close to that at SRT of 4 days in Phase 3. This finding suggested that when SRT was switched from SRT of 13.3 days in Phase 2 to 4.0 days in Phase 3, unlike accumulated particle mass percentage, the accumulated particle number percentage was not radically changed especially for particles smaller than 2 μm (Figure 2-6 and Figure 2-7).

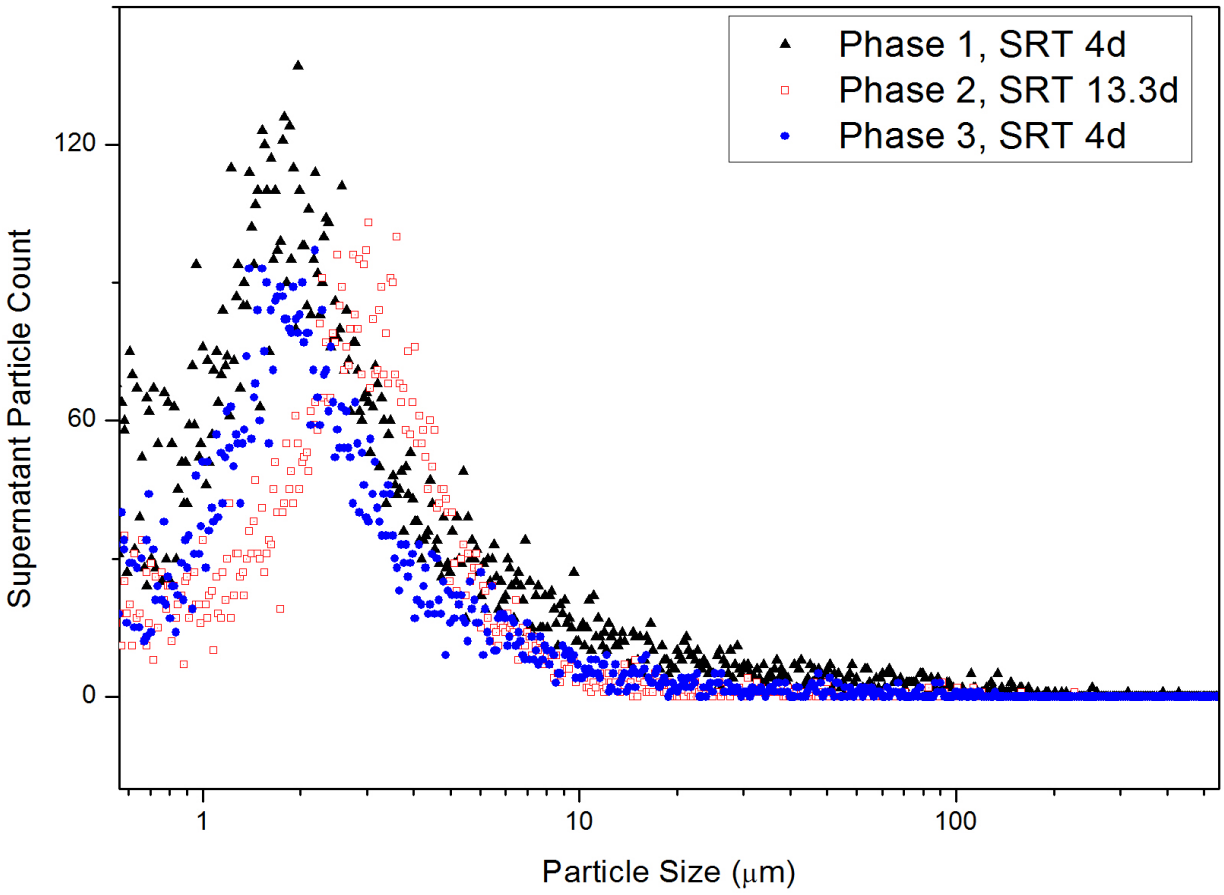

Figure 2-5. Particle size distribution in mixed liquor supernatant samples after 90 min sedimentation in Phases 1, 2 and 3. Average values are reported for at least three sampling events for each phase.

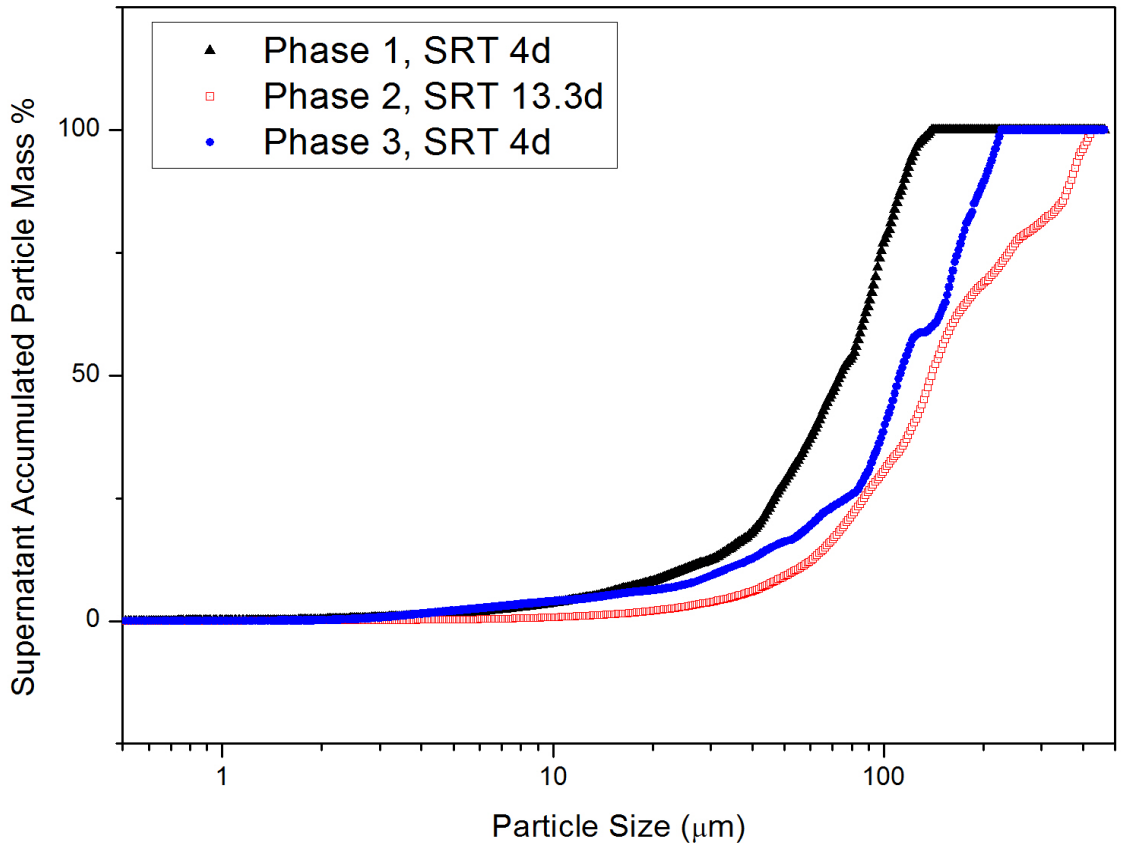

Figure 2-6. Accumulative Particle Mass % in supernatant of mixed liquor samples after 90 min sedimentation in Phases 1, 2 and 3.

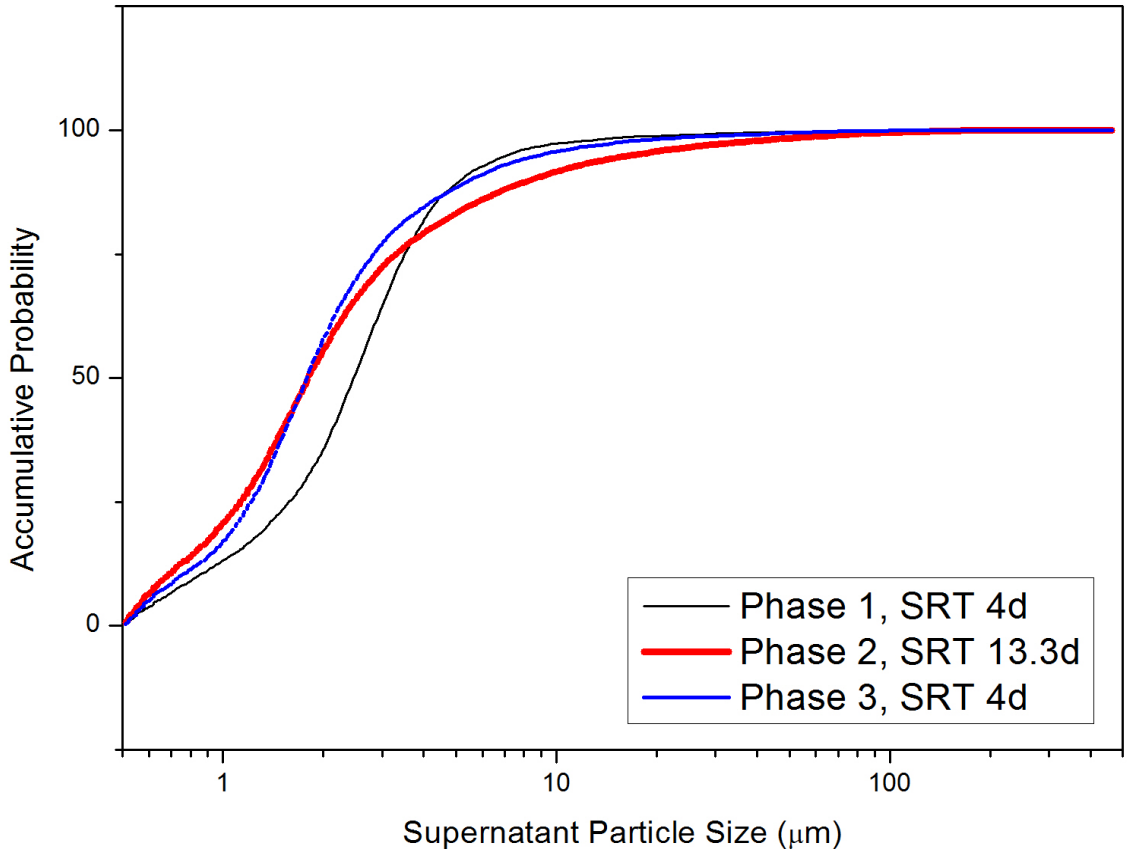

Figure 2-7. Accumulated probability of particle number in supernatant of mixed liquor samples after 90 min sedimentation in Phases 1, 2 and 3.

2.4 Discussion

In this study a lab-scale MLE reactor was established to evaluate the impact on reactor performance and activated sludge properties. Particle size is an important property of activated sludge which may impact sludge dewaterability (Karr and Keinath 1978, Knocke and Zentkovich 1986, Wisniewski and Grasmick 1998, Jin, Wilen et al. 2004), control oxygen transfer efficiency (Knudson, Williamson et al. 1982, Starkey and Karr 1984), and provide useful information for the

design of disinfection process (Parker and Darby 1995, Loge, Emerick et al. 2002, Templeton, Andrews et al. 2005, Kollu and Ormeci 2012).

Results in this study showed immediate impact of SRT on the particle size distribution in the mixed liquor of the MLE reactor. With the increase of SRT from 4 days to 13.3 days, the mean particle sizes at cut-off values of 50 μm, 100 μm, 200 μm, 300 μm, 400 μm, and 500 μm increased by 40.0%, 38.6%, 136.9%, 141.5%, and 154.6%, as shown in **Table 2-2**. The mean particle size data indicated that increased SRT had more significant impact on the generation of larger flocs. Similar findings are observed in previous field studies. Bisogni and Lawrence observed the decrease of small activated sludge flocs with increase SRT (Bisogni and Lawrence 1971). Knocke and Zentkovich observed a significant increase of activated sludge floc size when SRT was increased from 4 days to 8 days, but with no further increase when SRT was increased from 8 days to 15 days (Knocke and Zentkovich 1986). Settling test with activated sludge with sludge ages ranging from 0.25 days to 12 days shows that percent dispersion (nonflocculent or pin point floc) decreased exponentially with increased SRTs. Recent survey of particle size distribution at the end of treatment chain in conventional activated sludge process, high purity oxygen process, MLE process, step-anoxic process, and oxidation ditch process shows that mean particle size of activated sludge flocs increased with increasing SRT, and the number of particles in the sedimentation supernatant decreased with longer SRT (Leu, Chan et al. 2012). The current study under well controlled lab-scale reactor showed that SRT was an important parameter affecting particle size distribution in activated sludge process. Both increase and decrease of SRT seems to have an immediate effect on the particle size distribution in the mixed liquor.

Consequently, the particle size distribution of a certain activated sludge system may be used as an indicator of proper SRT control of sludge wasting, which is sometimes not well controlled by wasting thickened waste activated sludge.

Effluent particle may be a particular concern for secondary effluent disinfection. In this study SRT had influence on particle size and particle counts of supernatant samples of mixed liquor. Supernatant samples after 90 min sedimentation were collected for analysis. The distribution of accumulated particle mass percentage and particle number percentage from 0.5 μm to 500 μm were calculated. As shown in **Figure 2-6**, three distinct patterns of accumulated particle mass percentage in supernatant samples at Phase 1, Phase 2 and Phase 3 indicated that SRT has significant impact on the characteristics of activated sludge in regard to quantity of biomass in effluent. **Figure 2-7** on the other hand showed the accumulated particle number percentage of flocs with diameter from from 0.5 μm to 500 μm. The change of supernatant particle size distribution may likely require adjusting parameters for secondary effluent disinfection. For instance, an early study demonstrated shielding effect from Ultraviolet light disinfection (Parker and Darby 1995). In that study particle-associated total coliforms were significantly protected from UV radiation compared with free swimming coliforms. In addition, aggregated coliforms on and in particles posed a difficulty of accurate numeration of accurate number of coliforms in liquid samples. Effluent samples with low coliform counts (e.g. 0.8/100 mL) revealed significant increase of coliform counts after blending for 1.5 minutes at 19,000 rpm. The increase of coliform density was likely due to fragmentation of large particulates. A recent study of secondary effluent disinfection showed that only at high UV doses and for larger particles the shielding effect of

particles and bioflocculation on UV disinfection of E. coli was statistically significant, after the majority of free swimming bacteria were inactivated. In addition, flocculation may lead to better inactivation of E. coli, which was likely contributed by decreased scattering of light (Kollu and Ormeci 2012). In our study, effluent turbidity effluent turbidity decreased from 22.3±2.3 NTU to 7.5±4.3 NTU after SRT increased from 4 days to 13.3 days (**Figure 2-3** and **Figure 2-4**). Meanwhile, larger particles size and less numbers were observed (**Figure 2-5**). Findings in current study together with previous research suggest that operating at longer SRT of MLE reactor may produce secondary effluent with larger and fewer particles, which could be beneficial for secondary effluent disinfection using UV radiation.

Producing well settled activated sludge is crucial for successful operation of activated sludge process. Different parameters have been developed to characterize sludge properties in terms of SVI, organic loading, sludge retention time, composition, and content of polymers, density, porosity, viscosity, and particle size distribution (Hilligardt and Hoffmann 1997). In this study effluent turbidity and sludge SVI was constantly measured. Studies found that large flocs had a lower density and larger surface area. Higher SVI was observed with increasing floc size (Andreadakis 1993). Representative floc images of activated sludge samples along with MPS and SVI during Phase 1, Phase 2, and Phase 3 of MLE reactor operation was shown in **Figure 2-8**. Activated sludge flocs showed a more compacted pattern with more diverse ecology was observed after SRT increased from 4 days to 13.3 days. Previous research using quantitative image analysis demonstrated good prediction of sludge SVI based on morphological characteristics using partial least squares regression multivariable statistical technique. Although statistical image analysis

was not develop in current study, the change of activated sludge floc morphology indicated that operating at longer SRT could produce compacted sludge flocs with lower SVI.

A key aspect of the operation of activated sludge systems is the dewatering of the biological solids. Dewatering step is usually necessary to reduce sludge volume and facilitate transport and handling and to minimize the space and energy needed in landfill, land application, or incineration (Jin, Wilen et al. 2004). The water content of activated sludge can be grouped to free water and bound water. Free water can be remove by thickening and behaves as liquid water thermodynamically. Bound water can be divided into chemically or physically bound water and mechanically bound water. Chemically or physically bound water is the water that can only be removed by thermal evaporation above 105 ˚C. Mechanically bound water is bound by capillary forces in floc structures. Particle size of activated sludge have significant effect on sludge dewaterability (Karr and Keinath 1978). Kozeny-Carman equation has been used to describe the function of particle size in filtration resistance, which indicates that sludge filterability decreased with decreasing particle size (Sorensen, Christensen et al. 1995). Researchers also observed the relationship between particle size, filtration resistance, and solids retention time in both lab-scale reactors and full-scale WWTPs (Knocke and Zentkovich 1986). Solids retention time could affect dewaterability of activated sludge by determining the size of sludge particles in the system. In a later study where particle size was purposely controlled by recirculation in a membrane bioreactor (MBR), initial hydraulic resistance obtained from three set of sludge samples with different mean particle size indicated that larger particles generated less resistance initially, but build up the resistance quicker than smaller particles (Wisniewski and Grasmick 1998). The study also

revealed the contribution of soluble fraction of mixed liquor to total filtration resistance. 52% of filtration resistance generated from soluble fraction of supracolloidal-colloidal substances. Supracolloidal particles in the range of 1 μm to 100 μm were reported to be particularly resistant to be dewatered(Higgins and Novak 1997). Another study suggested that bound water contents decreased as floc size increased from 20 μm to 100 μm (Liao, Allen et al. 2001). Previous study indicated that increased activated sludge floc size may be beneficial sludge dewatering. In the current study, as SRT of the MLE reactor increases from 4 days to 13.3 days, MPS at 50 μm, 100 μm, and 500 μm cut-off values increased from 7.9±0.5 μm, 25.1±2.8 μm, and 34.3±1.2 μm to 26.9±7.8 μm, 50.0±10.0 μm, and 71.8±14.7 μm, respectively. Although dewaterability test was not developed in the current study, it was reasonable to speculate that the increase of SRT from 4 days to 13.3 days improved sludge dewaterability.

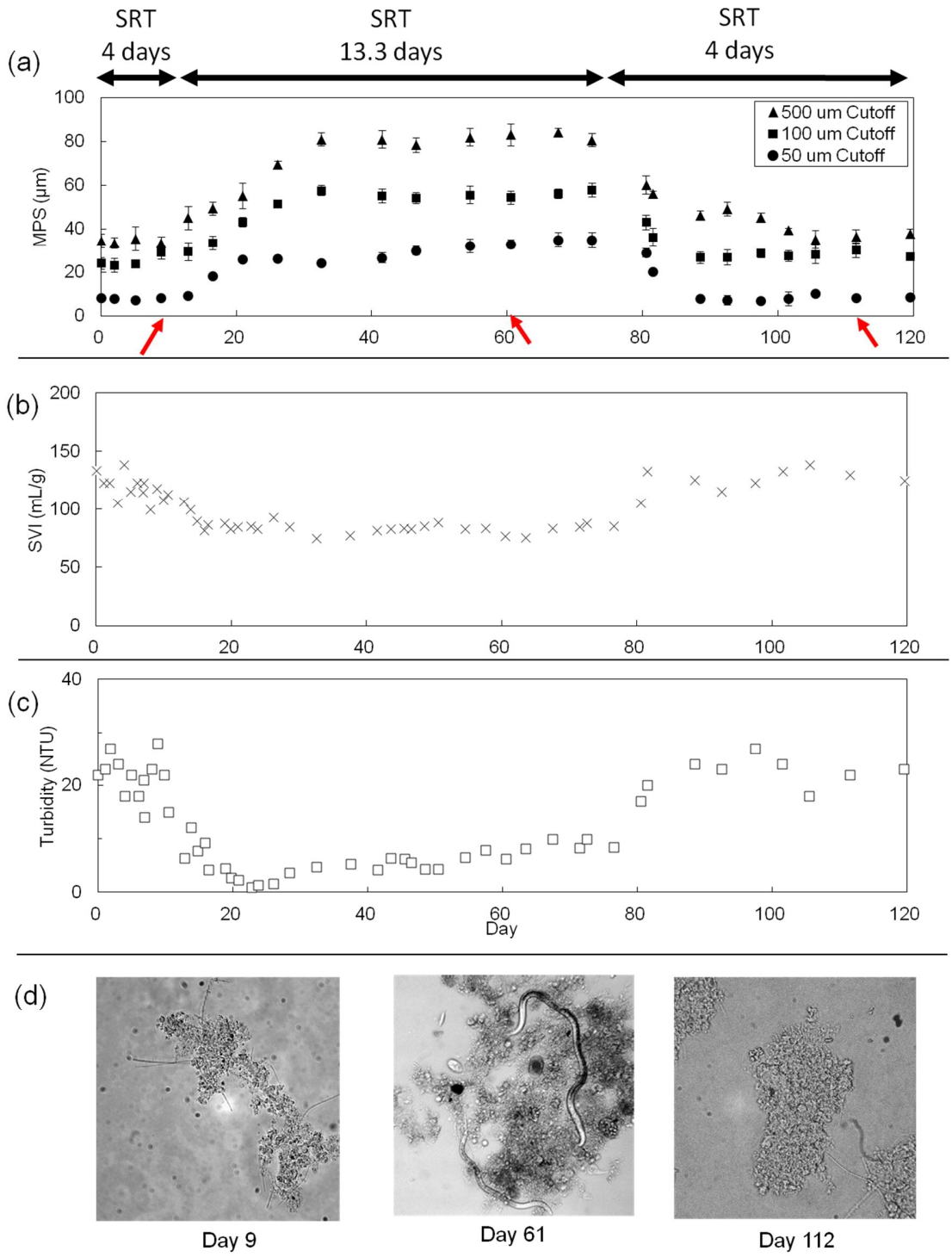

Figure 2-8. MPS, SVI, and representative floc images of the activated sludge in MLE reactor. (a) MPS of mixed liquor, (b) SVI of activated sludge sample after 30 min sedimentation, (c) effluent turbidity, and (d) representative floc images of activated sludge mixed liquor samples collected on Day 10, Day 61, and Day 112.

2.5 Conclusion

Chapter 2 investigated the impact of SRT on the MLE reactor performance, sludge settleability, and activated sludge floc size distribution.

(1) Change of SRT had immediate impact on the MPS of mixed liquor. SRT at 13.3 days produced activated sludge with larger floc size compared with that at SRT of 4 days. As SRT of the MLE reactor increases from 4 days to 13.3 days, mean particle size (MPS) at 50 μm, 100 μm, and 500 μm cut-off values increased from 7.9±0.5 μm, 25.1±2.8 μm, and 34.3±1.2 μm to 26.9±7.8 μm, 50.0±10.0 μm, and 71.8±14.7 μm, respectively. After SRT was decreased from 13.3 days to 4 days, MPS of the reactor at 50 μm, 100 μm, and 500 μm cut-off values gradually decreased from 26.9±7.8 μm, 50.0±10.0 μm, and 71.8±14.7 μm to 11.8±7.6 μm, 30.5±5.6 μm, and 45.2±8.8 μm. The increase of MPS may indicate improved sludge dewaterability.

(2) Operating at SRT of 13.3 days yielded activated sludge with better settleability than that at SRT of 4 days. More compacted activated sludge flocs were observed under microscopy when the reactor was operated at SRT of 13.3 days.

(3) Operating at longer SRT produced better effluent quality in terms of effluent turbidity and COD removal. After SRT increased from 4 days to 13.3 days, effluent turbidity decreased from 22.3±2.3 NTU to 7.5±4.3 NTU. Meanwhile, effluent COD decreased from 37.3±9.0 mg/L to 26.9±5.7 mg/L. Shorten the SRT from 13.3 days to 4 days had reverse effects on effluent turbidity and COD removal. Particle size analysis of reactor effluent showed that fewer and larger particles existed in effluent at longer SRT, which was beneficial for the disinfection of secondary effluent.

Chapter 3 Impact of SRT and Carbon Sources on Particle Size Distribution and Reactor Performance in Integrated Fixed Film Activated Sludge (IFAS) Reactor

3.1 Introduction

Integrated Fixed Film Activated Sludge (IFAS) system allows expansion of treatment capacity without the need for construction of new reactors by adding free floating or stationary fixed film media to conventional activated sludge process. IFAS system was first developed in full-scale in 1996 (Randall and Sen 1996) as a process modification of the Moving Bed Biofilm Reactor (MBBR) (Rusten, Odegaard et al. 1992, Odegaard, Rusten et al. 1994, Odegaard 2006). Long generation cycle bacteria adhered on carrier media could decouple their growth rate from the SRT of the mixed liquor controlled by sludge wasting (van den Akker, Beard et al. 2010). IFAS system is particularly attractive for nitrogen removal by retaining slow-growing nitrifying microorganisms in biofilm otherwise would be washed out when SRT is not long enough for proliferating nitrifying bacteria. The carrier media also provides increased biomass inventory, thus allowing higher organic and hydraulic loading rates without requiring tank expansion(Tseng, Gonsior et al. 2013). These advantages make IFAS system a viable technology for wastewater plants upgrade, especially under land-constrained situation (Andreottola, Foladori et al. 2003, Sriwiriyarat and Randall 2005, Di Trapani, Mannina et al. 2010, Rosso, Lothman et al. 2011). IFAS system has been installed at full-scale WWTPs worldwide (Yerrell 2001, Odegaard 2006, Maas, Parker et al. 2008, Regmi, Thomas et al. 2011).

IFAS system has been evaluated by treatment performances and operating parameters and have several advantages. Studies showed that IFAS system provided enhanced and stable nitrogen and phosphorous removals (Randall and Sen 1996, Sriwiriyarat and Randall 2005, Stricker, Barrie et al. 2009, Onnis-Hayden, Majed et al. 2011). Aeration studies of IFAS and conventional activated sludge process indicated that the two processes had comparable standard oxygen transfer rate. However, the IFAS system may have a higher energy footprint which is associated with increased aeration intensity (Rosso, Lothman et al. 2011). IFAS system could sustain a wider range of C/N ratio with sufficient carbon and nitrogen removals (Xia, Li et al. 2008), while excessively high C/N ratio could lead to viscous bulking (van den Akker, Beard et al. 2010). Temperature is an important environmental parameter for biological nitrification in wastewater treatment. Specific growth rate of nitrifying bacteria in activated sludge may decrease by 86% when temperature decreased from normal temperature (25˚C-30˚C) to temperatures lower than 15˚C (Knowles, Downing et al. 1965, Antoniou, Hamilton et al. 1990). Several studies evaluated the influence of temperature on nitrification in IFAS systems. An early work comparing conventional biological nutrient removal (BNR) plant with two types of modified IFAS system under 10±1˚C showed that while complete nitrification was achieved by both IFAS and three-state BNR system, IFAS system provided enhanced biological phosphorus removal (EBPR) at high SRT and greater denitrification at moderate temperature (Sriwiriyarat and Randall 2005). Another pilot-scale study showed that nitrification rate by biofilm doubled nitrification rate by activated sludge with operating temperature near 11.5 ˚C in an IFAS reactor (Di Trapani, Christensso et al. 2011). Studies of MBBR system, similar to IFAS but without sludge recycle, demonstrated that

nitrifying biofilm could quickly adapt low temperature and recover ammonia removal rate (Zhang, Wang et al. 2013, Gilbert, Agrawal et al. 2014, Hoang, Delatolla et al. 2014).

Molecular technologies, e.g., real-time PCR, fluorescence *in situ* hybridization (FISH), denaturing gradient gel electrophoresis (DGGE), and terminal restriction fragment length polymorphism (T-RFLP) have been used to study nitrifying microbial communities in biological wastewater treatment (Mobarry, Wagner et al. 1996, Nicolaisen and Ramsing 2002, Harms, Layton et al. 2003, Siripong and Rittmann 2007). Relative abundances of AOB, NOB and denitrifying bacteria were evaluated in IFAS system by DGGE (Li, Li et al. 2012). FISH was used to evaluate the dynamics of nitrifying bacteria in IFAS or MBBR systems under different C/N ratios (Aoi, Miyoshi et al. 2000), at different depth of carrier biofilm (Chae, Rameshwar et al. 2008), between suspended biomass and biofilm (Onnis-Hayden, Majed et al. 2011), with different flow patterns (e.g., either continuous or sequencing-batch) (Bassin, Kleerebezem et al. 2012), under different influent ammonia loadings (Zhang, Wang et al. 2013), and reactor configurations (Mahendran, Lishman et al. 2012, Gilbert, Agrawal et al. 2015). Real-time PCR was commonly applied to quantify nitrifying microorganism in carrier biofilm (van den Akker, Beard et al. 2010, Kim, Schuler et al. 2011, Shore, M'Coy et al. 2012). Previous studies offered valuable insights of the dynamics of microbial community in IFAS.

While considerable research effort has focused on the wastewater treatment performance by IFAS system, the sludge characteristics of IFAS system has been less studied. Previous studies have generated mixed results on the settleability of activated sludge from IFAS systems (McQuarrie, Rutt et al. 2004, Sriwiriyarat, Ungkurarate et al. 2008). Studies on sludge production

and sludge settling characteristics indicated that IFAS produce less activated sludge with better sludge settling performance than conventional activated sludge (Ross 2004, Li, Zhu et al. 2015). Study shows that IFAS system tends to generate activated sludge with lower density due to reduced polyphosphate storage (Kim, Gellner et al. 2010). However, particle size distribution of suspended sludge when a reactor is converted from traditional activated sludge process to an IFAS system is unknown. More knowledge is needed to understand the impact of SRT and carbon sources on the floc size distribution and sludge settleability in IFAS system.

Chapter 3 studies the impact of SRT on particle size distribution, sludge settleability, effluent turbidity, and removals of COD, NH4+-N, in a lab-scale Integrated Fixed Film Activated Sludge (IFAS) reactor. Chapter 3 further investigates the impact of difference carbon sources (Glucose vs. Sodium Acetate) on particle size distribution and reactor performance in the IFAS reactor. Settling test, water quality analyses, and microscopic examination are applied to evaluate the impact of different SRTs. Particle size distribution of the mixed liquor in the IFAS reactor is compared with that in MLE reactor operated at similar SRTs for suspended solids.

3.2 Materials and Methods

3.2.1 Reactor Set-up

The experiment was conducted in a lab-scale IFAS reactor for 260 days in a temperature control room. The rectangular reactor was 50 cm height, 25 cm length and 20 cm width with a working volume of 20 L. The reactor was inoculated with activated sludge from a conventional

municipal wastewater treatment plant. Polyethylene carriers with a density of 0.95–0.98 kg/m^3 and a specific surface area of 500 m^2/m^3 were added into the reactor. The carrier is a cylindrical shape with 8 mm height and 12 mm diameter. The reactor was filled with 4 L carriers to achieve a filling fraction of 20%. Influent was automatically pumped into the reactor at the flow rate of 2 L/h with a theoretical hydraulic retention time of 10 h. A settler was placed after the reactor for sludge separation. A peristaltic pump provided 0.6L/h of returned activated sludge (RAS) to the inlet of the rectangular reactor tank. Solids retention time (SRT) was controlled at 18 days by wasting appropriate amount of activated sludge from the settler. Synthetic influent was prepared using the following receipt: 350mg/L Glucose, 150 mg/L NH_4Cl, 55 mg/L K_2HPO_4, 20 mg/L $CaCl_2 \cdot 2H_2O$, 20 mg/L$MgSO_4 \cdot 7H_2O$, 10 mg/L $FeSO_4 \cdot 7H_2O$, 20 mg/L $MnSO_4 \cdot H2O$, and 20 mg/L KCl. Information about trace elements is available elsewhere (Chae, Rameshwar et al. 2008). pH of the mixed liquor was maintained approximately at 7.6 by adding $NaHCO_3$ solution. The reactor was aerated using filtered ambient air. The dissolved oxygen (DO) concentration in mixed liquor was maintained 3.5 ± 0.5 mg/L. Seeding activated sludge sample was collected from the Joint Water Pollutant Control Plant. 50 mL activated sludge from the Donald C. Tillman Water Reclamation Plant was seeded on Day 31 as additional source of nitrification microorganisms. Temperature, pH and DO were recorded using oxygen and pH meters. Concentrations of COD, ammonium, nitrite and nitrate were measured using HACH® kits and electrodes in compliance with the US Environmental Protection Administration (US EPA) Standard Methods.

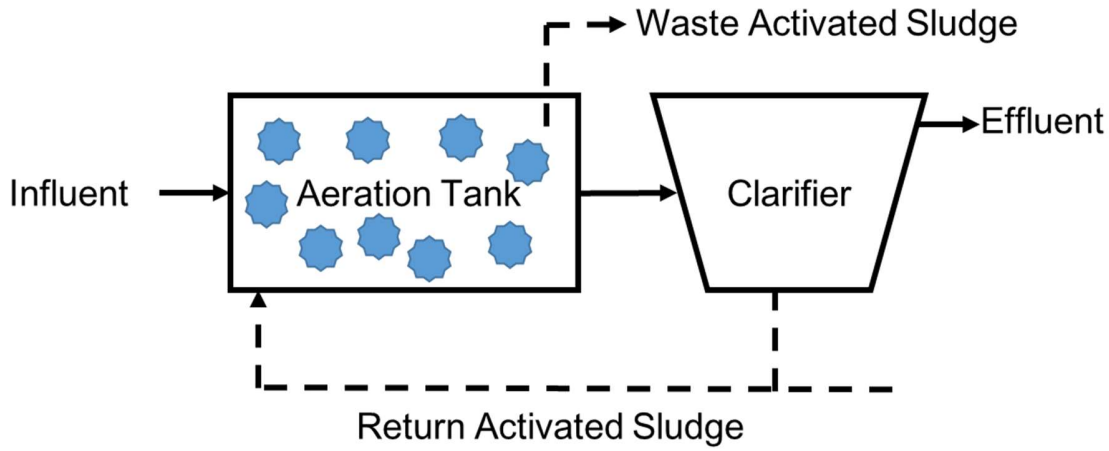

Figure 3-1. Schematics of the lab-scale IFAS reactor.

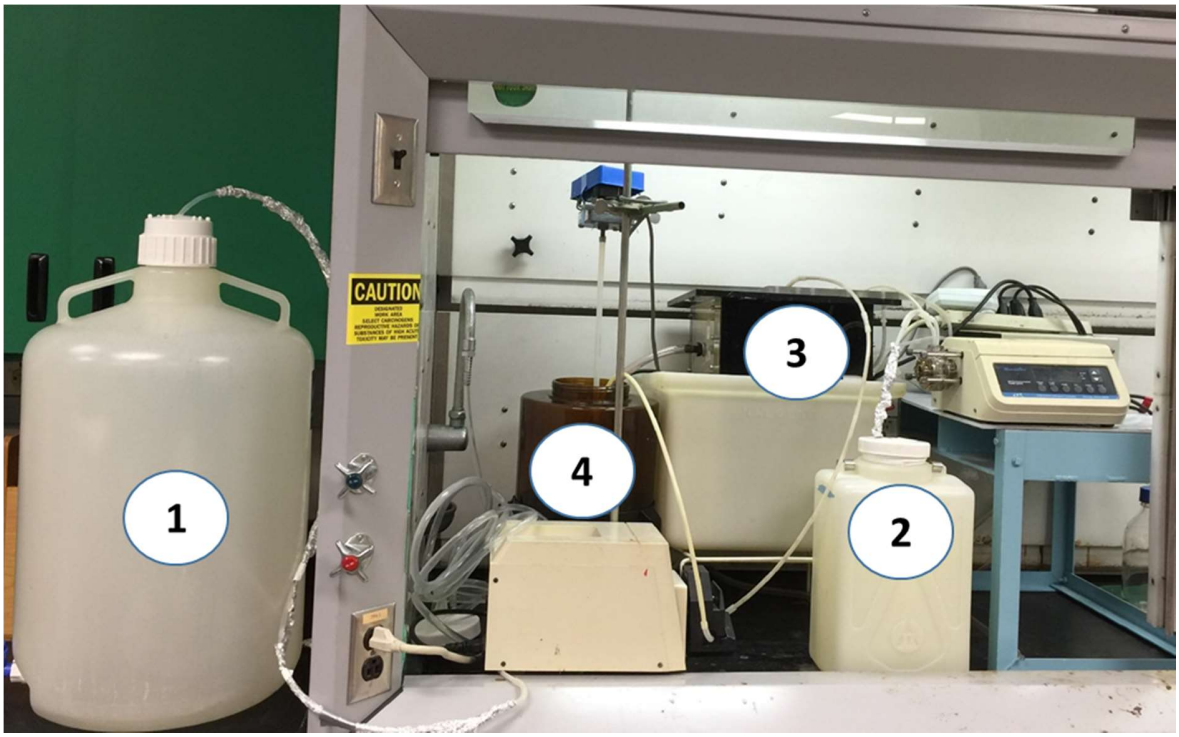

Figure 3-2. Illustration of the lab-scale IFAS reactor. 1) Inorganic solution storage tank, 2) organic solution storage tank, 3) IFAS tank, 4) sedimentation tank.

3.2.2 Sample Collection

Influent sample were collected at the combined inlet tube with 50 mL sample volume. Ammonia concentration and pH of influent samples were analyzed immediately after sample

collection. Influent DO concentrations in the storage tanks of inorganic and organic solutions (**Figure 3-2**) were measured directly using a DO probe. The influent DO concentration were calculated based on pump rate of inorganic and organic solutions and their representative DO concentrations.

Effluent samples were collected at the top layer of supernatant in the sedimentation tank. Care was taken to prevent disturbing the sludge blanket at the bottom of the sedimentation tank. Occasionally, a thin layer of floating activated sludge was observed at the top of the supernatant in the sedimentation tank. In this case, a pipette was used to collect the supernatant and minimize the inclusion of the floating activated sludge. Concentrations of ammonia, pH, turbidity and DO in effluent samples were measured immediately after sample collection. Samples reserved for COD analysis were acidified to pH of 2 and preserved at 4˚C in amber glass bottles.

3.2.3 Analysis of Particle Size Distribution

The PSD analysis was performed using an AccuSizer 780 optical particle sizer module (model LE400-0.5SE; Nicomp Particle Sizing Systems, Santa Barbra, California). The range of detection was set at 0.5 μm to 500 μm. For each experiment, 0.5 mL of liquid sample was delivered to the system by a customized wide-bore pipette (Chan, Leu et al. 2011). Between each PSD test, three auto-flush cycles were performed to ensure clean dilution chamber, system tubing, and sensor. Blank sample (reverse osmosis water) was used to check system baseline after every 15 sample injections. The sample method of mean particle size calculation were used as described in Chapter 2 and Appendix A.

3.3 Results

The reactor was originally operated as a conventional activated sludge process before converting to an IFAS reactor on Day 10. Reactor performance was stabilized prior Phase 1. The operational parameters are summarized in **Table 3-1Table 2-1**. Influent DO, COD, NH_4^+-N and pH were maintained relatively stabled through Phase 1 to Phase 5. The impacts of converting the reactor from traditional activated sludge process to IFAS were evaluated in Phase 1 and Phase 2 and were shown in **Figure 3-3**. The increased and sustained removal of ammonia indicated the development of nitrifying biofilm on IFAS carriers. It was worth noting that effluent turbidity increased from 12.5±3.5 NTU to 20.2±3.8 NTU from Phase 1 to Phase 2. Sludge settleability slightly decreased as SVI increased from 86.5±1.7 mL/g to 117.1±19.1 mL/g. Immediately after adding carriers on Day 10, an increase of MPS at 500 μm cut-off values increased from 33.8 ±1.0 μm to 42.7 ± 4.0 μm. Meanwhile, the MPS at 50 μm and 100 μm cut-off values were relatively stable. Together with carriers, 100 mL of activated sludge from nitrification plant was also added to the reactor as a source of nitrifying microorganisms.

The impacts of SRT on IFAS reactor performance and sludge characteristics were evaluated in Phase 3 and Phase 4. SRT of the IFAS reactor was increased from 4 days in Phase 2 to 13.3 Days in Phase 3 and subsequently decreased to 4 days in Phase 4. As shown in **Figure 3-4**, COD removal was above 90% consistently. NH4+-N removal increased from about 40.0% to 84.4% as mixed liquor SRT increased to 13.3 days and decreased to about 53.8% after SRT reduced back to 4 days. It took about 42 days for the MPS of mixed liquor to stabilize, increasing from

8.4±0.5 μm, 27.7±1.3 μm, and 40.6±5.5 μm to 28.0±2.9 μm, 53.8±4.5 μm, and 77.0±9.2 μm for 50 μm, 100 μm, and 500 μm MPS cut-off values, respectively. To further test the impact of SRT on reactor performance, SRT of the IFAS reactor was changed from 13.3 days back to 4 days from Phase 3 to Phase 4. As expected, NH4+-N removal decreased from about 84.4%. to 53.8%. MPS of mixed liquor decreased from 28.0±2.9 μm, 53.8±4.5 μm, and 77.0±9.2 μm to 11.4±4.8 μm, 29.2±3.3 μm, and 46.3±3.3 μm to for 50 μm, 100 μm, and 500 μm MPS cut-off values, respectively. Effluent turbidity increased from 7.5±3.9 NTU to 17.7±2.5 NTU. A moderate increased of SVI from 92.6±11.6 mL/g to 111.8±4.6 mL/g was observed.

The impacts of switching carbon sources on IFAS reactor performance and particle size distribution were evaluated in Phase 5. **Figure 3-5** showed that after carbon source in the reactor influent was switched from glucose to sodium acetate, the COD removal efficiency decreased from 91% on Day 180 to 69% ON Day 182 and then increased and stabilized near 87%. NH4+-N removal rate was relatively stable at 54.7% compared with that in Phase 4 of 53.8%. Effluent turbidity increased significantly from 18.5 NTU on Day 180 to 51 on Day 184 and subsequently decreased and stabilized to 25.5±1.5 NTU. Sludge settleability suffered initially by the change of carbon source with highest SVI of 235 mL/g observed on Day 182. SVI in Phase 5 gradually decreased to 114.1±11.3 mL/g.

Converting the reactor from a conventional activated to an IFAS reactor generated more turbid effluent with decreased MPS of particles in supernatant. Supernatant samples of mixed liquor after 90 min of sedimentation were analyzed when the reactor was operated at the most stable condition based on reactor performances. This sedimentation time is equal to the retention

time of the sedimentation tank for the reactor at HRT of 12 hours. Use the supernatant instead of reactor effluent minimized the impact of potential confounders such flow pattern in sedimentation tank. As shown in **Figure 3-6**, an increase of particles with diameter less than 2μm was observed after the reactor was converted from conventional activated sludge reactor in Phase 1 to an IFAS reactor in Phase 2. **Table 3-2** indicated that converting to IFAS reactor lead an decrease of MPS from 15.1±1.1 μm, 26.5±1.1 μm, and 28.1±1.1 μm to 11.2±1.5 μm, 22.9±1.8 μm, and 44.6±1.4 μm for cut-off values of 50 μm, 100 μm, and 500 μm, respectively. Accumulated particle mass percentage and particle number percentage also proved that converting to IFAS reactor produced supernatant with more small particles than conventional activated sludge reactor.

SRT had significant impact on the particle size distribution of supernatant in an IFAS reactor. MPSs for cut-off values of 50 μm, 100 μm, and 500 μm in supernatant samples was shifted from 11.2±1.5 μm, 22.9±1.8 μm, 28.1±1.1 μm of Phase 2 to 24.4±0.8 μm, 37.3±1.2 μm, and 40.7±1.8 μm of Phase 3 when SRT increased from 4 days to 13.3 days (**Table 3-2**). The increase of larger supernatant particles was as well observed in **Figure 3-6**. When SRT is reduced from 13.3 days back to 4 days, a corresponding decrease of MPS in supernatant was expected. As shown in , the MPSs of supernatant at cut-off values of 50 μm, 100 μm, and 500 μm in a Phase 4 samples were 11.8±0.8 μm, 13.7±0.9 μm, and 13.7±2.9 μm. Switching of carbon source from glucose to sodium acetate slightly increased MPS of supernatant particles. MPSs for cut-off values of 50 μm, 100 μm, and 500 μm in supernatant samples changed from 11.8±0.8 μm, 13.7±0.9 μm, and 13.7±2.9 μm of Phase 4 to 12.9±1.0 μm, 16.2±1.1 μm, and 19.5±1.3 μm of Phase 5 (**Table 3-2**).

Further analysis of the accumulative particle mass percentage shows distinct patterns in

Phase 1 to Phase 5 (**Figure 3-7**). 99% of the accumulated particle mass in supernatant were reached at 301.5 μm, 112.6 μm, and 86.0 μm, 43.8 μm, and 120.5 μm in Phases 1 to 5, respectively. Accumulated particle mass calculation was sensitive to the number of particles with larger diameters, making the calculation a sensitive tool to evaluate the presence of larger activated sludge flocs at longer SRT. In regard to particle number in mixed liquor, **Figure 3-8** showed 99% of the accumulated particle numbers in supernatant were reached at 66.5 μm, 40.4 μm, 63.9 μm, 20.9 μm, and 23.5 μm in Phases 1 to 5, respectively. It was noticed that increasing of SRT from 4 days in Phase 2 to 13.3 days in Phase 3 significantly changed the effluent particle size distribution (**Figure 3-6**) and accumulated particle number percentage (**Figure 3-8**). Meanwhile, on average 5.1±1.2 particle counts larger than 100 μm were observed in the supernatant of Phase 3 during Day 105 to Day 143. In contrast to Phase 3, on average 41.0±2.8 particle counts larger than 100 μm were observed in the supernatant of Phase 3 during Day 1 to Day 10 in Phase 1. The lack of the abundance of larger particles than 100 μm may lead the observation that the accumulated particle mass percentage in Phase 3 increased faster than that of in Phase 1, although the mixed liquor SRT in Phase 3 was longer than that of in Phase 1. Continued IFAS reactor operation in Phase 4 generated increasing smaller particles as indicated in the fast increase of accumulated mass percent curve and accumulated number percent curves as shown in **Figure 3-7**. When the carbon source was switched from glucose to sodium acetate, effluent particles exhibited similar pattern of particles size distribution with slightly smaller particles as shown in **Figure 3-8**.

Table 3-1. The operating condition and performance of the IFAS reactor.

Reactor Operation and Performance	Phase (Duration in days)				
	Phase 1 (1-10)	Phase 2 (11-65)	Phase 3 (66-155)	Phase 4 (156-180)	Phase 5 (181-240)
Influent					
DO (mg/L)	3.48±0.05	3.36±0.15	3.39±0.20	3.43±0.24	3.42±0.22
COD (mg/L)	250 mg/L in synthetic wastewater using glucose as carbon source				250 mg/L in synthetic wastewater using NaOAc as carbon source
NH_4^+-N (mg/L)	43.0±1.4	41.4±1.7	40.5±1.7	41.8±1.4	40.9±1.4
pH	7.4±0.1	7.2±0.4	7.2±0.15	7.2±0.1	7.2±0.1
Mixed Liquor					
MLSS (mg/L)	2430±56	2380±308	2970±361	2050±134	2130±146
SVI (mL/g)	86.5±1.7	117.1±19.1	92.6±11.6	111.8±4.6	129.1±38.9
SRT (days)	4	4	13.3	4	4
Effluent					
COD (mg/L)	19.0±1.4	30.1±8.8	26.9±6.3	22.6±6.3	25.1±8.9
NH_4^+-N (mg/L)	40.5±1.9	24.1±6.2	6.6±4.8	18.5±1.6	19.3±1.7
DO (mg/L)	3.48±0.05	3.36±0.15	3.39±0.20	3.43±0.24	3.42±0.22
pH	7.37±0.1	7.1±0.3	7.2±0.1	7.2±0.1	7.2±0.1
Turbidity (NTU)	12.5±3.5	20.2±3.8	7.5±3.9	17.7±2.5	30.0±8.9

Table 3-2. MPS in mixed liquor supernatant samples after 90 min sedimentation at different operation conditions.

Phase \ Cut-off Values	50 μm	100 μm	200 μm	300 μm	500 μm
1	15.1±1.1	26.5±1.1	41.9±1.4	43.6±1.4	44.6±1.4
2	11.2±1.5	22.9±1.8	28.1±1.2	28.1±1.2	28.1±1.1
3	24.4±0.8	37.3±1.2	40.7±1.9	40.7±1.9	40.7±1.8
4	11.8±0.8	13.7±0.9	13.7±2.4	13.7±2.9	13.7±2.9
5	12.9±1.0	16.2±1.1	19.5±1.3	19.5±1.2	19.5±1.3

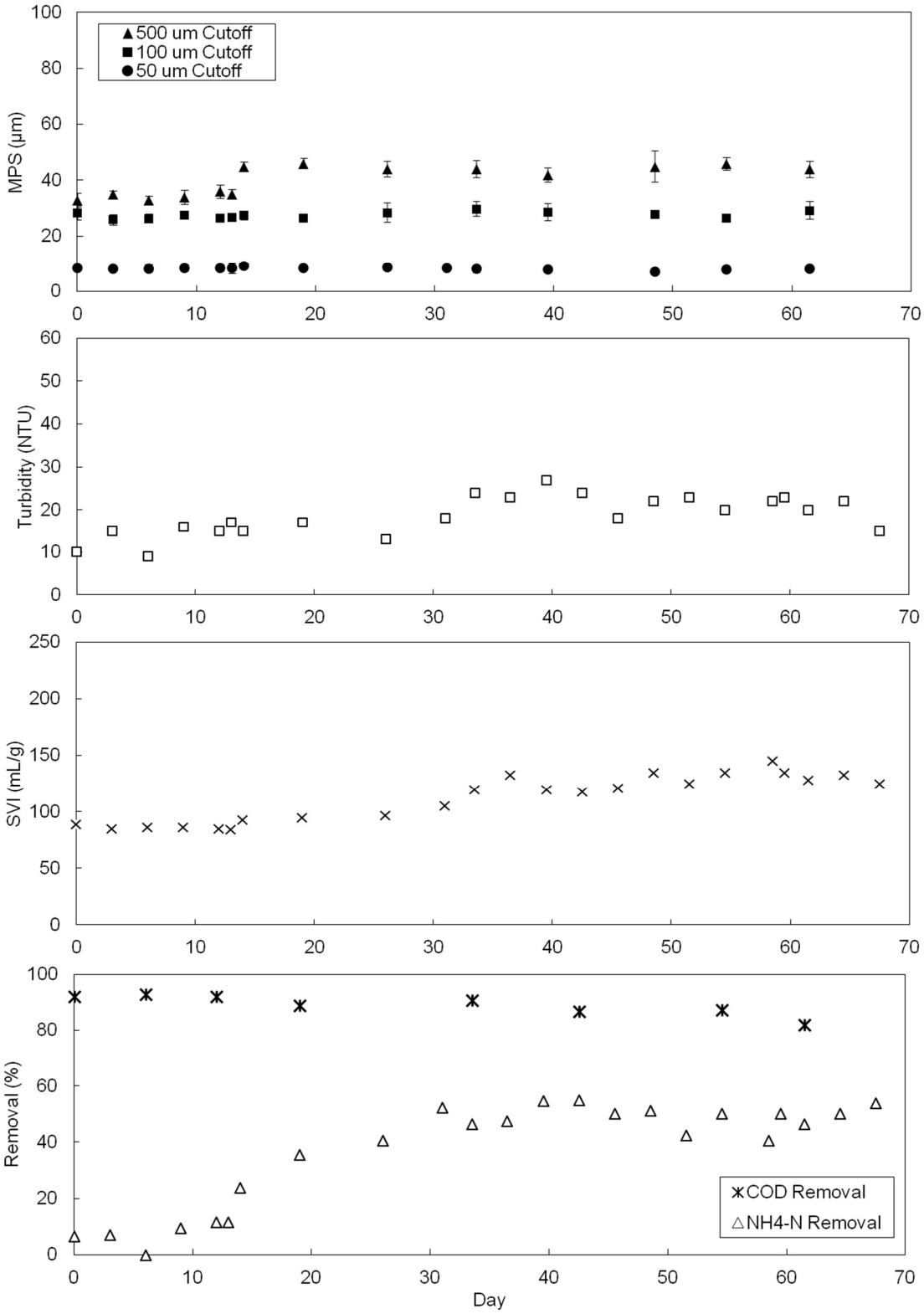

Figure 3-3. MPS, COD and ammonia removals, and effluent turbidity during Phase 1 and 2. Carriers were added to the system on Day 10.

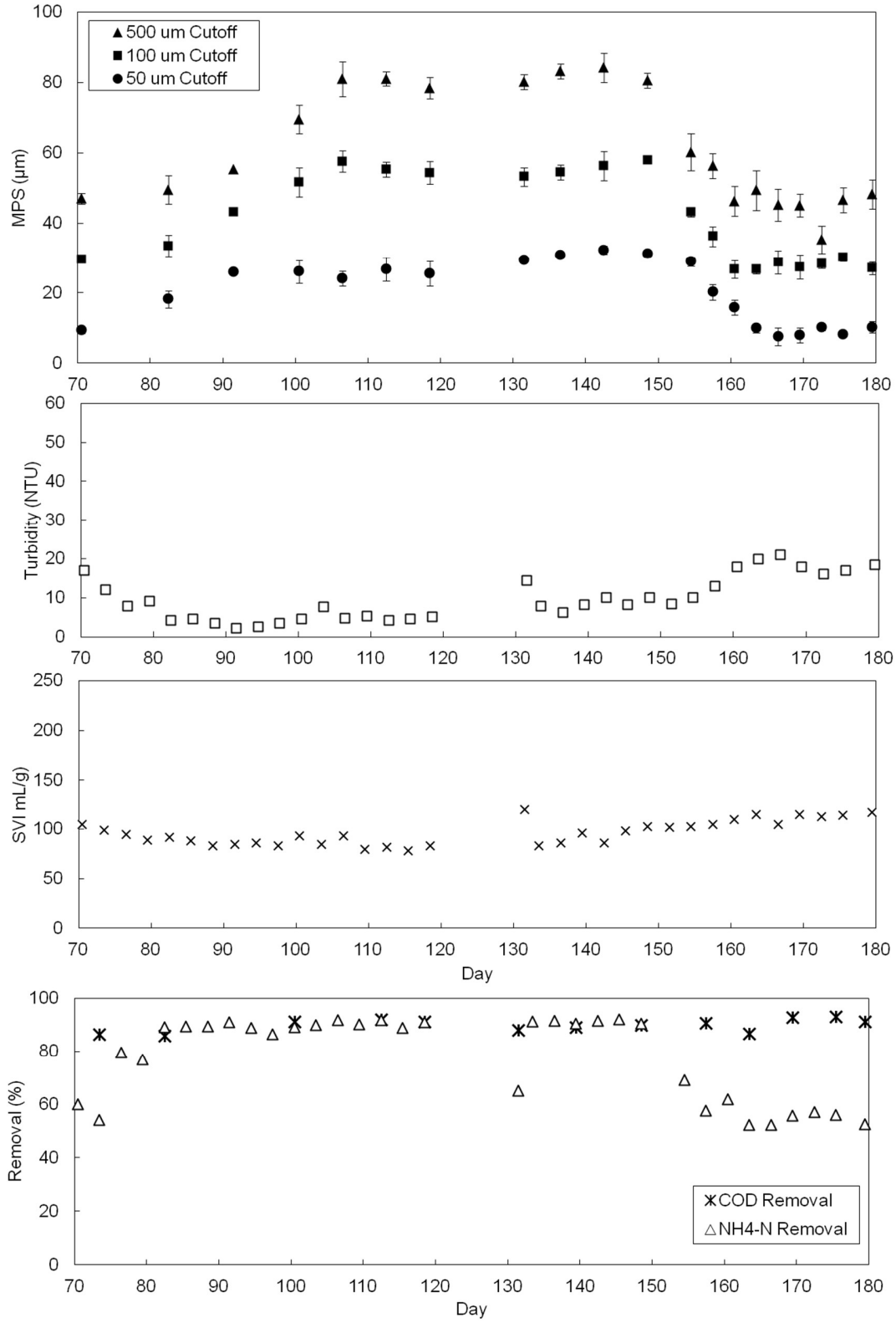

Figure 3-4. MPS, COD and ammonia removals, and effluent turbidity during Phase 3 and Phase 4.

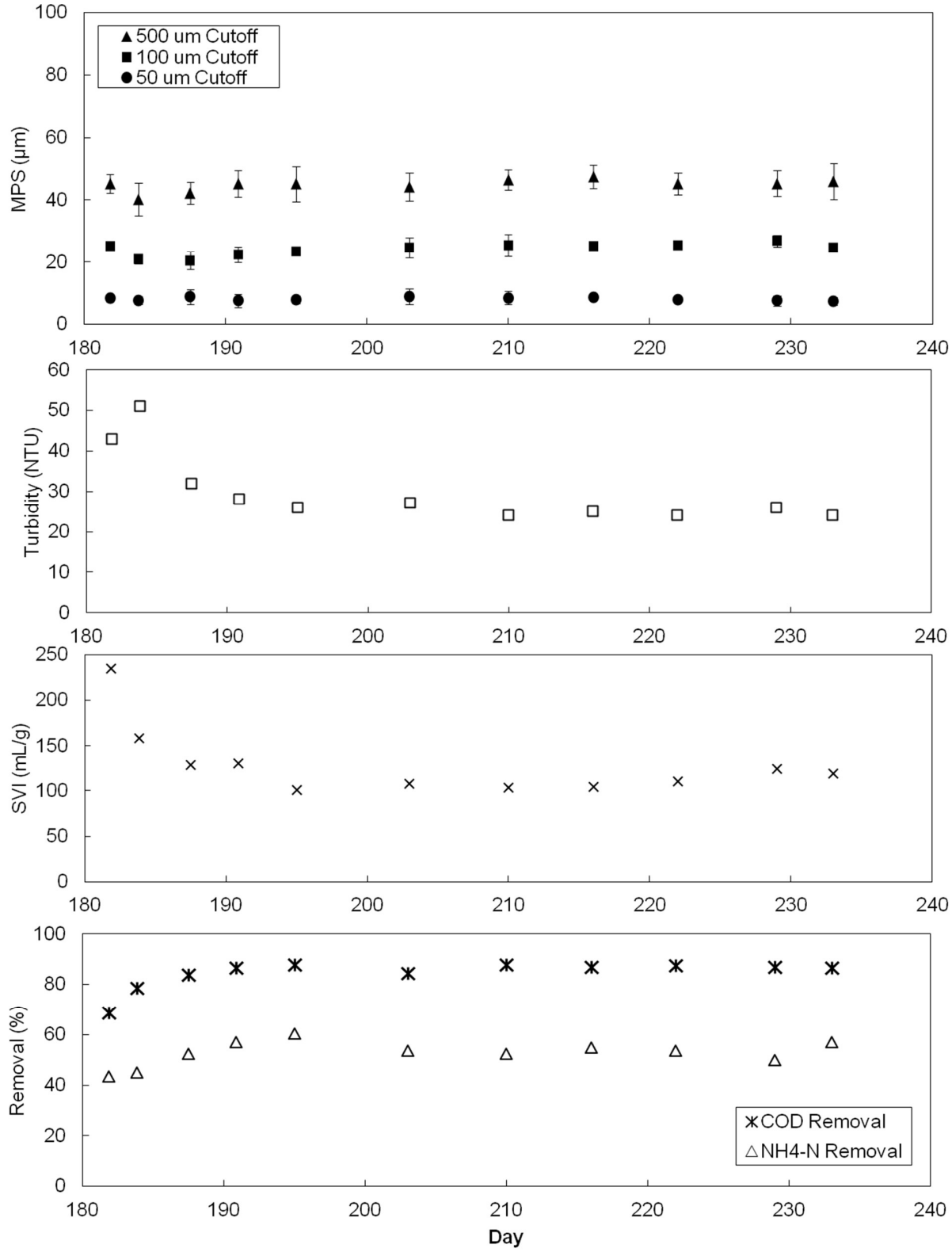

Figure 3-5. MPS, COD and ammonia removals, and effluent turbidity during Phase 5.

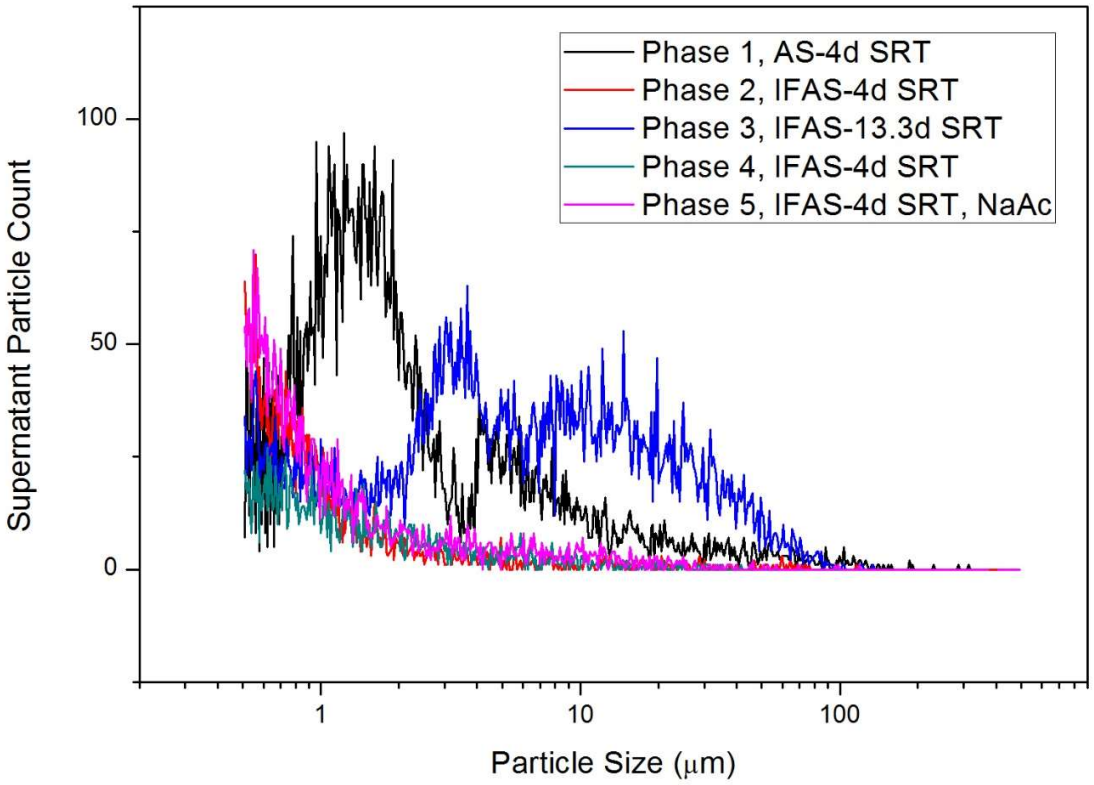

Figure 3-6. Particle size distribution in mixed liquor supernatant samples after 90 min sedimentation of mixed liquor samples collected in different phases.

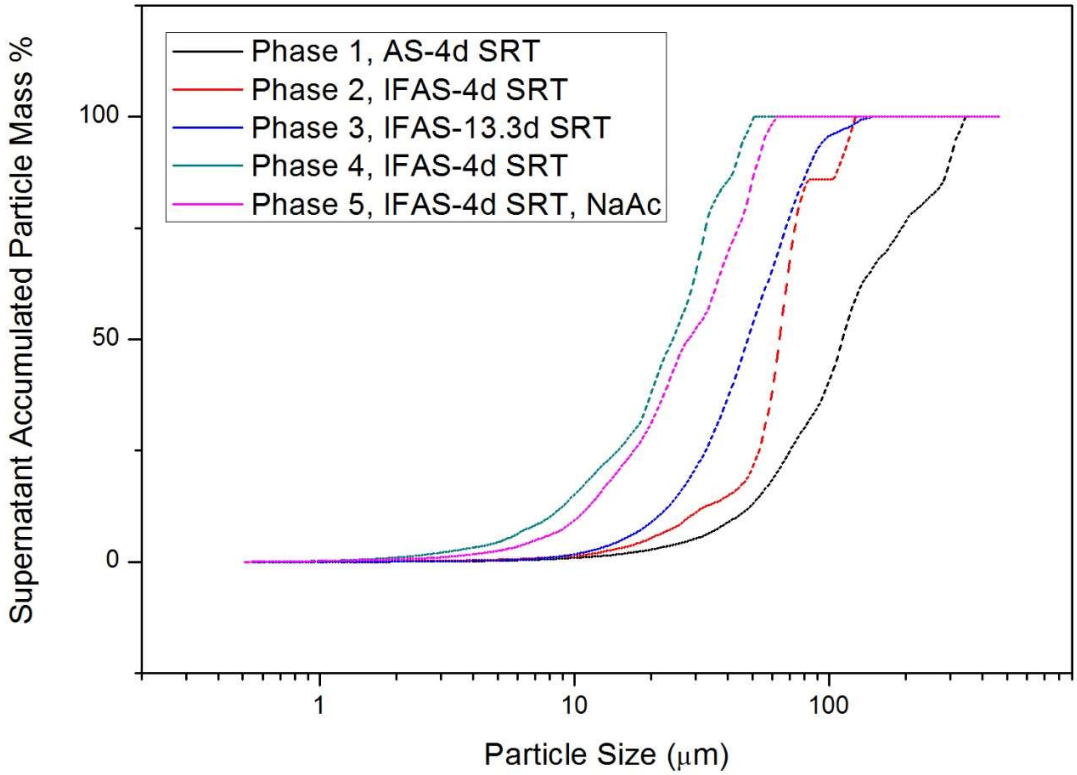

Figure 3-7. Accumulative Particle Mass % in supernatant of mixed liquor samples after 90 min sedimentation of mixed liquor samples collected in different phases.

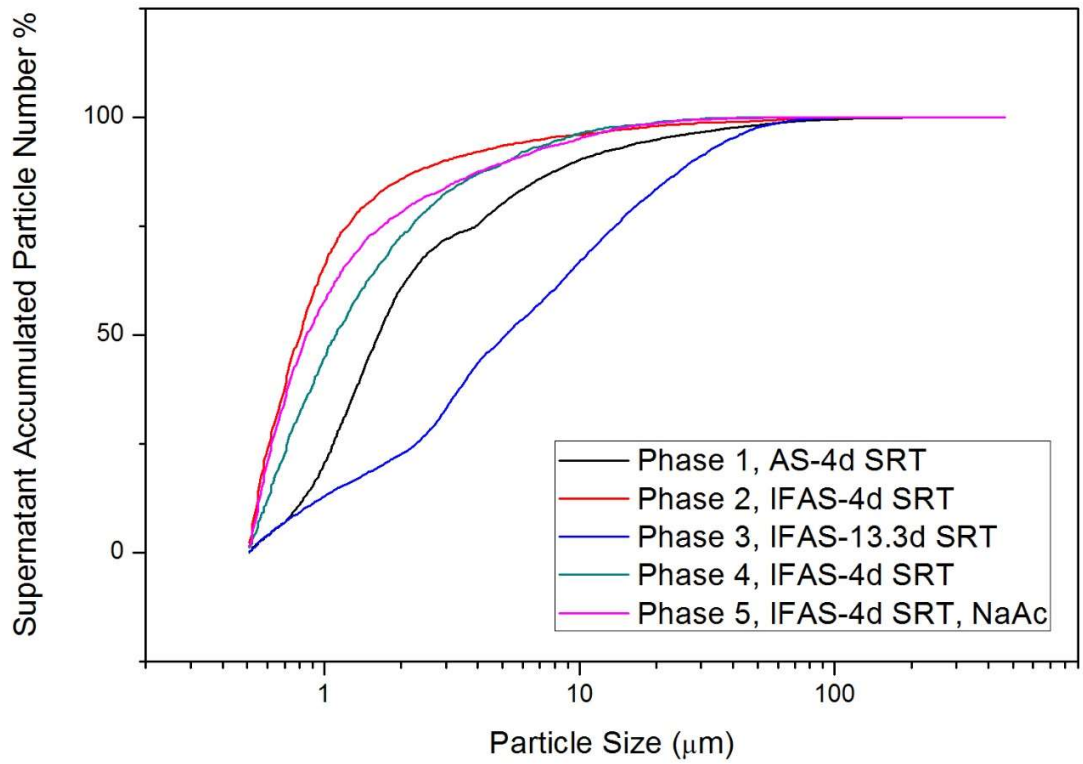

Figure 3-8. Accumulated Particle Number % in supernatant of mixed liquor samples after 90 min sedimentation in different phases.

3.4 Discussion

In this study a conventional activated sludge reactor was converted to an IFAS reactor. Reactor performances, particles size distribution of mixed liquor and reactor effluent, sludge settleability were evaluated under different reactor types, SRTs, and carbon sources.

The impact of mixed liquor SRT of the IFAS reactor on the particle size distribution was evaluated. After the increase of SRT from 4 days to 13.3 days, MPS of mixed liquor at cut-off values of 50 μm, 100 μm, and 500 μm increased in 42 days from 8.4±0.5 μm, 27.7±1.3 μm, and 40.6±5.5 μm to 28.0±2.9 μm, 53.8±4.5 μm, and 77.0±9.2 μm for 50 μm, 100 μm, and 500 μm MPS

cut-off values, respectively. The increase of MPS with increased SRT was observed in a MLE reactor in Chapter 2 as well as by other researchers. Bisogni and Lawrence observed the decrease of small activated sludge flocs with increase SRT (Bisogni and Lawrence 1971). Knocke and Zentkovich observed a significant increase of activated sludge floc size when SRT was increased from 4 days to 8 days, but with no further increase when SRT was increased from 8 days to 15 days (Knocke and Zentkovich 1986). Decrease of SRT from 13.3 days to 4 days had an immediate effect on the particle size distribution in the mixed liquor. When the IFAS reactor was stabilized at SRT of 4 days again in Phase 4, the MPS decreased back to similar values as in Phase 2.

Sludge settleability is an important parameter for activated sludge process control (Hilligardt and Hoffmann 1997).. Previous studies have generated mixed results on the settleability of activated sludge from IFAS systems (McQuarrie, Rutt et al. 2004, Sriwiriyarat, Ungkurarate et al. 2008). Full-scale test of an IFAS reactor showed improved sludge settleability with improved nitrogen removal (McQuarrie, Rutt et al. 2004). Another full-scale study indicated that IFAS reactor provided more stable ammonia removal at low temperature, sludge settleability was slight increased (Stricker, Barrie et al. 2007). Studies on sludge production and sludge settling characteristics indicated that IFAS produce less activated sludge with better sludge settling performance than conventional activated sludge (Ross 2004, Li, Zhu et al. 2015). No obvious difference of sludge settleability was observed between a MLE reactor and an IFAS reactor under different C/N ratio and DO concentrations (Sriwiriyarat, Ungkurarate et al. 2008). However, another study suggested that MLE reactor produced sludge with lower SVI values (Kim, Gellner et al. 2010). As shown in

Table 3-1, sludge SVI values increased moderately from 86.5±1.7 mL/g in Phase 1 to 117.1±19.1 mL/g in Phase 2. Our study supported the observation that IFAS reactor generated sludge with good settleability but slight higher SVI values compared with sludge generated from MLE reactor. Sludge with good settleability was defined as SVI less than 150 mL/g (David Jenkins 2003). Increased of SRT from 4 days in Phase 2 to 13.3 days in Phase 3 led an decrease of SVI from 117.1±19.1 mL/g to 92.6±11.6 mL/g. Subsequent decrease of SRT back to 4 days increased the SVI to 111.8±4.6 mL/g. It has been observed that the SVI is related to the median floc size for non-filamentous sludge (Barber and Veenstra 1986, Andreadakis 1993). It was also observed that Higher SVI was associated with lower activated sludge density at longer SRT in IFAS system, when biomass phosphorus content was low (Kim, Gellner et al. 2010). Our observations, however, suggested that increased SRT in the IFAS reactor improved sludge settleability. It was possible that the phosphate was not a limiting factor in this study since sodium bisphosphate was used as a receipt of buffer. Increase of SRT was expected to produce higher ratio of nonvolatile materials which has been linked with higher sludge density (Ekama and Wentzel 2004, Schuler and Jang 2007).

Particle size distribution is worth to study since it may affect efficacy of secondary effluent disinfection. As shown in **Figure 3-6**, an increase of particles with diameter less than 2μm was observed after the reactor was converted from conventional activated sludge reactor in Phase 1 to an IFAS reactor in Phase 2. The impact of SRT on particle size distribution and particle counts of

supernatant samples was evaluated during Phase 2 to 4. Findings in current study suggested that 1) operating as an IFAS reactor might produce secondary effluent with decreased mean particles size compared with a conventional activated sludge reactor with the same mixed liquor SRT and 2) increased of mixed liquor SRT of an IFAS reactor would reduce the present of particles smaller than 2 μm. The change of supernatant particle size distribution may likely require adjusting parameters for secondary effluent disinfection. For example, shielding effect would reduce the radiation intensity of ultraviolet light where article-associated total coliforms were significantly protected from UV radiation compared with free swimming coliforms (Parker and Darby 1995). In addition, aggregated coliforms on and in particles posed a difficulty of accurate numeration of accurate number of coliforms in liquid samples. A study showed that effluent samples with low coliform counts (e.g. 0.8/100 mL) revealed significant increase of coliform counts after blending for 1.5 minutes at 19,000 rpm. A recent study of secondary effluent disinfection showed that only at high UV doses and for larger particles the shielding effect of particles and bioflocculation on UV disinfection of E. coli was statistically significant, after the majority of free swimming bacteria were inactivated. In addition, flocculation may lead to better inactivation of E. coli, which was likely contributed by decreased scattering of light (Kollu and Ormeci 2012).

3.4 Conclusion

(1) Converting a conventional activated sludge reactor to an IFAS reactor did not significantly at the mixed liquor SRT of 4 days did not significantly affect particle size distribution

in the mixed liquor. However, the IFAS reactor produced secondary effluent with decreased MPS and higher turbidity.

(2) The IFAS reactor operated at SRT of 13.3 days produced activated sludge with larger floc size compared with that at SRT of 4 days. As SRT of the IFAS reactor increases from 4 days to 13.3 days, MPS at 50 μm, 100 μm, and 500 μm cut-off values increased from 8.4±0.5 μm, 27.7±1.3 μm, and 40.6±5.5 μm to 28.0±2.9 μm, 53.8±4.5 μm, and 77.0±9.2 μm, respectively. After SRT was decreased from 13.3 days to 4 days, MPS of the reactor at 50 μm, 100 μm, and 500 μm cut-off values gradually decreased from 28.0±2.9 μm, 53.8±4.5 μm, and 77.0±9.2 μm to 11.4±4.8 μm, 29.2±3.3 μm, and 46.3±3.3 μm.

(3) Operating at longer SRT produced better effluent quality in terms of effluent turbidity, COD and ammonia removals for the IFAS reactor. After SRT increased from 4 days to 13.3 days, effluent turbidity decreased from 20.2±3.8 NTU to 7.5±4.3 NTU. Meanwhile, effluent COD decreased from 30.1±8.8 mg/L to 26.9±5.7 mg/L. Effluent ammonia concentration decreased from 24.1±6.2 mg/L to 6.6±4.8 mg/L. Shorten the SRT from 13.3 days to 4 days had reverse effects on effluent turbidity and COD removal. Particle size analysis of reactor effluent showed that fewer and larger particles existed in effluent at longer SRT, which was beneficial for filtration and disinfection of secondary effluent.

(4) Switching of carbon source from glucose to sodium acetate slightly increased MPS of supernatant particles. Effluent turbidity increased from 17.7±2.5 to 30.0±8.9. MPSs for cut-off values of 50 μm, 100 μm, and 500 μm in supernatant samples changed from 11.8±0.8 μm, 13.7±0.9 μm, and 13.7±2.9 μm of Phase 4 to 12.9±1.0 μm, 16.2±1.1 μm, and 19.5±1.3 μm of Phase 5.

Carbon and nitrogen removals were not affected by the change of carbon source after the reactor reached stable operation in Phase 5.

Chapter 4 Survey of Particle Size Distribution in Full-scale Wastewater Treatment Plants

4.1 Introduction

Wastewater contains organic and inorganic compounds, which can be found in particulate or soluble form. The particle size distribution of the particulates is an essential characteristic of the wastewater quality. Particle size distribution has been used to predict COD, suspended solids, color, and turbidity (Chavez, Jimenez et al. 2004). The understanding of particle size distribution contributed to the better understanding of soluble and particulate COD fractions and benefited the modeling of activated sludge process (Henze, Gujer et al. 1999). Particle size distribution of wastewater particles was used to improve the understanding of both primary treatment (Levine, Tchobanoglous et al. 1991, Landa, Capella et al. 1997, Tiehm, Herwig et al. 1999, Chavez, Jimenez et al. 2004) and secondary treatment (Sophonsiri and Morgenroth 2004, Wu, Jiang et al. 2009, Garcia-Mesa, Poyatos et al. 2010).

Particle removal is a critical consideration for wastewater treatment. Particle removal in primary sedimentation tank is achieved primarily through gravity in wastewater treatment plants. Primary sedimentation tank usually has good removal efficiency for the particles (>50 μm) (Neis and Tiehm 1997). Chemically enhanced primary treatment and the chemical-biological flocculation can improve small particle removal greatly (Odegaard 1998, Jimenez, Chavez et al. 2000, Zhang, Zhao et al. 2007, Zamalloa, Boon et al. 2013). Particle size in the primary effluent

has impact on the efficiency of biodegradation of organic particles in biological secondary treatment. Increased microbial hydrolysis rate were observed for smaller particles due to increased surface area (Dimock and Morgenroth 2006, Puigagut, Salvado et al. 2007).

Secondary sedimentation of activated sludge is one of the most critical operations in activated sludge process. The performance of secondary sedimentation is crucial to overall effluent quality (Jin, Wilén et al. 2003). Activated sludge flocs are the major forms of particles in biological wastewater treatment. Different parameters have been developed to characterize sludge properties in terms of SVI, organic loading, sludge retention time, composition, and content of polymers, density, porosity, viscosity, and particle size distribution (Hilligardt and Hoffmann 1997). Most of modern secondary sedimentation tanks include thickening zone for sludge concentration and sludge storage in case of a high hydraulic loading period (Plosz, De Clercq et al. 2011). Residual biomass in secondary effluent have been characterized as volatile suspended solids and oxygen update rate. The residual biomass in secondary effluent was correlated with particle numbers, but suspended solids was found to be correlated with total volume of particles (Vollertsen, Jahn et al. 2001, Wu, Jiang et al. 2009).

Solids retention time (SRT) has been observed to be a parameter associated with mean particle size (Leu, Chan et al. 2012). Early work observed the decrease of small activated sludge flocs with increase SRT (Bisogni and Lawrence 1971, Chao and Keinath 1979). Settling test with activated sludge with sludge ages ranging from 0.25 days to 12 days shows that percent dispersion decreased exponentially with increased SRTs. The impacts of SRT on a lab-scale MLE reactor and a lab-scale IFAS reactor have been investigated in Chapter 2 and Chapter 3. Those results

strongly suggest that SRT is an important parameter affecting particle size distribution in activated sludge process. However, limited data was available from full-scale WWTPs about the particle size distribution in both primary and secondary treatment processes.

Chapter 4 surveys particle size distribution in 5 full-scale WWTPs with different SRTs and treatment processes in the Los Angeles County. Particles size distribution profiles were surveyed in raw wastewater, across primary sedimentation tank, biological treatment basins, and secondary sedimentation tanks. Particle size distributions of High Purity Oxygen (HPO) process, Modified Ludzack-Ettinger (MLE) Nitrification and Denitrification (NDN) process, and Step Feed NDN process were studied detail. Particle size distributions of activated sludge samples in the mixed liquor of biological treatment basins and secondary effluent were compared under different SRTs.

4.2 Materials and Methods

4.2.1 Selection of Full-scale WWTPs

The major WWTPs in the Los Angeles County included Modified MLE process, Step-Feed Nitrification and Denitrification (NDN) process, MLE NDN process, and High Purity Oxygen (HPO) process, as listed in **Table 4-1**. The total current flow of major WWTPs in the Los Angeles County was 756.7 mgd based on most recently available data. Five-full scale WWTPs are selected for the survey of particle size distribution, namely Donald C. Tillman Water Reclamation Plant (DCT WRP), San Jose Creek Water Reclamation Plant East (SJCE), San Jose

Creek Water Reclamation Plant West (SJCW), Whittier Narrows Water Reclamation Plant (WN WRP), and Joint Water Pollution Control Plant (JWPCP). The treatment plants were selected based on their service area coverage, treatment process, and thoroughness of plant operation and operation. Selected treatment plants were well operated with historically stable treatment performances and stable sources of wastewater to minimize variation of unintentional changes of reaction operations.

Table 4-1. Major WWTPs in Los Angeles County

Name of WWTP	Current Flow (MGD)	Type of Activated Sludge Process
LA Sanitation (City of Los Angeles Department of Public Works)		
Donald C. Tillman Water Reclamation Plant*	35.0	MLE NDN
Los Angeles-Glendale Water Reclamation Plant	15.0	MLE NDN
Hyperion Treatment Plant	280.0	High Purity Oxygen (HPO)
Terminal Island Water Reclamation Plant	15.0	MLE NDN
Sanitation Districts of Los Angeles County		
La Canada Water Reclamation Plant	0.1	Extended Aeration
Long Beach Water Reclamation Plant	25.0	Step-Feed NDN
Los Coyotes Water Reclamation Plant	37.5	Step-Feed NDN
Pomona Water Reclamation Plant	15.0	MLE NDN
San Jose Creek Water Reclamation Plant East*	50.0	Step-Feed NDN
San Jose Creek Water Reclamation Plant West*	50.0	Step-Feed NDN
Whittier Narrows Water Reclamation Plant*	15.0	MLE NDN
Joint Water Pollution Control Plant*	280.0	HPO
Saugus Water Reclamation Plant	6.5	MLE NDN
Valencia Water Reclamation Plant	21.6	Step-Feed NDN
Lancaster Water Reclamation Plant	18.0	Step-Feed NDN
Palmdale Water Reclamation Plant	12.0	Step-Feed NDN

*Surveyed WWTPs in this study.

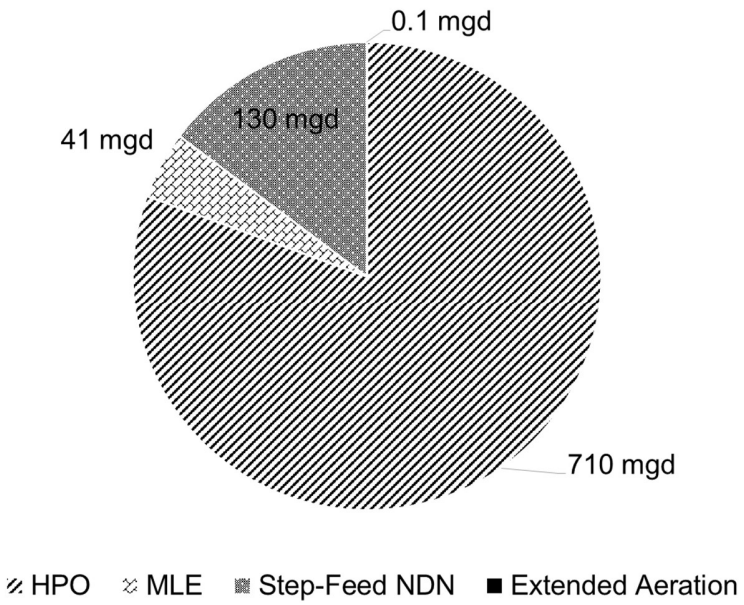

Figure 4-1. Major types of WWTPs in the Los Angeles County.

4.2.2 Sample Collection

Grab samples were collected for each plant visit event. Briefly, 50 to 75 mL samples were collected in 250 mL polyethylene bottles. Raw wastewater samples were collected at the designated auto-sampler under manual mode. Before collecting raw wastewater, the sampling tube was flushed with raw wastewater for 30 seconds to remove residue wastewater. Samples from primary sedimentation tank were collected from sampling window of the cover of primary sedimentation tank. Care was taken to avoid collecting sum/foams. Mixed liquor samples in biological treatment tank for High Purity Oxygen process were collected from designated sampling hoses in underground pipeline galleries of the aeration tank. Mixed liquor samples in biological treatment tank for other processes were grabbed directly from the open surface of mixed liquor in reaction tanks. Detailed sampling locations for selected WWTPs were provided

in **Table 4-2**, **Table 4-3**, **Table 4-4**, **Table 4-5**, and **Table 4-6**. Two sampling events, one for wet weather condition and one for dry weather condition, were conducted for JWPCP, SJCE, and SJCW, respectively. One sampling event was conducted for WN WRP and DCT WRP, respectively. Sample dates were listed in **Table 4-7**.

Table 4-2. Sampling location of Joint Water Pollutant Control Plant.

Sample No.	Sampling Location	Distance from unit inlet (m)	Distance from plant inlet (m)
1	Raw wastewater	0	0
2	Grit chamber effluent	10	10
3	Sampling point 1 of primary sedimentation tank	0	10
4	Sampling point 2 of primary sedimentation tank	22	32
5	Sampling point 3 of primary sedimentation tank	40	72
6	Sampling point 4 of primary sedimentation tank	60	132
7	Sampling point 1 of HPO tank	10	142
8	Sampling point 2 of HPO tank	26	168
9	Sampling point 3 of HPO tank	46	214
10	Sampling point 4 of HPO tank	56	270
11	Sampling point 5 of HPO tank	77	347
12	Sampling point 1 of secondary clarifier	4	351
13	Sampling point 2 of secondary clarifier	24	375
14	Sampling point 3 of secondary clarifier	48	423

Table 4-3. Sampling location of San Jose Creek East Water Reclamation Plant.

Sample No.	Sampling Location	Distance from tank inlet (m)	Distance from plant inlet (m)
1	Raw wastewater	0	0
2	Sampling point 1 of primary sedimentation tank	15	15
3	Sampling point 2 of primary sedimentation tank	40	55
4	Sampling point 3 of primary sedimentation tank	60	115
5	Sampling point 4 of primary sedimentation tank	90	205
6	Sampling point 1 of the first step anoxic tank	4	209
7	Sampling point 2 of the first step anoxic tank	30	239
8	Sampling point 3 of the first step anoxic tank	66	305
9	Sampling point 1 of the second step anoxic tank	2	307
10	Sampling point 2 of the second step anoxic tank	30	337
11	Sampling point 3 of the second step anoxic tank	66	403
12	Sampling point 1 of the third step anoxic tank	2	405
13	Sampling point 2 of the third step anoxic tank	30	435
14	Sampling point 3 of the third step anoxic tank	66	501
15	Sampling point 4 of the third step anoxic tank	66	567
16	Sampling point 1 of secondary clarifier	4	571
17	Sampling point 2 of secondary clarifier	24	595
18	Sampling point 3 of secondary clarifier	48	643

Table 4-4. Sampling location of San Jose Creek West Water Reclamation Plant.

Sample No.	Sampling Location	Distance from tank inlet (m)	Distance from plant inlet (m)
1	Raw wastewater	0	0
2	Sampling point 1 of primary sedimentation tank	15	15
3	Sampling point 2 of primary sedimentation tank	36	51
4	Sampling point 3 of primary sedimentation tank	60	111
5	Sampling point 4 of primary sedimentation tank	80	191
6	Sampling point 1 of the first step anoxic tank	2	193
7	Sampling point 2 of the first step anoxic tank	30	223
8	Sampling point 3 of the first step anoxic tank	66	289
9	Sampling point 1 of the second step anoxic tank	2	291
10	Sampling point 2 of the second step anoxic tank	30	321
11	Sampling point 3 of the second step anoxic tank	66	387
12	Sampling point 1 of the third step anoxic tank	2	389
13	Sampling point 2 of the third step anoxic tank	30	419
14	Sampling point 3 of the third step anoxic tank	66	485
15	Sampling point 4 of the third step anoxic tank	30	515
16	Sampling point 5 of the third step anoxic tank	66	581
17	Sampling point 1 of secondary clarifier	6	587
18	Sampling point 2 of secondary clarifier	15	602
19	Sampling point 3 of secondary clarifier	30	632
20	Sampling point 3 of secondary clarifier	49	681

Table 4-5. Sampling location of Whittier Narrows Water Reclamation Plant.

Sample No.	Sampling Location	Distance from inlet (m)	Distance from plant inlet (m)
1	Raw Wastewater	0	0
2	Primary Effluent	93	93
3	Sampling point 1 of anoxic zoon	1	94
4	Sampling point 2 of anoxic zoon	25	119
5	Sampling point 1 of aeration zoon	40	159
6	Sampling point 2 of aeration zoon	45	604
7	Sampling point 3 of aeration zoon	75	679
8	Sampling point 3 of aeration zoon	85	764
9	Sampling point 1 of secondary clarifier	5	769
10	Sampling point 2 of secondary clarifier	27	796
11	Sampling point 3 of secondary clarifier	40	836

Table 4-6. Sampling location of Donald C Tillman Water Reclamation Plant.

Sample No.	Sampling Location	Distance from inlet (m)	Distance from plant inlet (m)
1	Raw Wastewater	0	0
2	Primary Effluent	50	50
3	Sampling point 1 of anoxic zoon	4	54
4	Sampling point 2 of anoxic zoon	28	82
5	Sampling point 1 of aeration zoon	57	149
6	Sampling point 2 of aeration zoon	86	235
7	Sampling point 1 of secondary clarifier	2	237
8	Sampling point 2 of secondary clarifier	10	247
9	Sampling point 3 of secondary clarifier	32	279
10	Sampling point 4 of secondary clarifier	40	319

4.2.3 Analysis of Particle Size Distribution

The PSD analysis was performed using an AccuSizer 780 optical particle sizer module (model LE400-0.5SE; Nicomp Particle Sizing Systems, Santa Barbra, California). The range of detection was set at 0.5 μm to 500 μm. For each experiment, 0.5 mL of liquid sample was delivered to the system by a customized wide-bore pipette (Chan, Leu et al. 2011). Between each PSD test,

three auto-flush cycles were performed to ensure clean dilution chamber, system tubing, and sensor. Blank sample (reverse osmosis water) was used to check system baseline after every 15 sample injections. Detailed description of particle size analysis can be found in Chapter 2 and Appendix A.

4.3 Results and Discussion

Particle size distributions from raw wastewater to secondary sedimentation effluent were surveyed in five full-scale WWTPs. Mean particle size (MPS) values of surveyed WWTPs were reported at cut-off values of 50 μm, 100 μm, and 500 μm, as shown in **Figure 4-2** (JWPCP), **Figure 4-3** (SJCE WRP), **Figure 4-4** (SJCW WRP), **Figure 4-5** (WN WRP) and **Figure 4-6** (DCT WRP).

MPS of raw wastewater in all surveyed samples were in the range of 10.0±0.3 μm to 22.0±0.2 μm. Across rectangular primary sedimentation tanks in all survey WWTPs, the MPS values of the primary effluent ranged from 6.4±1.3 μm to 17.5±0.5 μm (**Table 4-7**). No consistent trends of change particle size distribution of primary effluent particles were observed between dry weather condition and wet weather condition. As shown in **Figure 4-2** (JWPCP), **Figure 4-3** (SJCE WRP), **Figure 4-4** (SJCW WRP), **Figure 4-5** (WN WRP) and **Figure 4-6** (DCT WRP), the MPS of supernatant particles across primary sedimentation tanks were relatively stable, suggesting sampling at primary effluent could be representative for whole primary sedimentation tank. Previous study showed that pretreatment of wastewater could have a major impact on process performance and reliability of high-rate biological treatment processes, such as HPO process. Treatment kinetics could be influenced by particle size of particulate organic substances (Levine,

Tchobanoglous et al. 1991). In our stable the MPS in primary effluent ranged from 6.4±1.3 μm to 17.5±0.5 μm (**Table 4-7**). Further removal of particles in primary effluent could be achieved by coagulation or filtration (Levine, Tchobanoglous et al. 1991, Landa, Capella et al. 1997, Tiehm, Herwig et al. 1999).

Immediately after the inlet of the biological treatment tank, the MPS was controlled by activated sludge flocs instead of primary effluent particles. MPS of activated sludge flocs collected from aeration basins from full-scale WWTPs were compared in **Figure 4-7** and **Table 4-8**. Based on MPS analysis, it was observed that long SRT particularly associated with the presence of particles larger than 100 μm. MPS values integrated to 50 μm were relatively stable under various treatment processes and SRTs. A previous study surveyed double-step activated sludge system, medium-load activated sludge system, extended aeration system, and membrane bioreactor system indicated that particle size distribution could be fitted to power law model with variable β coefficient (slope of double logarithmic diagram). Moderate correlation between *A coefficient* (total concentration of particulate matter) and suspended solids concentration, turbidity and COD were established (Garcia-Mesa, Delgado-Ramos et al. 2012).

Presence of large particles during secondary sedimentation was observed, evidenced by increased MPSs at 500 μm cut-off values along secondary sedimentation processes (**Table 4-9**). This observation was in contrast with theoretical calculation of particle removal by sedimentation, as shown in **Figure 4-8**. It was speculated that the movement of flight travel in rectangular sedimentation tank may carrier over small amount of activated sludge from sludge blanket and introduced large particles into supernatant.

Chapter 4 surveys particle size distribution in raw wastewater, across primary sedimentation tank, biological treatment basins, and secondary sedimentation tanks of five full-scale WWTPs in the Los Angeles County. Study in this chapter means to profile particle size distribution in full-scale WTTPs and to investigate possible relationship between MPS and SRTs at full-scale. MPS of raw wastewater in all surveyed samples were in the range of 10.0±0.3 μm to 22.0±0.2 μm. Comparison of MPS of mixed liquor in biological treatment basins indicated that long SRT particularly associated with the presence of particles larger than 100 μm. Survey of MPS in secondary sedimentation tank indicated that filtration of secondary effluent may be needed for improved disinfection and water reuse.

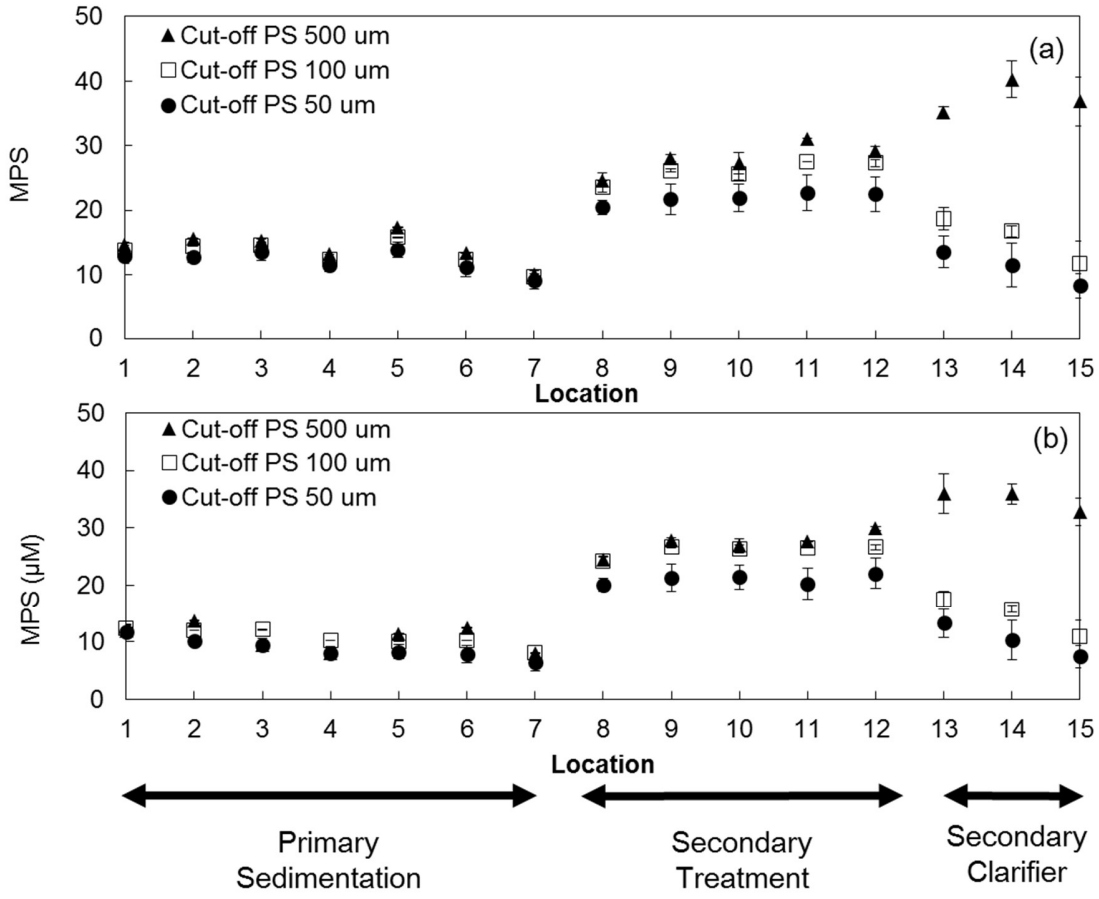

Figure 4-2. Mean particle size of activated sludge flocs at different cut-off values of JWPCP on (a) 09/12/2014 and (b) 02/08/2015.

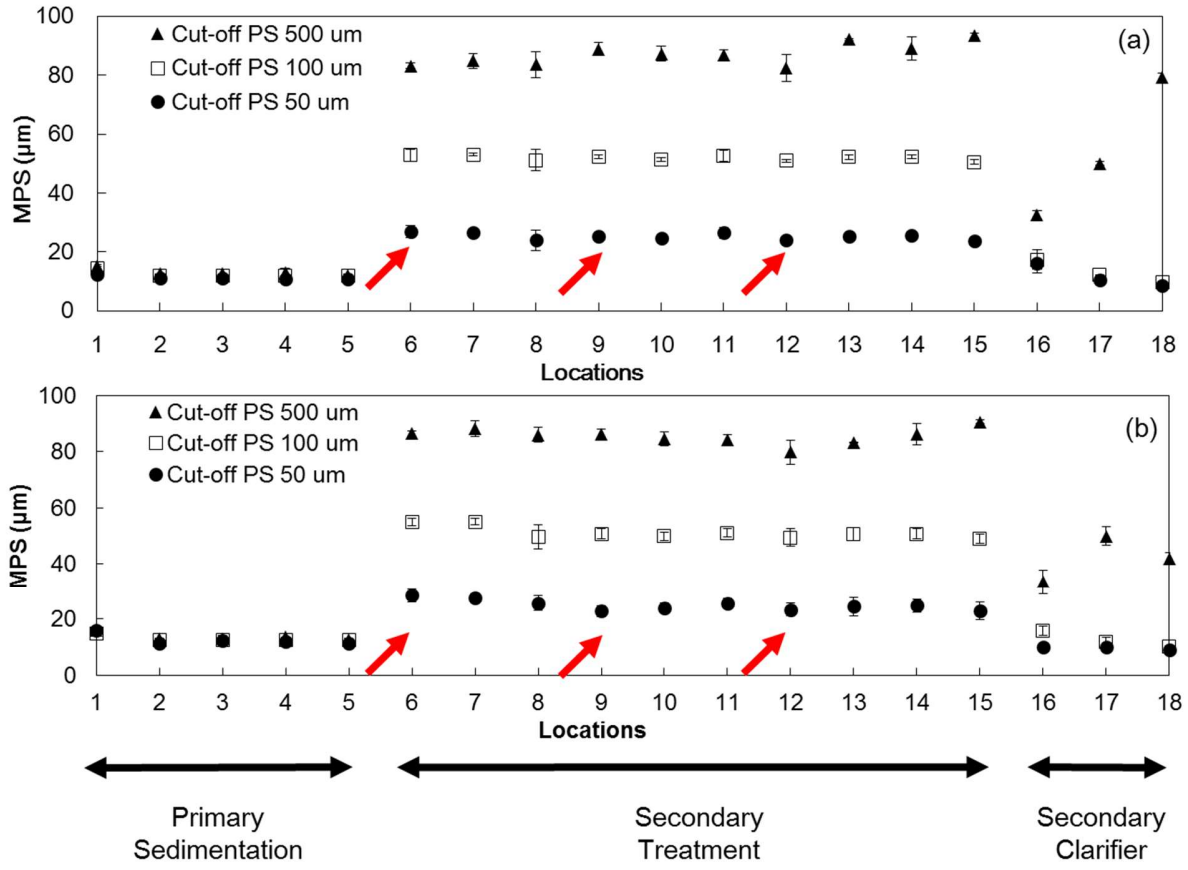

Figure 4-3. Mean particle size of activated sludge flocs at different cut-off values of SJCE WRP on (a) 09/17/2014 and (b) 03/26/2015. Arrows indicates the locations of step seed.

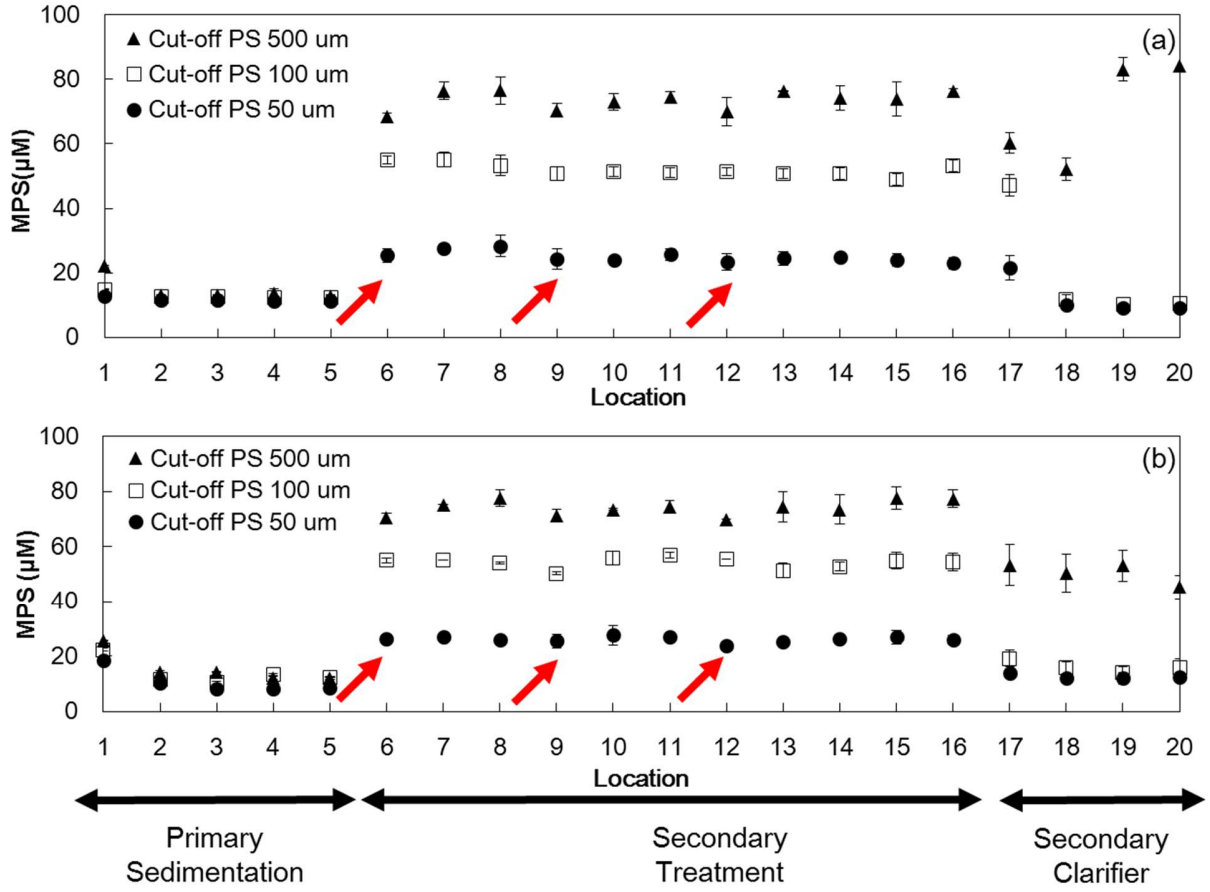

Figure 4-4. Mean particle size of activated sludge flocs at different cut-off values of SJCW WRP on (a) 09/17/2014 and (b) 03/26/2015. Arrows indicates the locations of step seed.

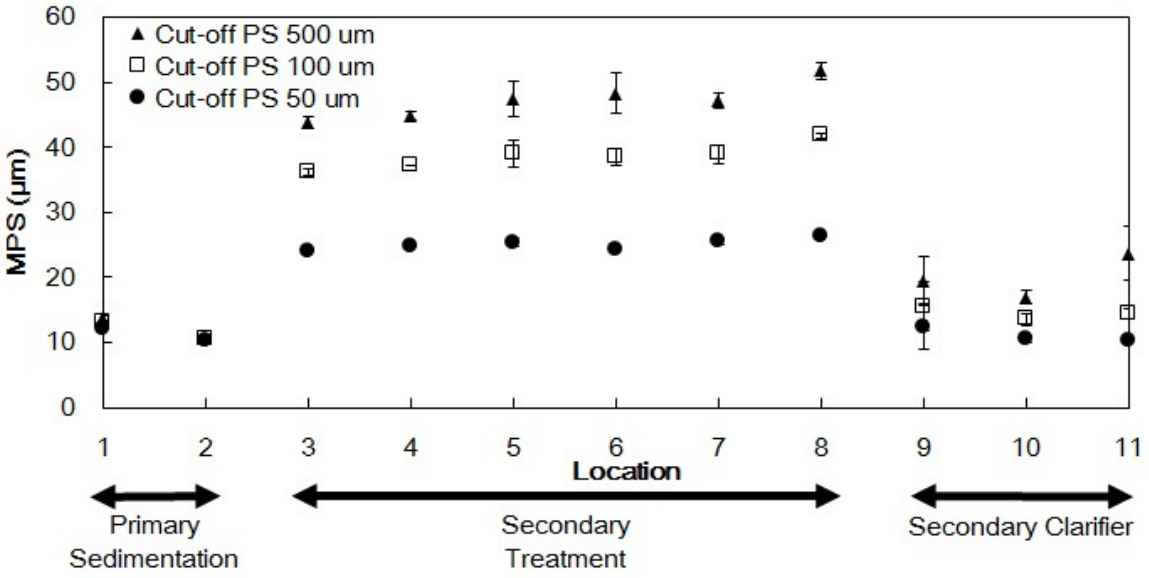

Figure 4-5. Mean particle size of activated sludge flocs at different cut-off values of Whittier Narrows WRP on 03/26/2015.

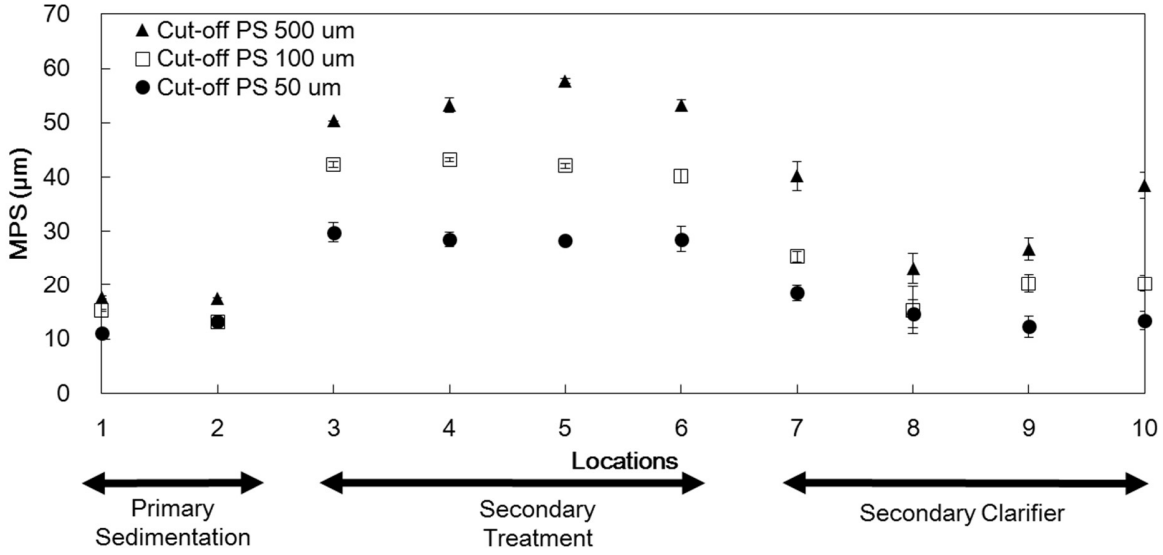

Figure 4-6. Mean particle size of activated sludge flocs at different cut-off values of Donald C Tillman WRP on 08/27/2015.

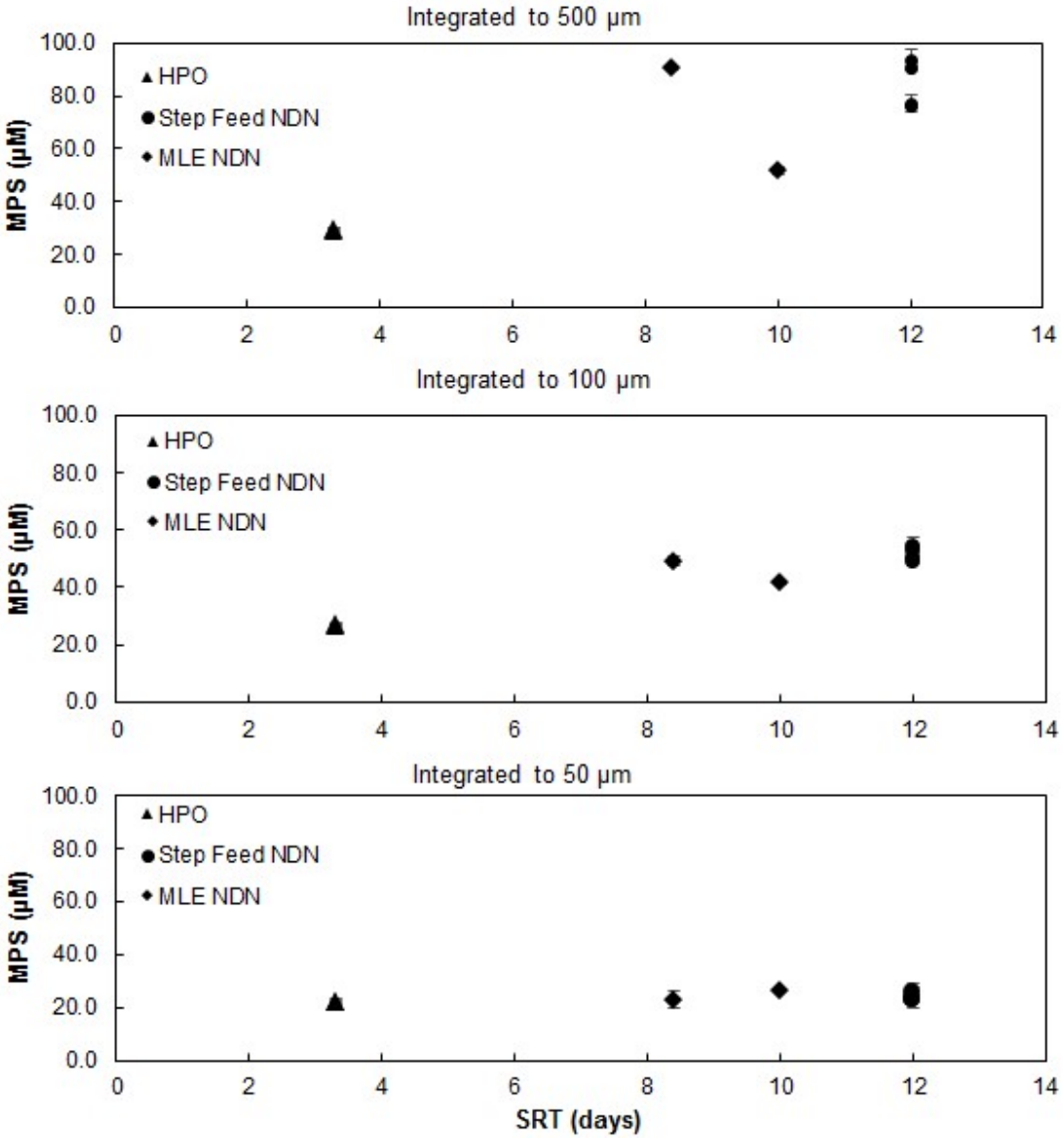

Figure 4-7. MPS of samples collected from the end stage of aeration basins of surveyed WWTPs with different SRTs.

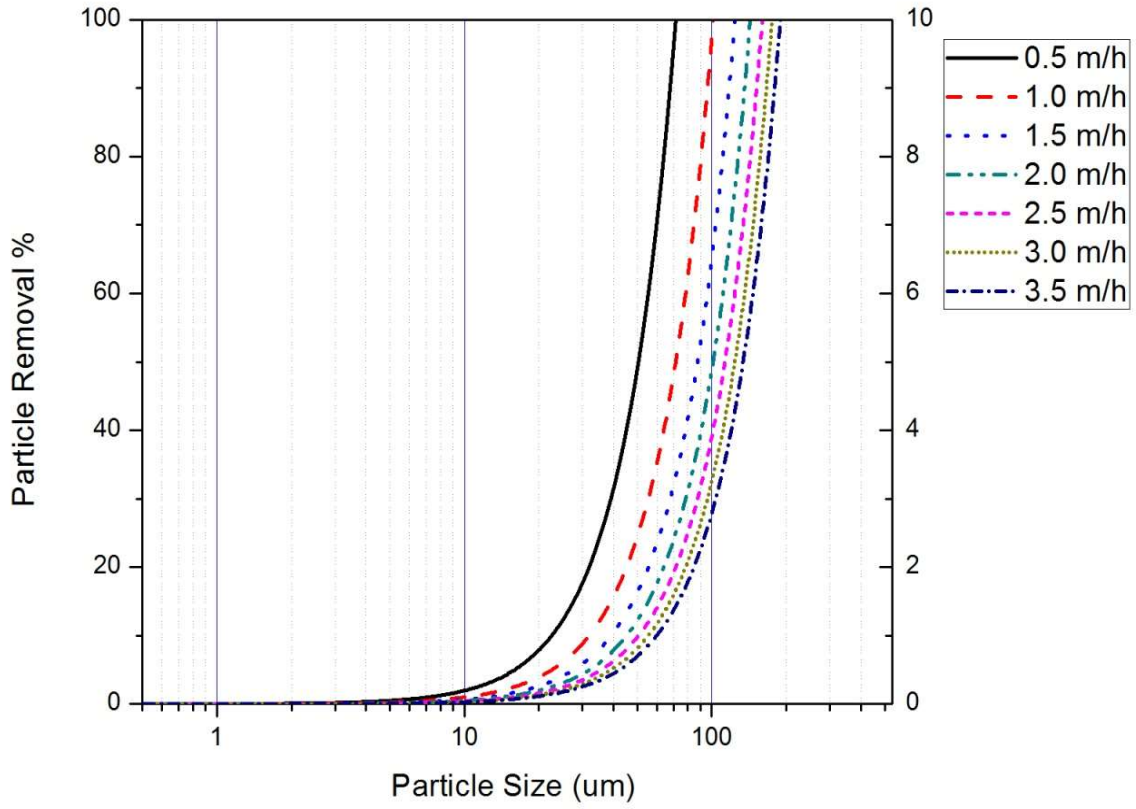

Figure 4-8. Particle Removal percentage, particle size, and overflow rate of surveyed WWTPs with different overflow rates as indicated in the legend.

Table 4-7. Comparison of MPS of samples collected from primary sedimentation tank effluent of surveyed WWTPs.

Wastewater Treatment Plants	SRT (days)	Integrated to 50 μm		Integrated to 100 μm		Integrated to 500 μm	
		MPS (μm)	SD	MPS (μm)	SD	MPS (μm)	SD
JWPCP 9/12/2014	3.3	9.2	0.4	9.8	0.5	10.1	1.6
JWPCP 2/9/2015	3.3	6.4	1.3	8.1	1.0	8.0	1.0
DCT WRP 8/27/2015	8.4	11.0	0.4	15.3	0.5	17.5	0.5
WN WRP 3/26/2015	10.0	10.3	0.7	10.6	0.7	10.7	0.6
SJCE WRP 9/17/2014	12.0	10.9	0.4	12.0	0.4	12.2	0.4
SJCE WRP 3/3/2015	12.0	11.3	0.4	12.4	0.5	12.7	0.5
SJCW WRP 9/17/2014	12.0	8.6	0.5	12.4	0.3	11.9	0.2
SJCW WRP 3/26/2015	12.0	11.3	0.4	12.4	0.5	12.7	0.5

Table 4-8. Comparison of MPS of samples collected from the end stage of aeration basins of surveyed WWTPs.

Wastewater Treatment Plants	SRT	Integrated to 50 μm		Integrated to 100 μm		Integrated to 500 μm	
	(days)	MPS (μm)	SD	MPS (μm)	SD	MPS (μm)	SD
JWPCP 9/12/2014	3.3	22.5	0.6	27.3	0.5	29.2	0.6
JWPCP 2/9/2015	3.3	22.0	0.5	26.6	0.4	29.5	0.4
DCT WRP 8/27/2015	8.4	28.6	3.3	40.1	1.7	53.2	0.7
WN WRP 3/26/2015	10	26.4	0.1	41.7	0.5	51.7	1.4
SJCE WRP 9/17/2014	12	23.7	0.8	50.5	1.8	93.5	3.9
SJCE WRP 3/3/2015	12	23.0	3.3	49.0	1.7	90.7	0.7
SJCW WRP 9/17/2014	12	25.9	1.7	54.4	3.1	77.4	3.3
SJCW WRP 3/26/2015	12	23.0	1.8	53.2	1.7	76.3	0.7

Table 4-9. Comparison of MPS of samples collected from the secondary sedimentation tank effluent of surveyed WWTPs.

Wastewater Treatment Plants	SRT (days)	Integrated to 50 μm		Integrated to 100 μm		Integrated to 500 μm	
		MPS (μm)	SD	MPS (μm)	SD	MPS (μm)	SD
JWPCP 9/12/2014	3.3	8.3	1.9	11.7	3.5	36.8	3.7
JWPCP 2/9/2015	3.3	7.4	1.6	11.0	2.7	32.8	2.4
DCT WRP 8/27/2015	8.4	13.5	0.2	20.3	0.2	38.5	2.1
WN WRP 3/26/2015	10.0	10.5	0.2	14.4	0.7	23.7	4.1
SJCE WRP 9/17/2014	12.0	8.6	0.2	9.8	0.2	79.1	1.5
SJCE WRP 3/3/2015	12.0	9.1	0.2	10.3	0.2	1.9	2.1
SJCW WRP 9/17/2014	12.0	12.6	1.3	15.8	3.2	45.2	4.4
SJCW WRP 3/26/2015	12.0	9.2	1.3	10.4	0.2	84.2	3.6

Table 4-10. Comparison of mean particle size of samples collected from aeration basins of the lab-scale MLE reactor (Chapter 2) and the lab-scale IFAS reactor (Chapter 3)

Wastewater Treatment Plants	SRT (days)	Integrated to 50 µm		Integrated to 100 µm		Integrated to 500 µm	
		MPS (µm)	SD	MPS (µm)	SD	MPS (µm)	SD
MLE Reactor Phase 1	4	10.0	0.8	17.6	0.7	18.3	0.9
MLE Reactor Phase 2	13.3	14.0	1.1	23.5	0.8	46.6	1.2
MLE Reactor Phase 3	4	10.9	1.8	16.7	1.7	22.0	1.8
IFAS Reactor Phase 2	4	11.2	1.5	22.9	1.8	28.1	1.1
IFAS Reactor Phase 3	12.0	24.4	0.8	37.3	1.2	40.7	1.8
IFAS Reactor Phase 4	4	11.8	0.8	13.7	0.9	13.7	2.9
IFAS Reactor Phase 5	4	12.9	1.0	16.2	1.1	19.5	1.3

Chapter 5 Summary

This work aims at providing a better understanding of particle size distribution in activated sludge process through lab-scale reactor work and full-scale WWTP surveys.

Chapter 2 investigates the impact of SRT on particle size distribution, sludge settleability, effluent turbidity, and removals of COD and NH_4^+-N in the MLE reactor. Change of SRT had immediate impact on the MPS of mixed liquor. SRT at 13.3 days produced activated sludge with larger floc size compared with that at SRT of 4 days. As SRT of the MLE reactor increases from 4 days to 13.3 days, mean particle size (MPS) at 50 μm, 100 μm, and 500 μm cut-off values increased from 7.9±0.5 μm, 25.1±2.8 μm, and 34.3±1.2 μm to 26.9±7.8 μm, 50.0±10.0 μm, and 71.8±14.7 μm, respectively. Operating at SRT of 13.3 days yielded activated sludge with better settleability than that at SRT of 4 days. More compacted activated sludge flocs were observed under microscopy when the reactor was operated at SRT of 13.3 days.

Chapter 3 studies the impact of SRT on particle size distribution, sludge settleability, effluent turbidity, and removals of COD, NH_4^+-N, in the IFAS reactor. Converting a conventional activated sludge reactor to an IFAS reactor did not significantly at the mixed liquor SRT of 4 days did not significantly affect particle size distribution in the mixed liquor. The IFAS reactor operated at SRT of 13.3 days produced activated sludge with larger floc size compared with that at SRT of 4 days. Operating at longer SRT produced better effluent quality in terms of effluent turbidity, COD and ammonia removals for the IFAS reactor.

Chapter 3 further investigates the impact of difference carbon sources (Glucose vs. Sodium Acetate) on particle size distribution and reactor performance in the IFAS reactor. Switching of carbon source from glucose to sodium acetate slightly increased MPS of supernatant particles.

Chapter 4 surveys particle size distribution in 5 full-scale WWTPs with different SRTs and treatment processes in the Los Angeles County. Particles size distribution profiles from primary influent to secondary effluent are fully evaluated. MPS of raw wastewater in all surveyed samples were in the range of 10.0±0.3 μm to 22.0±0.2 μm. Across rectangular primary sedimentation tanks in all survey WWTPs, the MPS values of the primary effluent ranged from 6.4±1.3 μm to 17.5±0.5 μm. The relationship between SRT and particle size of activated sludge in biological process and sedimentation process are studied. It was observed that long SRT particularly associated with the presence of particles larger than 100 μm. MPS values integrated to 50 μm were relatively stable under various treatment processes and SRTs. Presence of large particles during secondary sedimentation was observed, evidenced by increased MPSs at 500 μm cut-off values along secondary sedimentation processes.

The work conducted in this study provided practical knowledge for WWTPs operation. SRT was verified as an effective parameter for intervening particle size distribution of activated sludge in a variety of treatment processes. Operating of activated sludge process will not only improve ammonia removal but also improve sludge settleability in MLE process. Based on lab-scale study, operating at longer SRT for IFAS system will enhance nutrient removal as well as significantly reduce effluent turbidity. Effluent particle size distribution

could also be influenced by SRT. Operating at longer SRT may benefit filtration and disinfection of secondary effluent with fewer but larger particles and reduced turbidity.

The observation that longer SRT will promote the formation of larger flocs may lead future study of the microbial community dynamics among different size range of activated sludge flocs. Focuses may be put on the percentage of model microorganisms among different size range of activated sludge flocs. New development of separation techniques are needed to differentiate and separate activated sludge flocs based on particle size.

Appendix A AccuSizer Technology

1. Overview of the AccuSizer Technology

AccuSizer 780 is the instrument for particle size analysis (Particle Sizing Systems (Santa Barbara, CA, USA). The technique of single particle optical sensing is adopted to detect individual particles in a certain size range as each individual particle passes through a thin optical detecting zone. Samples containing particles should be diluted sufficiently so that only a single particle will pass the optical detecting zone at a given time. Light Extinction (LE) method and Light Scattering (LS) method are used to capture signals from detection chamber. The capture signals will be converted to particle count dataset by CW780 Software provided by the manufacture.

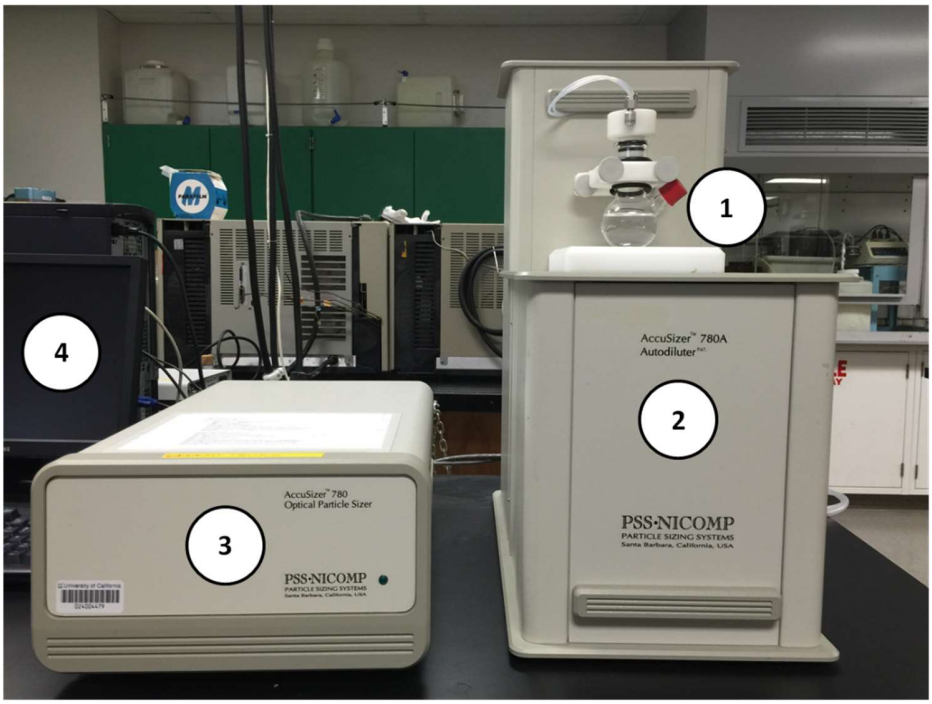

Figure Appendix A-1. Set-up of AccuSizer 780. (1) Auto-dilution chamber, (2) optical sensor box, (3) controller box, (4) computer and software.

2. Light Extinction (LE) Method

The LE method mode is to detect the decrease of the intensity of light transmitted across a flow channel. The decrease of light intensity is caused by the passage of an individual particles through the light beam. Demission of the passage or "optical sensing zone" is 400 μm (width)×1000μm (length) ×35 μm (depth). The underlying physical effect for LE method is light refraction. Most particles have a refractive index that is different from the surrounding fluid. The detection range under LE method mode for the sensor LE400-05SE is approximately 1.3 to 500 μm.

3. Light Scattering (LS) Method

Light Scattering (LS) detector views the same optical sensing zone perpendicular to the light beam from the light source. With LS method there is ideally little or no light intensity detected from the optical sensing zone in the absence of a particle. The LS detector captures the light that is scattered over an optimized range of solid angles. LS method can detect particles that are considerably smaller than that can be detected by LE method.

The detection range of the LS method is limited by the wavelength of the light source. Scattering intensity increases as the 6th power of the diameter of particles at the Rayleigh region, where the diameter of particles are considerably smaller than the wavelength of the light source (700 nm). With the increase of particle matter, the scattering intensity decreases to the 4th power of the diameter of particles. The detected will be quickly approaches saturation and limit the detection range. For the sensor LE400-05SE the effective detection

range under LS method is approximately 0.5μm to 5μm. LS method and LE method are designed complementary in the AccuSizer 780.

Appendix B Operation Data of the MLE Reactor

Table Appendix B-1. Reactor Operational Parameter for the MLE Reactor.

Days	Flow Rate Inorganic Solution (mL/min)	Inorg. Solution Storage Volume (L)	Flow Rate of Organic Solution (mL/min)	Org. Sol. Storage (L)	Total Flow Rate (mL/min)	Recycle Flow Rate (mL/min)	MLSS Waste Volume (mL/day)	SRT
0	1.4	2.0	9.7	14.0	11	16	4000	4.0
1	1.4	2.0	9.7	14.0	11	16	4000	4.0
2	1.4	2.0	9.7	14.0	11	16	4000	4.0
3	1.4	2.0	9.7	14.0	11	16	4000	4.0
4	1.4	2.0	9.7	14.0	11	16	4000	4.0
5	1.4	2.0	9.7	14.0	11	16	4000	4.0
6	1.4	2.0	9.7	14.0	11	16	4000	4.0
7	1.4	2.0	9.7	14.0	11	16	4000	4.0
7	1.4	2.0	9.7	14.0	11	16	4000	4.0
8	1.4	2.0	9.7	14.0	11	16	4000	4.0
9	1.4	2.0	9.7	14.0	11	16	4000	4.0
10	1.4	2.0	9.7	14.0	11	16	4000	4.0
11	1.4	2.0	9.7	14.0	11	16	1200	13.3
13	1.4	2.0	9.7	14.0	11	16	1200	13.3
14	1.4	2.0	9.7	14.0	11	16	1200	13.3
15	1.4	2.0	9.7	14.0	11	16	1200	13.3
16	1.4	2.0	9.7	14.0	11	16	1200	13.3
17	1.4	2.0	9.7	14.0	11	16	1200	13.3
19	1.4	2.0	9.7	14.0	11	16	1200	13.3
20	1.4	2.0	9.7	14.0	11	16	1200	13.3
21	1.4	2.0	9.7	14.0	11	16	1200	13.3
23	1.4	2.0	9.7	14.0	11	16	1200	13.3
24	1.4	2.0	9.7	14.0	11	16	1200	13.3
26	1.4	2.0	9.7	14.0	11	16	1200	13.3
29	1.4	2.0	9.7	14.0	11	16	1200	13.3
33	1.4	2.0	9.7	14.0	11	16	1200	13.3
38	1.4	2.0	9.7	14.0	11	16	1200	13.3
42	1.4	2.0	9.7	14.0	11	16	1200	13.3
44	1.4	2.0	9.7	14.0	11	16	1200	13.3
46	1.4	2.0	9.7	14.0	11	16	1200	13.3
47	1.4	2.0	9.7	14.0	11	16	1200	13.3
49	1.4	2.0	9.7	14.0	11	16	1200	13.3

51	1.4	2.0	9.7	14.0	11	16	1200	13.3
55	1.4	2.0	9.7	14.0	11	16	1200	13.3
58	1.4	2.0	9.7	14.0	11	16	1200	13.3
61	1.4	2.0	9.7	14.0	11	16	1200	13.3
64	1.4	2.0	9.7	14.0	11	16	1200	13.3
68	1.4	2.0	9.7	14.0	11	16	1200	13.3
72	1.4	2.0	9.7	14.0	11	16	1200	13.3
73	1.4	2.0	9.7	14.0	11	16	1200	13.3
77	1.4	2.0	9.7	14.0	11	16	1200	13.3
78	1.4	2.0	9.7	14.0	11	16	4000	4.0
82	1.4	2.0	9.7	14.0	11	16	4000	4.0
89	1.4	2.0	9.7	14.0	11	16	4000	4.0
93	1.4	2.0	9.7	14.0	11	16	4000	4.0
98	1.4	2.0	9.7	14.0	11	16	4000	4.0
102	1.4	2.0	9.7	14.0	11	16	4000	4.0
106	1.4	2.0	9.7	14.0	11	16	4000	4.0
112	1.4	2.0	9.7	14.0	11	16	4000	4.0
120	1.4	2.0	9.7	14.0	11	16	4000	4.0

Table Appendix B-2. Removal of COD and NH_4^+-N by the MLE Reactor

Days	Effluent COD (mg/L)	COD Removal (%)	Influent NH_4^+-N (mg/L)	Effluent NH_4^+-N (mg/L)	NH_4-N Removal (%)
0	23	90.8	43	40	7.0
1	28	88.8	40	N/A	N/A
2	N/A	N/A	42	41	2.4
3	33	86.8	40	N/A	N/A
4	N/A	N/A	40	39	2.5
5	34	86.4	41	38	7.3
6	N/A	N/A	40	37	7.5
7	32	87.2	40	35	12.5
7	N/A	N/A	42	37	11.9
8	N/A	N/A	40	37	7.5
9	45	82	43	33	23.3
10	N/A	N/A	40	36	10.0
11	36	85.6	39	30	23.1
13	N/A	N/A	40	31	22.5
14	34	86.4	37	17	54.1
15	N/A	N/A	40	8.2	79.5
16	N/A	N/A	39.5	9.1	77.0
17	35	86	40	4.4	89.0
19	N/A	N/A	39	6.2	84.1
20	N/A	N/A	40	4.1	89.8
21	N/A	N/A	40	7.1	82.3
23	N/A	N/A	40	8.9	77.8
24	N/A	N/A	38	11	71.1
26	22	91.2	40	10	75.0
29	N/A	N/A	40	8.8	78.0
33	N/A	N/A	39	9.2	76.4
38	N/A	N/A	40	12	70.0
42	20	92	42	8.6	79.5
44	N/A	N/A	N/A	N/A	N/A
46	N/A	N/A	N/A	N/A	N/A
47	25	90	38	7.8	79.5
49	N/A	N/A	N/A	6.8	N/A
51	22	91.2	39	6.6	83.1
55	N/A	N/A	N/A	7.4	N/A
58	31	87.6	38	7.9	79.2
61	N/A	N/A	N/A	8.1	N/A
64	27	89.2	42	8.1	80.7

68	N/A	N/A	N/A	6.2	N/A
72	N/A	N/A	41	9.2	77.6
73	25	90	44	8.8	80.0
77	N/A	N/A	N/A	N/A	N/A
78	N/A	N/A	42	18	57.1
82	23	90.8	40	30	25.0
89	N/A	N/A	N/A	N/A	N/A
93	33	86.8	44	35	20.5
98	N/A	N/A	42	40	4.8
102	18	92.8	43	38	11.6
106	20	92	42	36	14.3
112	17	93.2	41	37	9.8
120	22	91.2	40	39	2.5

Table Appendix B-3. pH and DO at sampling points of the MLE Reactor

Days	SVI (mL/g)	Effluent Turbidity	Influent pH	Anoixc Tank pH	Aeration Tank pH	Effluent pH	Anoxic Tank DO (mg/L)	Aeration Tank DO (mg/L)	Effluent DO (mg/L)
0	134	22	7.02	6.4	6.8	6.1	0.2	5.9	6.4
1	123	23	5.9	5.5	6.5	5.9	0.3	5.7	6.6
2	123	27	7.21	5.5	6.8	6.1	0.2	5.9	6.6
3	106	24	7.01	5.3	6.4	5.9	0.1	5.8	6.6
4	139	18	6	5.9	6.8	6.2	0	6.2	6.4
5	116	22	7.02	5.6	6.8	6.1	0.2	5.8	6.6
6	123	18	6.3	5.3	6.2	5.9	0.2	5.9	6.6
7	115	21	4	5.9	6.3	6.2	0.3	5.8	6.4
7	123	14	3.7	6.2	7.2	6.3	0.3	5.9	6.6
8	100	23	3.7	6.1	7.2	6	0.3	5.8	6.6
9	118	28	3.6	7.3	7.7	7.2	0.4	7.8	6.6
10	108	22	7.17	7.7	8.3	8.17	0.4	7	6.5
11	113	15	7.3	6.7	7.12	7.63	0.6	7	6.6
13	107	6.36	7.4	6.62	7.62	7.63	0.3	6.6	6.4
14	100	12.1	7.25	6.6	7.2	7.8	0.25	6.6	6.6
15	90	7.8	7.3	6.46	6.83	7.21	0.3	7	6.6
16	82	9.2	7.46	6.55	6.97	7.09	0.3	6.9	6.4
17	87	4.23	7.3	6.61	7.03	7.2	0.3	7.4	6.5
19	88	4.54	6.78	6.6	7.2	7.18	0.3	7	6.6
20	83	2.7	7.0	6.63	7	7.12	0.3	6.9	6.4
21	85	2.3	7.3	6.46	7	7.12	0.3	7.5	6.6
23	86	0.87	7.3	6.46	6.83	7.21	0.3	6.9	6.6
24	83	1.39	7.46	6.55	6.97	7.09	0.3	6.8	6.3
26	93	1.56	7.04	6.6	7.28	7.32	0.25	6.2	6.4
29	85	3.67	7.2	6.5	7.2	7.1	0.3	6.5	6.6
33	75	4.7	7.2	6.9	7.5	7.4	0.4	6.8	6.3
38	78	5.3	7.2	6.2	7.3	7	0.3	5.9	6.4
42	82	4.2	7.4	6.8	7.2	6.6	0.2	6.4	6.6
44	83	6.4	7.2	6.5	7.1	7.1	0.3	6.4	6.6
46	84	6.3	7.1	6.6	7.2	7.1	0.2	6.8	6.6
47	83	5.6	7.2	6.5	6.8	7	0.2	6.4	6.3
49	86	4.3	7.2	6.6	6.8	7.1	0.3	6.3	6.4
51	89	4.4	7.2	6.6	6.9	7.1	0.3	6.7	6.6
55	83	6.5	7.2	6.5	7.1	7.2	0.3	6.6	6.6
58	84	7.9	7.2	6.6	7.1	6.8	0.3	6.7	6.6

61	77	6.3	7.2	6.6	6.9	6.9	0.3	6.4	6.5
64	76	8.2	7.2	6.5	6.9	6.9	0.3	6.6	6.6
68	84	10	7.1	6.9	6.7	7.2	0.3	6.8	6.5
72	85	8.3	7.2	6.5	7	7.1	0.3	6.5	6.7
73	88	10	7.1	6.8	7.2	6.8	0.3	6.6	6.5
77	86	8.4	7.1	6.7	6.9	6.9	0.3	6.7	6.6
78	106	17	7.2	6.2	7.3	7	0.3	6.6	6.6
82	133	20	7.4	6.8	7.2	6.6	0.4	6.7	6.6
89	126	24	7.2	6.5	7.1	7.1	0.3	6.8	6.5
93	116	23	7.1	6.6	7.2	7.1	0.4	6.8	6.5
98	123	27	7.2	6.2	7.3	7	0.3	6.5	6.7
102	133	24	7.4	6.8	7.2	6.6	0.3	6.6	6.5
106	139	18	7.2	6.5	7.1	7.1	0.3	6.8	6.5
112	130	22	7.1	6.6	7.2	7.1	0.2	6.5	6.7
120	125	23	7.2	6.5	6.8	7	0.3	6.6	6.5

Table Appendix B-4. Mean Particle Size of Activated Sludge Flocs and MLSS in Mixed Liquor the MLE Reactor.

Days	Mean Particle Size at 50 µm Cut-off (µm)	Mean Particle Size at 50 µm Cut-off Standard Deviation	Mean Particle Size at 100 µm Cut-off (µm)	Mean Particle Size at 100 µm Cut-off Standard Deviation	Mean Particle Size at 500 µm Cut-off (µm)	Mean Particle Size at 500 µm Cut-off Standard Deviation	Mean MLSS (mg/L)	MLSS Standard Deviation
0	8.2	1.3	24.1	2.7	34.5	3.1	1835	78
1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	8.0	0.1	23.2	3.1	33.5	2.6	1951	86
3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5	7.1	0.3	23.9	1.2	35.6	5.5	1933	77
6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
7	N/A	N/A	N/A	N/A	N/A	N/A	2042	212
8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
9	8.2	0.8	29.3	3.1	33.4	3.0	N/A	N/A
10	N/A	N/A	N/A	N/A	N/A	N/A	2101	279
11	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
13	9.3	1.3	29.5	4.2	45.2	5.3	N/A	N/A
14	N/A	N/A	N/A	N/A	N/A	N/A	2461	57
15	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
16	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
17	18.2	0.9	33.5	3.2	49.5	3.0	2696	17
19	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
21	25.9	1.4	43.2	2.1	55.3	5.8	N/A	N/A
23	N/A	N/A	N/A	N/A	N/A	N/A	2845	56
24	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
26	26.1	0.9	51.6	0.3	69.5	1.5	2989	104
29	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
33	24.2	1.5	57.6	2.3	81.0	3.0	3140	115
38	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
42	26.7	2.4	55.3	3.1	81.0	4.0	3000	139
44	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
46	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
47	30.0	2.1	54.3	2.4	78.4	3.3	3212	153
49	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

51	N/A	N/A	N/A	N/A	N/A	N/A	3217	289
55	32.2	3.3	55.7	4.1	82.0	4.0	3267	204
58	N/A	N/A	N/A	N/A	N/A	N/A	3332	126
61	33.0	2.1	54.4	3.1	83.1	5.0	3205	116
64	N/A	N/A	N/A	N/A	N/A	N/A	3460	242
68	35.0	3.3	56.3	2.1	84.2	2.0	N/A	N/A
72	N/A	N/A	N/A	N/A	N/A	N/A	3052	227
73	35.0	3.5	58.0	3.2	80.6	3.0	N/A	N/A
77	N/A	N/A	N/A	N/A	N/A	N/A	2939	89
78	29.0	2.1	43.2	3.3	60.2	4.2	2336	148
82	20.2	0.7	36.2	4.1	56.3	1.2	1862	57
89	7.8	0.5	26.8	2.7	46.3	2.1	2215	23
93	7.3	2.2	26.8	3.5	49.3	3.2	1952	85
98	6.9	1.0	28.7	2.1	45.2	2.1	2262	71
102	8.0	3.2	27.5	2.6	39.5	0.8	2101	125
106	10.2	1.2	28.3	4.2	35.3	4.2	2217	134
112	8.2	0.8	30.1	3.5	36.6	3.2	2057	94
120	8.7	1.1	27.1	0.4	38.0	2.1	2068	78

Appendix C Operational Data of the IFAS Reactor

Table Appendix C-1. Reactor Operational Parameter for the IFAS reactor.

Days	Flow Rate Inorganic Solution mL/min	Inorganic Solution Storage Volume L	Flow Rate of Organic Solution mL/min	Organic Solution Storage Volume L	Total Flow Rate mL/min	Recycle Flow Rate mL/min	Recycle Rate %	MLSS Waste Volume mL/day	SRT days
0	1.4	2.0	9.7	14.0	15.4	16	104	3500	4.0
3	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
6	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
9	1.4	2.0	9.7	14.0	15.4	20	130	4000	4.0
12	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
13	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
14	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
19	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
26	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
31	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
34	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
36	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
40	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
43	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
46	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
49	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
52	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
55	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
59	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
60	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
62	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
65	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
68	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
71	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
74	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
77	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
80	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
83	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
86	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
89	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3

92	1.4	2.0	9.7	14.0	15.4				
95	1.4	2.0	9.7	14.0	15.4				
98	1.4	2.0	9.7	14.0	15.4				
101	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
104	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
107	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
110	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
113	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
116	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
119	1.4	2.0	9.7	14.0	15.4	16	145	1200	13.3
122	1.4	2.0	9.7	14.0	15.4	16	104	1200	13.3
125	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
128	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
132	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
134	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
137	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
140	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
143	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
146	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
149	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
152	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
155	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
158	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
161	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
164	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
167	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
170	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
173	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
176	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
180	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
182	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
184	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
188	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
191	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
195	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
203	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
210	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
216	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
222	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
229	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0
240	1.4	2.0	9.7	14.0	15.4	16	104	4000	4.0

Table Appendix C-2. Removal of COD and NH_4^+-N by the IFAS Reactor.

Days	Effluent COD (mg/L)	COD Removal (%)	Influent NH_4^+-N (mg/L)	Effluent NH_4^+-N (mg/L)	NH4-N Removal (%)
0	20	92	45	42	6.7
3			43	40	7.0
6	18	93	42	42	0.0
9			42	38	9.5
12	20	92	43	38	11.6
13			43	38	11.6
14			42	32	23.8
19	28	89	45	29	35.6
26			42	25	40.5
31			42	20	52.4
34	23	91	43	23	46.5
36			38	20	47.4
40			42	19	54.8
43	33	87	40	18	55.0
46			40	20	50.0
49			41	20	51.2
52			40	23	42.5
55	32	87	40	20	50.0
59			42	25	40.5
60			40	20	50.0
62	45	82	43	23	46.5
65			40	20	50.0
68			39	18	53.8
71			40	16	60.0
74	34	86	37	17	54.1
77			40	8.2	79.5
80			40	9.1	77.0
83	35	86	40	4.4	89.0
86			39	4.1	89.5
89			40	4.2	89.5
92			40	3.6	91.0
95			40	4.5	88.8
98			38	5.1	86.6
101	22	91	40	4.3	89.3
104			40	4	90.0
107			39	3.2	91.8
110	`		40	3.9	90.3

113	20	92	42	3.5	91.7
116			40	4.5	88.8
119	22	91	44	4	90.9
132	30	88	43	15	65.1
134			40	3.5	91.3
137			43	3.6	91.6
140	27	89	42	4	90.5
143			41	3.5	91.5
146			41	3.2	92.2
149	25	90	44	4.2	90.5
152					
155			42	13	69.0
158	23	91	40	17	57.5
161			42	16	61.9
164	33	87	44	21	52.3
167			42	20	52.4
170	18	93	43	19	55.8
173			42	18	57.1
176	17	93	41	18	56.1
180	22	91	40	19	52.5
182	78	69	39	22	43.6
184	53	79	40	22	45.0
188	40	84	42	20	52.4
191	33	87	42	18	57.1
195	30	88	43	17	60.5
203	38	85	39	18	53.8
210	30	88	42	20	52.4
216	32	87	40	18	55.0
222	31	88	41	19	53.7
229	32	87	40	20	50.0
240	33	87	42	18	57.1

Table Appendix C-3. pH and DO at sampling points of the IFAS Reactor.

Days	SVI (mL/g)	Effluent Turbidity (NTU)	Influent pH	Aeration Tank pH	Effluent pH	Aeration Tank DO (mg/L)	Effluent DO (mg/L)
0	89.0	10	7.45	7.45	7.45	3.5	3.5
3	85.0	15	7.45	7.45	7.35	3.5	3.5
6	86.0	9	7.33	7.35	7.35	3.5	3.5
9	86.0	16	7.45	7.25	7.31	3.4	3.4
12	85.0	15	7.45	7.21	7.21	3.6	3.6
13	84.0	17	7.65	7	7.12	3.6	3.6
14	93.0	15	7.65	6.89	7.12	3.6	3.6
19	95.0	17	7.45	6.99	7.01	3.4	3.4
26	97.0	13	7.45	6.87	6.87	3.4	3.4
31	105.0	18	7.54	6.82	6.82	3.3	3.3
34	120.0	24	7.46	6.97	7.20	3.30	3.30
36	133.0	23	7.04	7.03	7.10	3.40	3.40
40	120.0	27	7.20	7.20	6.80	3.40	3.40
43	118.0	24	7.20	7.00	6.90	3.20	3.20
46	121.0	18	7.20	7.00	7.00	3.40	3.40
49	135.0	22	7.40	7.20	6.80	3.40	3.40
52	125.0	23	6.30	7.00	6.90	3.20	3.20
55	135.0	20	6.70	7.62	7.63	3.40	3.40
59	145.0	22	6.70	7.20	7.80	3.20	3.20
60	135.0	23	6.70	6.83	7.21	3.20	3.20
62	128.0	20	6.60	6.97	7.09	3.20	3.20
65	133.0	22	7.17	7.03	7.20	3.20	3.20
68	125.0	15	7.30	7.20	7.18	3.20	3.20
71	105.0	17	7.40	7.00	7.12	3.40	3.40
74	99.0	12.1	7.25	7.00	7.12	3.50	3.50
77	95.0	7.8	7.30	6.83	7.21	3.00	3.00
80	89.0	9.2	7.46	6.97	7.09	3.40	3.40
83	92.0	4.23	7.30	7.03	7.20	3.50	3.50
86	88.0	4.54	6.78	7.20	7.18	3.00	3.00
89	83.0	3.5	7.20	7.00	7.12	3.40	3.40
92	85.0	2.3	7.30	7.00	7.12	3.50	3.50
95	86.0	2.5	7.30	6.83	7.21	3.50	3.50
98	83.0	3.5	7.46	6.97	7.09	3.60	3.60
101	93.0	4.5	7.04	7.28	7.32	3.40	3.40
104	85.0	7.6	7.20	7.20	7.10	3.40	3.40
107	93.0	4.7	7.20	7.50	7.40	3.80	3.80

110	80.0	5.3	7.20	7.30	7.00	3.40	3.40
113	82.0	4.2	7.40	7.20	6.60	3.30	3.30
116	78.0	4.5	7.10	7.20	3.50	3.30	3.30
119	83.0	5.2	7.00	7.30	6.80	3.50	3.50
122							
125							
128							
132	120.0	14.5	7.20	7.10	7.20	3.50	3.50
134	83.0	7.9	7.20	7.10	6.80	3.40	3.40
137	86.0	6.3	7.20	6.90	6.90	3.20	3.20
140	96.0	8.2	7.20	6.90	6.90	3.60	3.60
143	86.0	10	7.10	6.70	7.20	3.80	3.80
146	98.0	8.3	7.20	7.00	7.10	3.40	3.40
149	103.0	10	7.10	7.20	6.80	3.20	3.20
152	102.0	8.4	7.10	6.90	6.90	3.30	3.30
155	103.0	10	7.20	7.30	7.00	3.02	3.02
158	105.0	13	7.40	7.20	6.60	3.20	3.20
161	110.0	18	7.20	7.10	7.10	3.40	3.40
164	115.0	20	7.10	7.20	7.10	3.00	3.00
167	105.0	21	7.20	7.30	7.00	3.80	3.80
170	115.0	18	7.40	7.20	6.60	3.50	3.50
173	113.0	16	7.20	7.10	7.10	3.60	3.60
176	114.0	17	7.10	7.20	7.10	3.40	3.40
180	117.0	18.5	7.20	6.80	7.00	3.50	3.50
182	235.0	43	7.2	7.2	7	3.4	3.4
184	158	51	7.1	7.2	6.8	3.4	3.4
188	128	32	7.2	7.3	7.2	3.5	3.5
191	130	28	7.2	7.2	6.6	3.5	3.5
195	101	26	7.2	7.1	6.8	3.1	3.1
203	108	27	7.15	7.1	6.8	3.2	3.2
210	103	24	7.2	7	6.9	3.8	3.8
216	104	25	7.32	7.21	6.8	3.7	3.7
222	110	24	7.59	7.12	6.7	3.4	3.4
229	124	26	7.24	7.3	6.8	3.14	3.14
240	119	24	7.24	7.28	6.9	3.5	3.5

Table Appendix C-4. Mean Particle Size of Activated Sludge Flocs and MLSS in Mixed Liquor the IFAS Reactor.

Days	Mean Particle Size at 50 µm Cut-off (µm)	Mean Particle Size at 50 µm Cut-off Standard Deviation	Mean Particle Size at 100 µm Cut-off (µm)	Mean Particle Size at 100 µm Cut-off Standard Deviation	Mean Particle Size at 500 µm Cut-off (µm)	Mean Particle Size at 200 µm Cut-off Standard Deviation	Mean MLSS (mg/L)	MLSS Standard Deviation
0	8.5	0.3	28.4	2.5	33.0	2.5	2394	7
3	8.2	0.2	25.9	1.8	35.0	1.3		
6	8.3	1.3	26.4	1.5	33.0	1.4	2473	23
9	8.5	1.2	27.5	0.5	34.0	2.5		
12	8.5	1.2	26.6	1.5	36.0	2.4	2473	102
13	8.4	1.9	26.7	1.4	35.0	1.7		
14	9.3	1.0	27.5	1.5	45.0	1.6	2405	72
19	8.4	0.9	26.5	1.4	46.0	1.9		
26	8.8	1.2	28.5	3.5	44.0	2.8	3033	694
31	8.6							
34	8.2	1.3	29.8	2.7	44.0	3.1	2540	42
36								
40	8.0	0.1	28.7	3.1	42.0	2.6		
43							2365	35
46								
49	7.1	0.3	27.8	1.2	45.0	5.5	1935	78
52								
55	8.0	0.4	26.5		46.0	2.3		
59							2275	106
60								
62	8.2	0.8	29.3	3.1	44.0	3.0	2265	49
65							2100	283
68								
71	9.3	1.3	29.5	4.2	47.0	5.3		
74							2460	57
77								
80								
83	18.2	0.9	33.5	3.2	49.5	3.0	2930	50
86								
89								
92	25.9	1.4	43.2	2.1	55.3	5.8		
95							2845	55

98								
101	26.1	0.9	51.6	0.3	69.5	1.5	2990	100
104								
107	24.2	1.5	57.6	2.3	81.0	3.0	3135	115
110								
113	26.7	2.4	55.3	3.1	81.0	4.0	3000	141
116								
119	25.5	3.5	54.3	4.5	78.4	4.8	3206	6
122								
125								
128								
132	29.3	3.3	53.2	4.1	80.2	4	3265	205
134								
137	30.9	2.1	54.4	3.1	83.1	5	3205	120
140							3460	240
143	32.3	3.3	56.3	2.1	84.2	2		
146							3050	226
149	31.2	3.5	58	3.2	80.6	3		
152							2935	92
155	29.0	2.1	43.2	3.3	60.2	4.2	2065	49
158	20.2	0.7	36.2	4.1	56.3	1.2	1860	57
161	15.8	0.5	26.8	2.7	46.3	2.1		
164	9.9	2.2	26.8	3.5	49.3	3.2	1950	85
167	7.5	1.0	28.7	2.1	45.2	2.1	2255	78
170	8.0	3.2	27.5	2.6	45.0	0.8	2100	127
173	10.2	1.2	28.3	4.2	35.3	4.2		
176	8.2	0.8	30.1	3.5	46.6	3.2	2055	92
180	10.2	1.1	27.1	0.4	48.2	2.1	2070	85
182	8.3	1.2	25.2	1.2	45.2	3.1	1865	64
184	7.7	1.3	20.8	1.3	40.2	5.2	1995	21
188	8.8	2.3	20.5	2.8	42.3	3.5	2175	35
191	7.5	2.1	22.5	2.5	45.3	4.3	2135	49
195	7.9	1.3	23.5	1.3	45.2	5.6		
203	9.0	2.5	24.6	3.3	44.2	4.5	2302	144
210	8.5	2.1	25.5	3.5	46.5	3.2		
216	8.5	0.9	25.1	1.2	47.5	3.8	2225	78
222	8.0	0.8	25.4	1.1	45.2	3.6		
229	7.6	1.6	26.8	1.8	45.3	4.2	2256	77
240	7.4	1.2	24.7	1.3	45.9	5.7	2055	64

Appendix D Sampling Locations of Surveyed WWTPs

1. Sampling at JWPCP

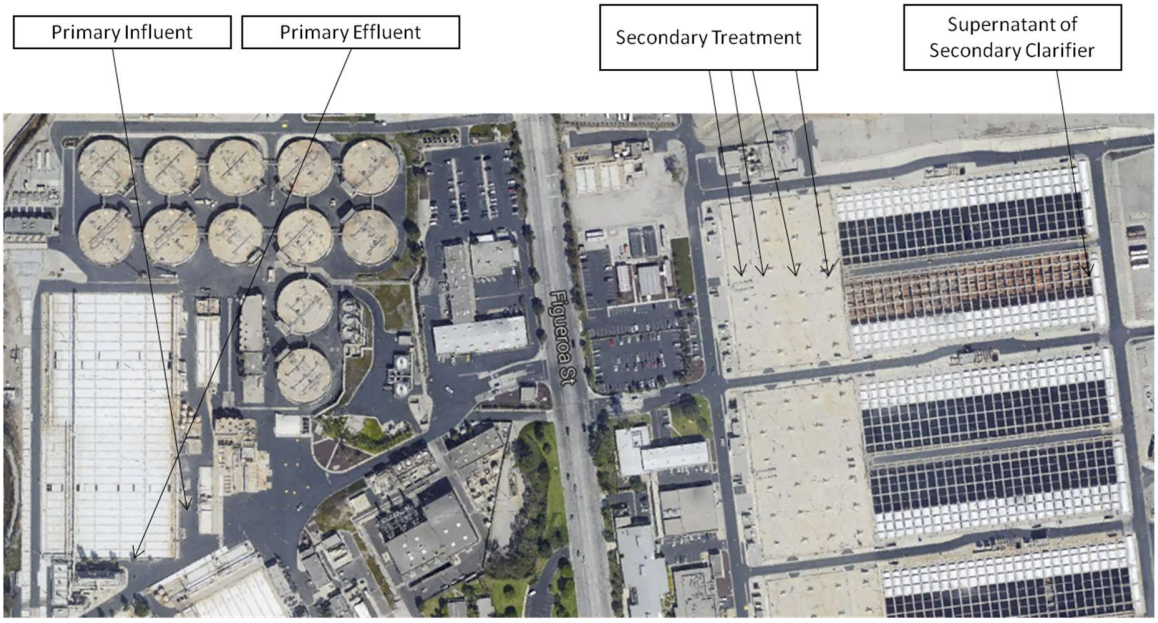

Figure Appendix D-1. Overview of treatment process of JWPCP.

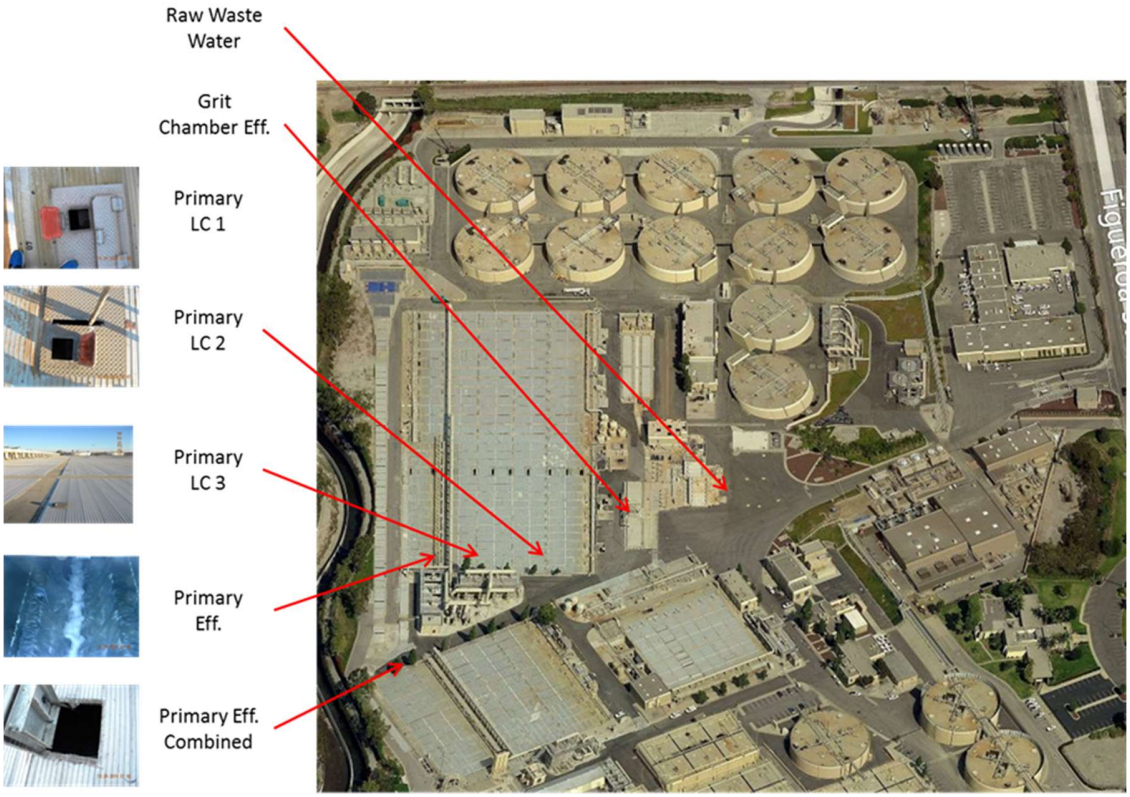

Figure Appendix D-2. Sampling locations in JWPCP at west side.

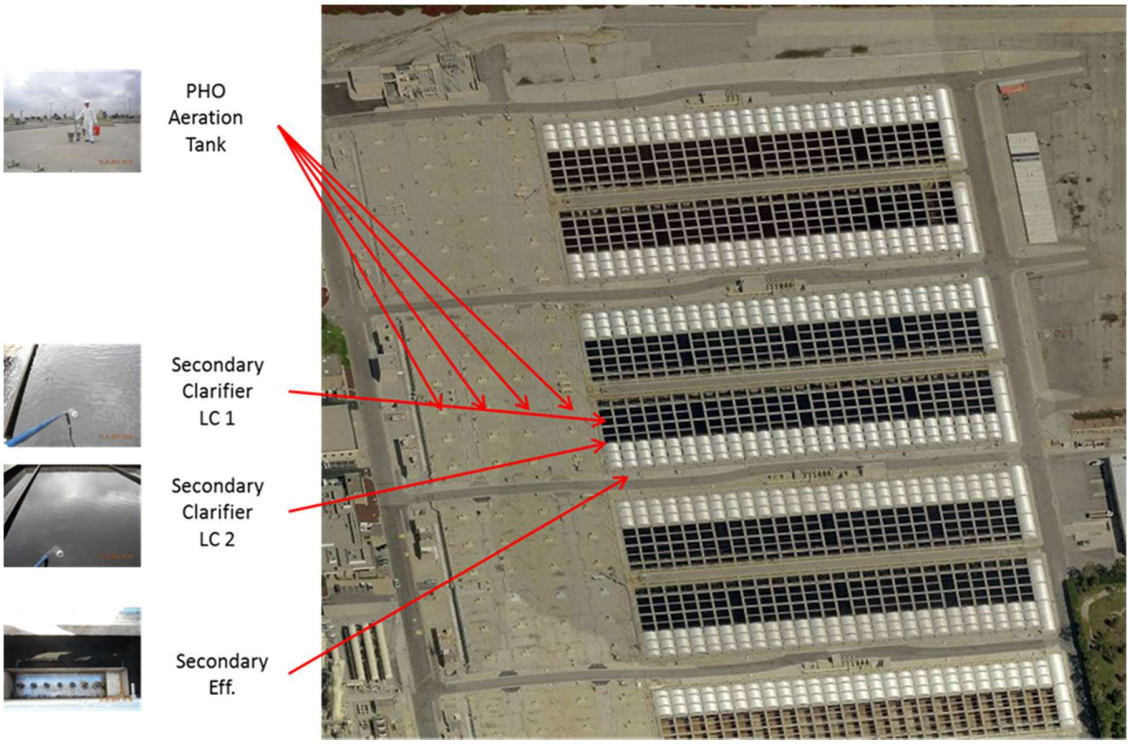

Figure Appendix D-3. Sampling locations in JWPCP at east side.

2. Sampling at SJCE WRP

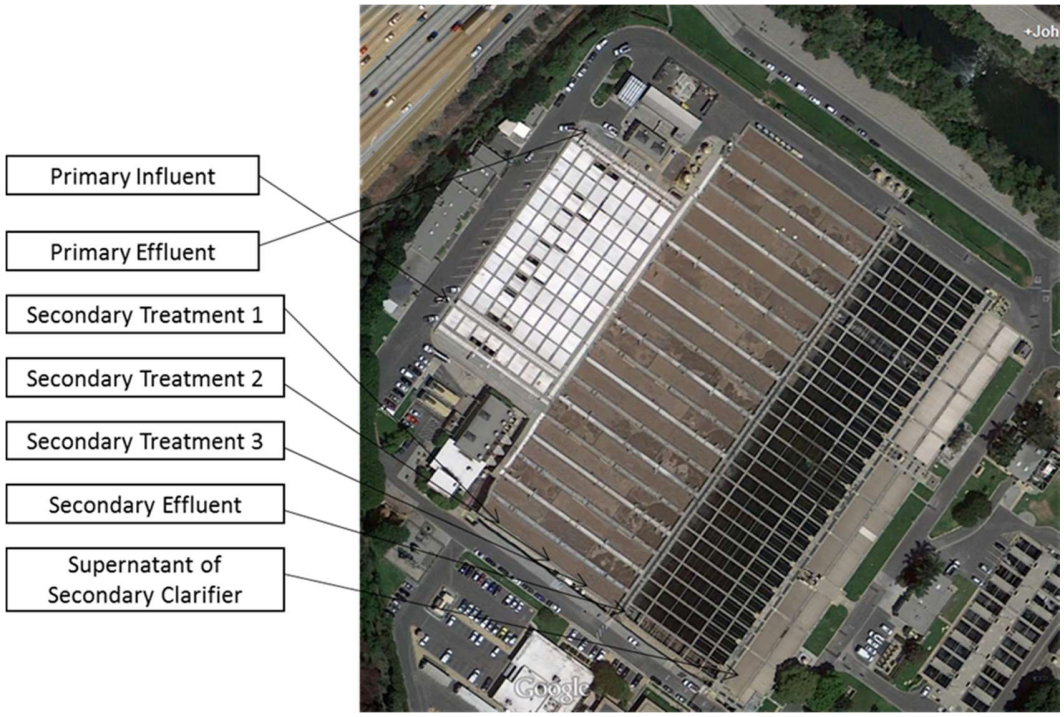

Figure Appendix D-4. Overview of treatment process of SJCE WRP.

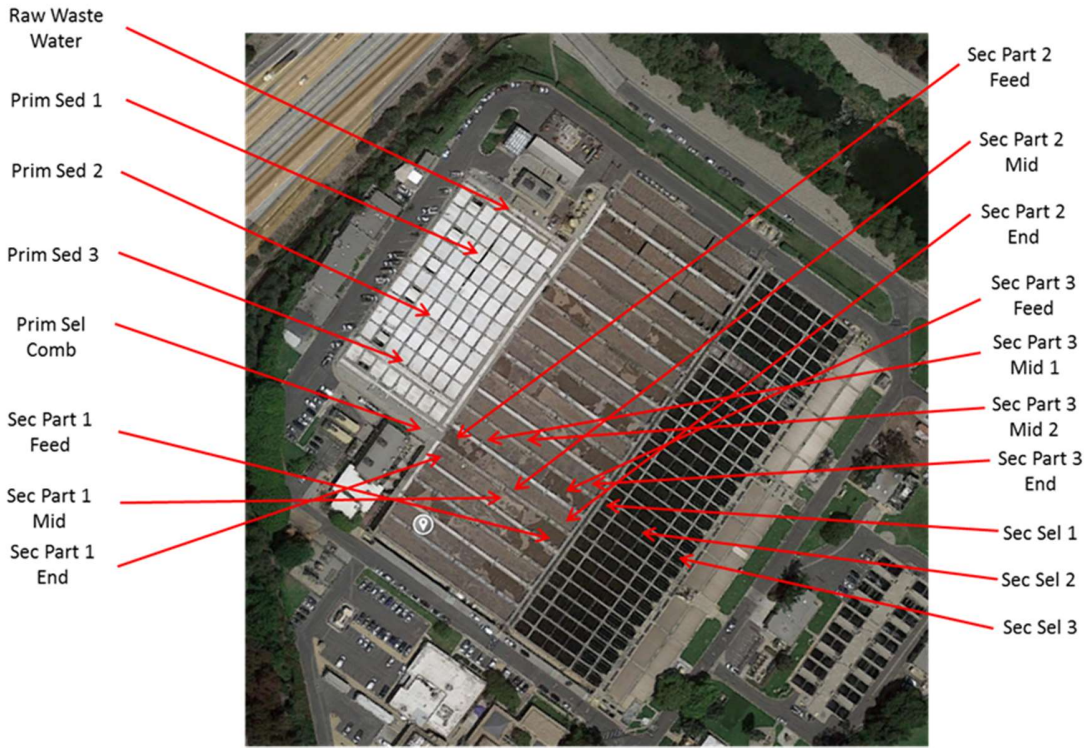

Figure Appendix D-5. Sampling locations in JSCE WRP.

3. Sampling at SJCW WRP

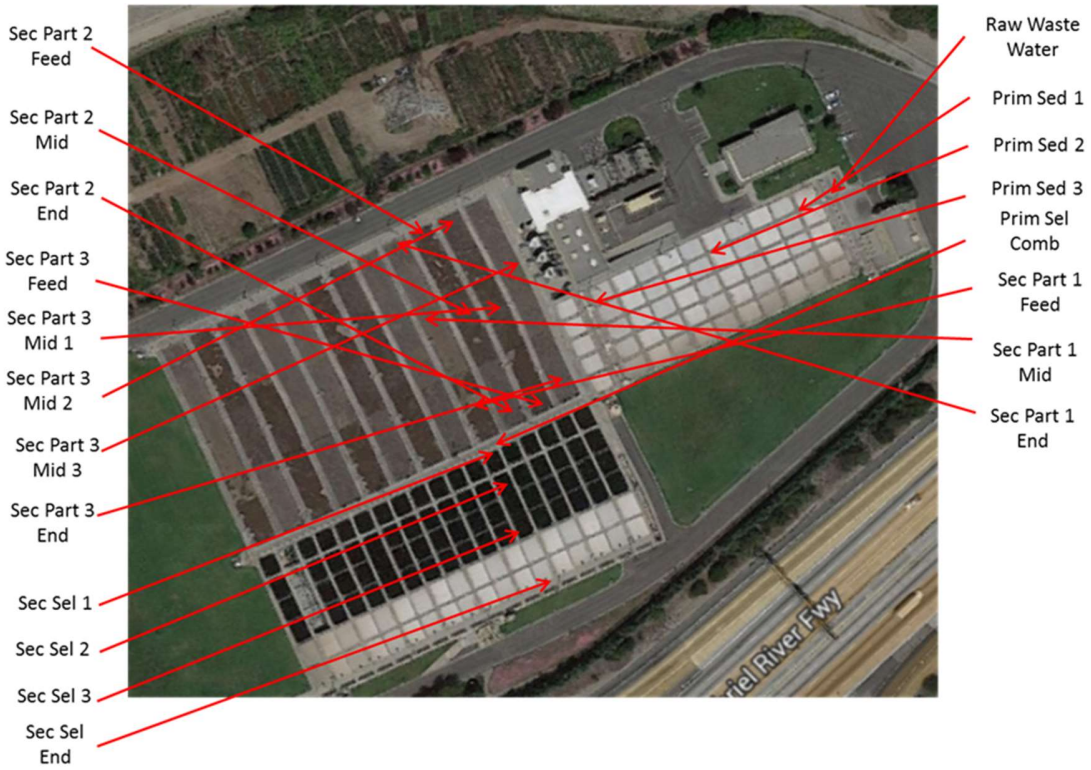

Figure Appendix D-6. Sampling locations in JSCW WRP.

4. Sampling at Whitter Narrows WRP

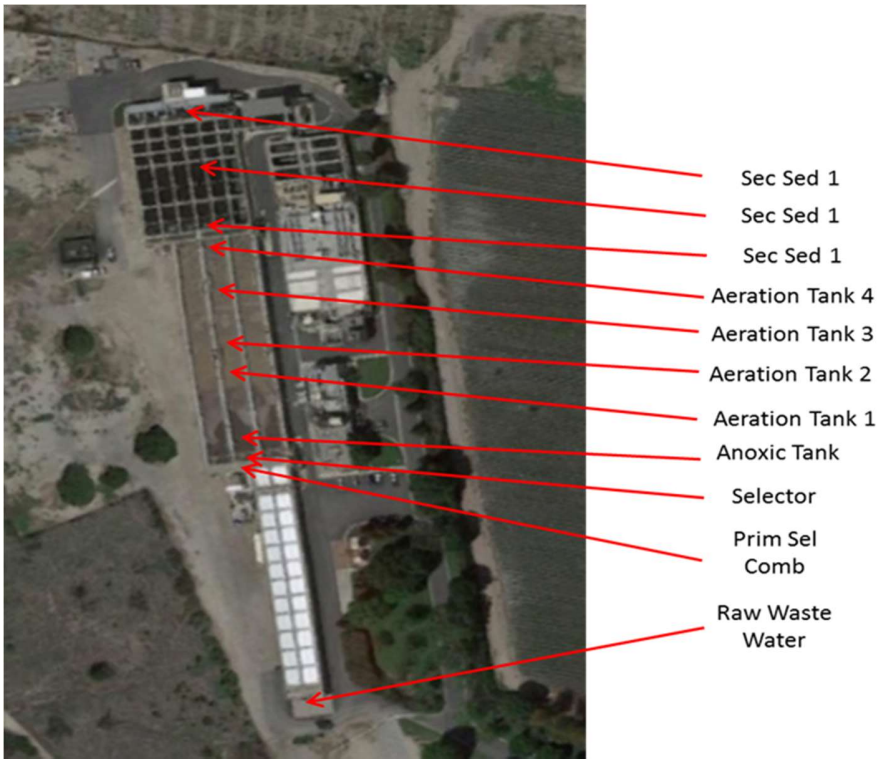

Figure Appendix D-7. Sampling locations in Whittier Narrows WRP.

5. Sampling at Donald C. Tillman WRP

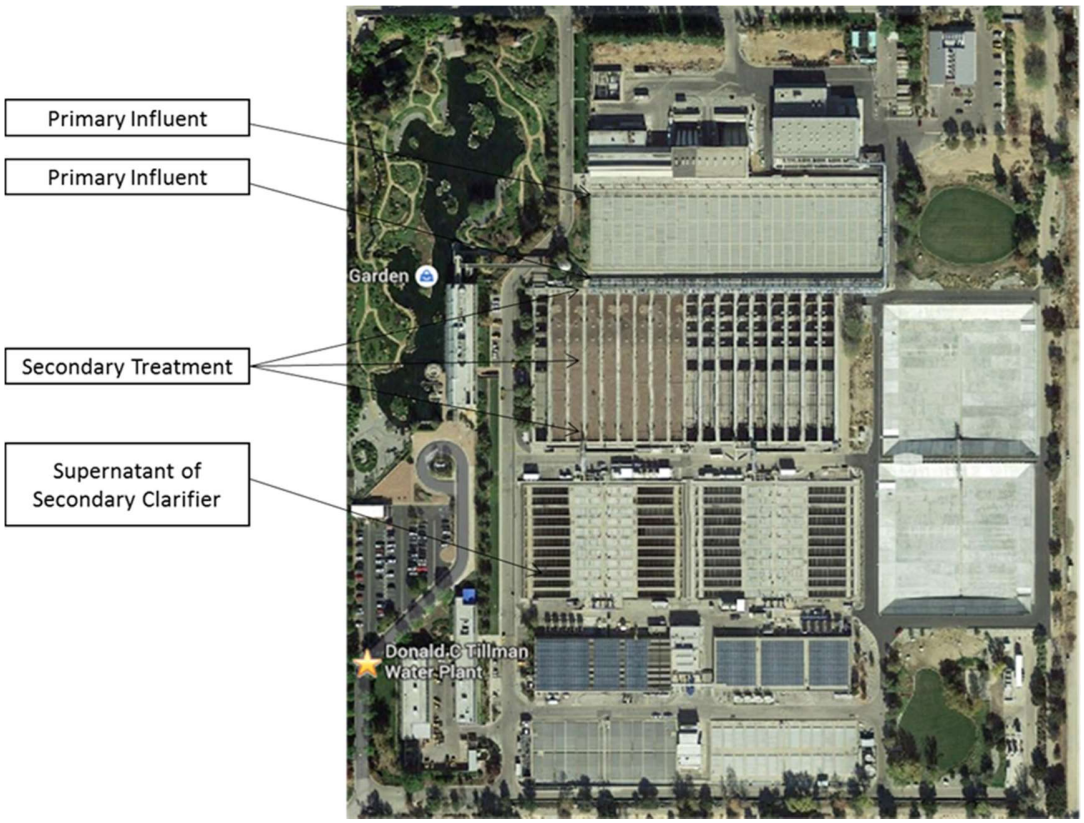

Figure Appendix D-8. Overview of treatment process of Donald C Tillman WRP.

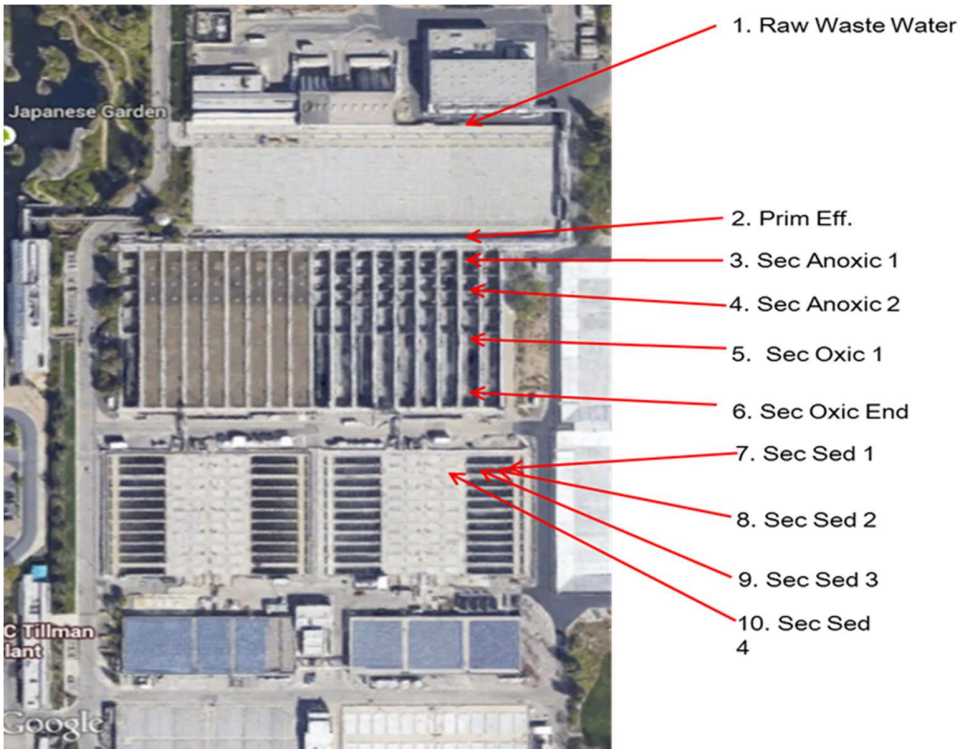

Figure Appendix D-9. Sampling locations in Donald C Tillman WRP.

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