REPUBLIC OF TURKEY
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DEVELOPMENT OF A MATHEMATICAL MODEL OF A SECONDARY SETTLING TANK IN WASTEWATER TREATMENT PLANTS WITH CONTROL PURPOSES

M. Sc. THESIS
IN
ELECTRICAL AND ELECTRONICS ENGINEERING

BY
FOUZAN ISHAQUI SYED
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Asst. Prof. Dr. Tolgay KARA

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Fouzan Ishaqui SYED

ABSTRACT

DEVELOPMENT OF A MATHEMATICAL MODEL FOR A SECONDARY SETTLING TANK IN WASTEWATER TREATMENT PLANTS WITH CONTROL PURPOSES

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M.Sc. in Electrical and Electronics Engineering
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Sedimentation is one the most important processes in the understanding of wastewater treatment plants, and secondary settling tanks have been frequently investigated with mathematical models for design and operation. Modeling of secondary settling tanks has been a difficult problem due to highly coupled dynamics and non-linearity in the settling of sludge particles. A process control engineering approach is required to formulate the settling process and provide feedback control solutions for compensation of disturbances like rainfall and overflow. The main purpose of this research is to develop a mathematical model that covers all significant dynamics involved in the secondary settling tank of a typical wastewater treatment plant. The developed model is simple enough for computer simulations and convenient for feedback control applications, and it allows for freedom to maneuver with hindered settling, compression and dispersion properties of the suspended solids in a settling tank. Computer simulations are performed for testing the developed model in realistic conditions, and results are analyzed. A discussion of the simulation results is presented to reveal the efficacy of the developed model and possible implementation for feedback control solutions.

Key Words: Secondary Settling Tanks, Mathematical Modeling, Wastewater Treatment, Feedback Control.

ÖZET

ATIKSU ARITMA TESİSLERİNDE İKİNCİL ÇÖKELTME TANKININ KONTROL AMAÇLI MATEMATİKSEL MODELİNİN GELİŞTİRİLMESİ

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İkincil çökeltme tankları, atık su arıtma tesislerinde yer alan önemli süreçlerden biridir. Sürecin tasarım ve istenen değerlerde çalıştırılması için matematiksel modeline sıklıkla başvurulur. İkincil çökeltme tanklarının modellenmesi, çamur taneciklerinin çökelmesinden dolayı doğrusal olmayan ve yüksek derecede birbirine bağlı dinamikler ortaya çıkmaktadır bu sebeple oldukça zor bir problem haline dönüşür. Yağmur ve taşma gibi bozucuların etkilerini kaldırmak için çökeltme sürecini formüle etmek ve geri beslemeli kontrol çözümleri sağlamak amacıyla bir süreç kontrol mühendisliği yaklaşımı gerekmektedir. Bu araştırmanın temel amacı, tipik bir atıksu arıtma tesisinin ikincil çökeltme tankının yer alan tüm önemli dinamikleri kapsayan bir matematiksel modelini geliştirmektir. Geliştirilen model, bilgisayar simülasyonları için yeterince basit ve geri beslemeli kontrol uygulamaları için elverişlidir ayrıca çökeltme tankındaki asılı katıların sıkıştırma, dağılma ve engellenmiş çökeltme özelliklerini manevra özgürlüğü de kazandırır. Gerçekçi koşullarda geliştirilen modeli test etmek için bilgisayar simülasyonları yapılmış ve sonuçlar analiz edilmiştir. Geliştirilen modelin etkinliğini ve geri beslemeli kontrol çözümleri için olası uygulamayı ortaya koymak için simülasyon sonuçları tartışılmıştır.

Anahtar Kelimeler: İkincil Çökeltme Tankları, Matematiksel Modelleme, Atıksu Arıtma Tesisi, Geri Beslemeli Kontrol.

To My Parents

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LIST OF SYMBOLS/ABREVIATIONS

A	Cross-sectional area of SST [m^2]
B	Depth of thickening zone [m]
C	Concentration in SST [g/L]
C_c	Critical concentration [g/L]
C_{min}	Parameter in settling velocity function [g/L]
C_{max}	Maximum concentration [g/L]
d_{comp}	Compression function [m^2 s]
d_{disp}	Dispersion function [m^2 s]
F	Convective flux function [kg/ (m^{2}s)]
F^{num}	Numerical flux [kg/ (m^{2}s)]
f_{bk}	Kynch batch flux density function [kg/ (m^{2}s)]
G	Godunov numerical flux [kg/ (m^2/ s)]
g	Acceleration of gravity [m/s^2]
H	Height of clarification zone [m]
J_{disp}, J_{comp}	Dispersive and compressive fluxes [kg/ (m^{2}s)]
N	Number of layers in SST
Q	Volumetric flow rate [m^3/h]
r_v	Parameter in Vesilind settling function [m^3/kg]

t	Time [h]
v_o	Model parameter [m/h]
v_{hs}	Hindered settling velocity [m/h]
X	Concentration in SST [g/L]
z	Depth from feed level in SST [m]
ΔC	Step-size of discretization of C-axis [kg/m^3]
Δz	Layer width of numerical method [m]
α	Parameter in effective solid stress function [Pa]
α_1, α_2	Parameters in dispersion coefficient ([m^{-1}] and [s/m^2])
β	Parameter in effective solid stress function [kg/m^3]
γ	Characteristic function, equals 1 inside and 0 outside SST
δ	Dirac delta distribution [1/m]
ρ_s	Density of solids [kg/m^3]
ρ_f	Density of fluid [kg/m^3]
σ_e	Effective solid stress [Pa]
e, f, u	Effluent, feed, underflow (subscripts)
num	Numerical (convective, compressive or dispersive) flux function (superscript)
ASP	Activated Sludge Process
BD	Bürger-Diehl
COD	Chemical oxygen demand
CFL	Courant, Friedrichs and Lewy
ML	Mixed liquor

MLSS	Mixed liquor suspended solids
ODE	Ordinary Differential Equation
PDE	Partial Differential Equation
RAS	Return Activated Sludge
SBH	Sludge Blanket Height
SST	Secondary Settling Tank
SVI	Sludge Volume Index
TN	Total nitrogen
TP	Total phosphorus
WWTP	Wastewater Treatment Plant

CHAPTER 1
INTRODUCTION

1.1 Background

Water is a precious resource in our age of development. With the current research being made all over the world on how to achieve clean water with less consumption of energy and time, methods like desalination, reverse osmosis and water beds are popping up in various parts of the world. With the advancement in clean water the next generation of clean water will be presumably be expected from wastewater treatment plants.

Likewise, extreme weather conditions and climate change can be excruciating factor in determining the performance of secondary settling tanks (SST) in wastewater treatment plants (WWTP). A secondary settling tank's performance proportionally relates to the concentration of sludge in the effluent flow. A poorly performing SST can result in high solid sludge concentration and an unclean effluent.

In extreme weather conditions like periods of drought and heavy rainfall would result in biological and hydraulic overload in SSTs. The best way to overcome such a calamity is optimizing and controlling the tank. With recent studies in the field of WWTPs, we have been presented with numerous mathematical models studying the dynamics but up till now it has been a very daunting task to apply in the real field. This thesis will discuss various mathematical models proposed over the time, however, failed to predict the settling behavior under heavy load conditions or very low load conditions and also introducing the recently proposed new model by Bürger et al. [33] which overcame the drawbacks of other models.

1.2 Objectives and Contributions of the Thesis

A secondary settling tank is a combination of discontinuous and nonlinear complex processes, it is the aim of this thesis to provide a good overview of the processes and present a comprehensive mathematical model with at least 80% accuracy.

The SST is often referred to as the bottleneck of the activated sludge process, the highly complex 2-D and 3-D models which recently became popular are still too complex for simple computation and practicality. The second objective is to compare the simulated data from the proposed model with literature data. Simultaneously, to verify the model's efficiency by comparing the real data from the Oğuzeli wastewater treatment plant with data from the achieved simulated model.

The final objective is to present a process control engineer's approach to the mathematical model by presenting an applicable controller. Therefore, to present the model in a manner that it should be identifiable for process control and provide a starting point for classical, adaptive, neural or fuzzy-logic based control. In a broader perspective, the objective of this thesis is to cover different aspects of secondary clarifier.

The main results of this thesis are summarized in Chapter 5 together with some suggestions for future research.

The major contributions of the thesis are given below.

- A modelling methodology is discussed when presenting a new mathematical model.
- A potential one-dimensional mathematical settler model is thoroughly discussed, its validity is assessed through testing under different weather conditions.
- A comparison is laid out with a real wastewater treatment plant with different seasonal offline data.
- Different control strategies are proposed for efficient output of the model under different load conditions.
- A pseudo code explaining the modelling of the said model is presented for future researches to follow up with the research.
- At its entirety, a model which is easily computable with higher efficacy and possible control structures is presented.

1.3 Outline

From second chapter onwards, the background and functions of a secondary settling tanks are discussed, followed by the settling behavior within a settler is discussed in detail.

In the third chapter, 1-D modelling and its methodology will be discussed. In the second part, various models proposed from Takács et al. model to the latest Bürger et al. will be mentioned.

The fourth chapter will present simulations of the model for various weather conditions and validating the model by comparing the data collected from the wastewater treatment plant with the simulated data. The achieved results will be discussed and in the latter part a control strategy will be proposed for the model. The final chapter will discuss the conclusion drawn and areas for further research.

CHAPTER 2

LITERATURE REIVEW

2.1 Wastewater Treatment

As civilization developed and cities urbanized, the domestic sewage and industrial waste were directly flown into the drainage or sewer systems which would lead to the nearest watercourse. For major cities, the discharge was enough to destroy the whole water bodies. Since the advent of wastewater treatment plants, the issue of polluting the water sources has been averted. But in recent times, a demand for much cleaner and chemical free water from the wastewater treatment plants is on the rise. This has led to more research and development in the field of wastewater treatment.

The conventional wastewater treatment plant uses a combination of three different process: a primary treatment, secondary treatment and tertiary treatment (see Figure 2.1). During the primary treatment the most objectionable content which pollutes the water, coarse material, large particles and floating oils and greases can be removed.

The secondary treatment is mostly referred to as biological treatment and the organic component present in the wastewater is generally degraded through different methods of introducing chemical compounds. The most commonly used method is Activated Sludge, which was first introduced by Arden & Lockett [1]. The activated sludge (AS) system allows to overcome the natural limitation for bioconversion such as limited aeration and limited amount of biomass [2]. Therefore, the AS system has the possibility of accelerating the natural purification process that occurs in our water systems, which is a major advantage. Additionally, the process structure can also be adapted to include nutrient removal in the biological process [3].

A typical AS system consists of two main components: a biological process and a sedimentation process. The wastewater once treated at primary treatment is transferred to an aeration tank. Here, it is mixed with a diversified set of microorganisms, also called activated sludge, mainly for converting the organic matter into biofilms. The biomass concentration in the tank is called the mixed liquor suspended solids (MLSS) concentration. The tank is aerated in order to keep the sludge in suspension and providing the microorganisms with adequate oxygen for the biochemical conversion of the organic matter. The process is completed by transferring the mixed liquor from the aeration tank to the secondary settling tank.

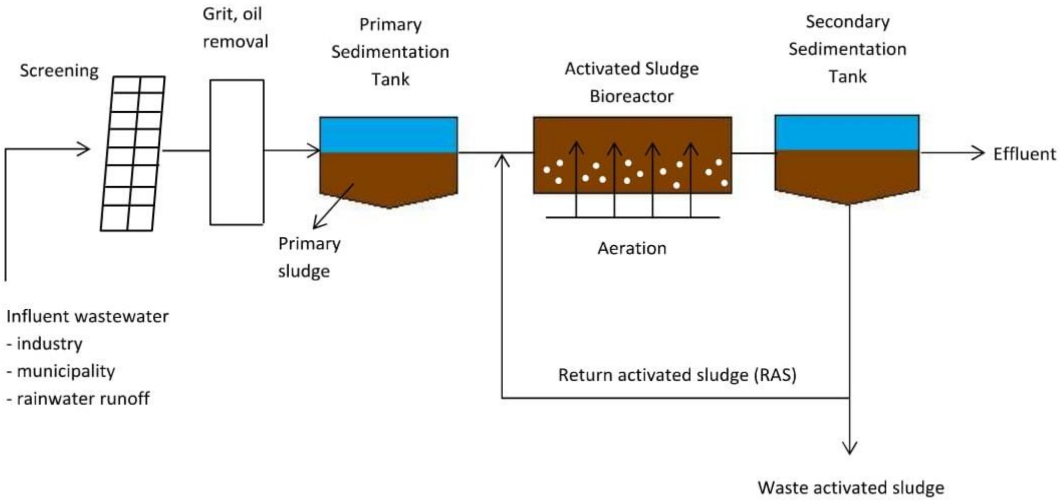

Figure 2.1 Schematic diagram of Wastewater Treatment Plant (modified from [64])

Part of the settled sludge is recycled to the aeration tank (Return Activated Sludge - RAS) and the remaining part is wasted called Waste Activated Sludge [3]. Besides sedimentation settling, the wastewater treatment plants increasingly use membranes to perform the solid-liquid separation. However, they are still expensive and additional research is required to deal with operational problems (e.g. membrane fouling) [4, 5].

Finally, the tertiary treatment is the final treatment process where the effluent is disinfected in order to destroy pathogens [6]. More rigorous processes are implemented with respect to the effluent concentration requirements. However, rarely do we see them implemented in WWTPs, usually the effluent from the sedimentation tank is flown into the river directly.

2.2 Secondary Settling Tank

2.2.1 Layout of a Typical SST

As mentioned earlier, the final step of the activated sludge process requires the mixed liquor transferred to the secondary settling tank. It is usually performed in a concrete basin where the heavy solid activated sludge mass is collected at the bottom of the tank as sediments while the cleaner much purer water is flown out through the output effluent [2]. The most commonly used clarifier configurations are circular and rectangular tanks.

- Rectangular clarifiers are basically big concrete structures with similar interior structures with inlet and outlet channels (see Figure 2.2). Tanks are retrofitted with sludge collection mechanisms which transports the settled sludge to a waste disposal truck. Alternatively, a suction based sludge removal can also be implemented for solid removal from bottom of the tank. The length-to-width ratio of the each settler basin is usually 3:1 to 15:1 [7]. Rectangular clarifiers are construction cost reduction due to use of common walls between individual tanks and longer flow path minimizes uneven flows. Also, the sludge bulking and thickening are reasonably better leading to higher effluent weir loading rates. On the other hand, long detention time of settled sludge causes ineffective high solids loading conditions.

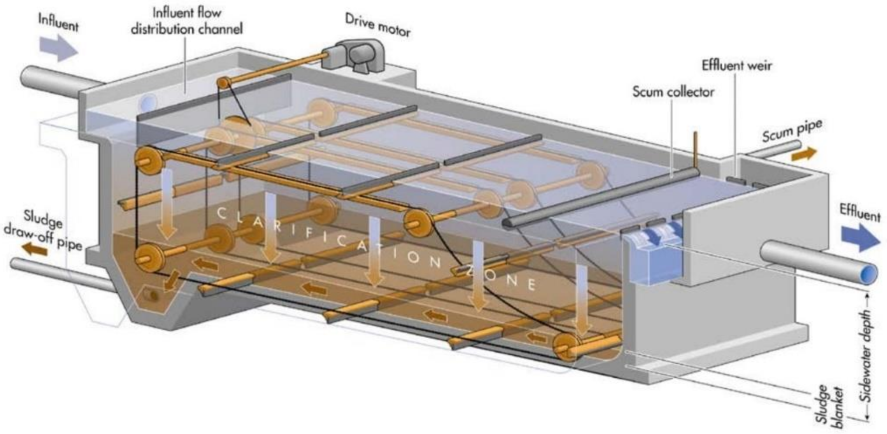

Figure 2.2 Schematic Diagram of Rectangular clarifier [7]

- Circular clarifiers usually comprise of an inlet structure, a cylindrical clarification zone, a conical sludge accumulation zone, and effluent weirs (Figure 2.3). The influent is introduced at the center of the tank or around the periphery of the tank. It is designed to distribute the flow equally in all the directions achieving a radial flow pattern. It is usually has 1:10 to 1:12 slope ratio of the bottom conical surface and depends on the type of the sludge collection mechanism. Generally, the circular tanks with center feed are widely utilized [7].

  In these tanks, an orifice channel is present around the periphery of the tank and from there the flow discharges into the sedimentation tank. The SST provides quiescent flow conditions in the sludge mass settling. The thickened sludge blanket formed at the bottom of the tank is collected and directed to the sludge hopper by the tilted tank slope and a rotating sludge removal system. Circular clarifier have shorter detention time for settling sludge and much simpler sludge collection system. However, lower sludge settling detention causes higher short-circuiting potential and higher flow distribution head losses.

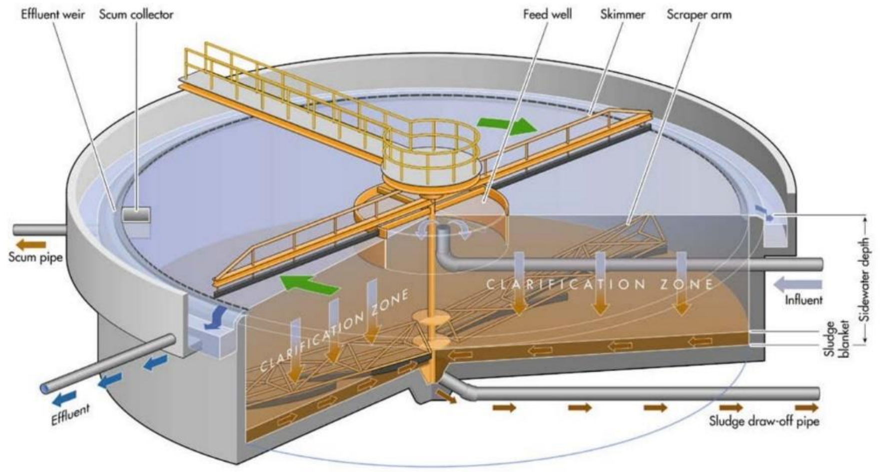

Figure 2.3 Schematic Diagram of a Circular Clarifier [7]

A circular settling tank with a central feed system is one of the most popular configuration, characterized by a radially outward flow of ML to a peripheral effluent weir [2,3,8]. This thesis will be focused on circular configuration tank.

2.2.3 Performance of a SST

The different factors affecting the performance of the SST are related to the clarifier tank design and the operational controls [9] divided into three important functions:

1. Thickening function: A continuous production of underflow thickened sludge to return to the aeration tank. It depends on the settling and thickening behavior and concentration of the sludge in the tank.
2. Clarification function: The efficiency of clean and desirable effluent concentration. The amount of biomass entering the SST settles is around 98% and the remaining biomass has a significant effect on the effluent quality as it contributes to COD, TN and TP.

3. Storage function: During non-deal flows: rainfall, storm or flooding, the SST is expected to store sludge without causing an increase in effluent sludge concentration.

If the clarifier failed to achieve the functions above, the resulted effluent quantity will be poor and an uncontrolled decrease of MLSS causing the sludge age to have a deteriorating influence on the performance of the biological process [9].

2.3 Settling of Activated Sludge

Settling process of an activated sludge is the foundation of the SST functioning [10, 11]. The settling behaviors of the activated sludge can be described in four different categories [9]. The four classes are listed below and are illustrated in Figure 2.5.

- Class I: Discrete non-flocculent settling or discrete settling.
- Class II: Discrete flocculent settling or flocculent settling.
- Class III: Zone settling or hindered settling.
- Class IV: Compression settling.

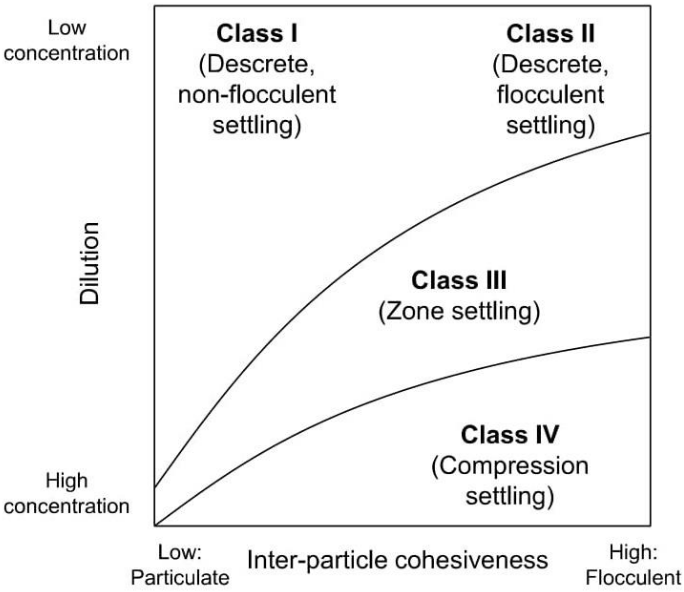

Figure 2.4 Sludge settling behavior [12]

At lower concentrations, the activated sludge tends to naturally settle down within a SST [9]. However, in the top region of a SST the concentration is typically too diluted for particles to sense each other. The particles at this concentration are so dispersed having no physical contact and with the least propensity to flocculate. Particles settle at a terminal velocity based on the physical characteristics. This phenomenon is called discrete non-flocculent settling (Class I). However, when the particles choose to flocculate, they settle down as individual large flocs. This regime of settling is called discrete flocculent settling (Class II). As the concentration of the solid particles increases in the tank, the distance between the flocs decreases, and they no longer settle as individuals but rather in bulk, resulting in hindered/zone settling (Class III). These two settling regimes are also called as clarification, because they both occur in the clarification zone. Both these regimes play an important role in the performance of the SST because of its direct relation to the effluent concentration. Poorly settled particles remain in the supernatant and are eventually carried over to the effluent weir. The phenomenon of hindered settling can be easily understood using Probstein's two phase method. [13]. As the particles settle, an upward motion of water causes an increase in the particle drag, resulting in a decreased relative settling velocity of MLSS. This idea was further researched by Kynch [14] based on the assumption that the particles settle with the velocity that is only a function of local concentration. In this regime, the indirect interaction forces of the sludge particles becomes sufficiently strong enough to cause a zone settling and an interface can be observed. This distinct interface between the clear supernatant and the subsiding flocs is called the sludge blanket. As the flocs reach the sludge bed at the bottom of the tank, and concentration increases above 3-7g/L, the particles, in addition to gravity and drag forces, are exposed to the inter-particle compressive stress and settle slower than in zone settling, the settling behavior changes to compressive settling (Class IV). The dependency rate of exact transition concentration is based on the settleability of the sludge [15]. The particles at these high concentrations, with no room to move, are compacted and compressed due to the sheer weight of the settled particles. This leads the flocs to an additional force

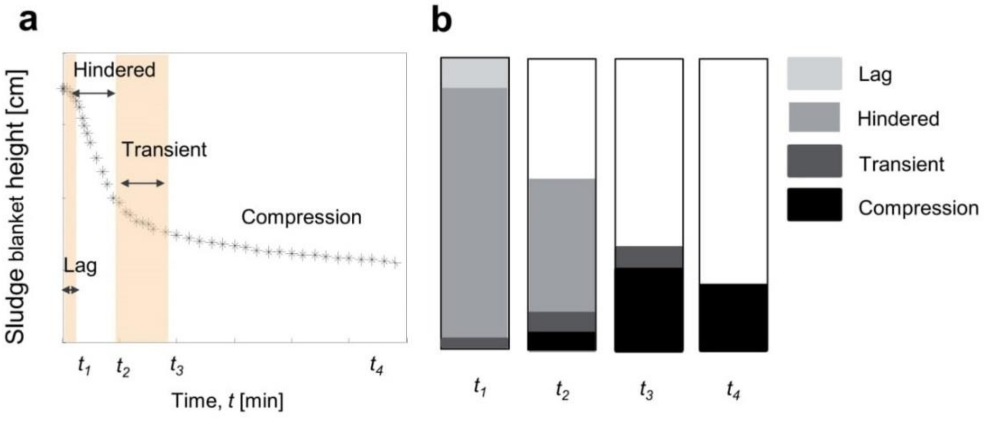

Figure 2.5 (a) Graphs of different settling regimes of activated sludge observed by measuring the sludge blanket height, (b) batch settling tests [12]

due to a compressive stress which thickens each layer and pushes the water in an upward direction.

Normally, batch column settling tests are performed for understanding the settling characteristics of solid sludge particles, where the height of the descending liquid or solid interface level (SBH) is measured and observed at several time instants. During the settling test, four different settling regimes are typically identified (Figure 2.6): (1) lag, (2) hindered/zone, (3) transient, and (4) compression settling [9].

At the beginning of the test up to time t_1 the fluid is in the lag phase. In this particular phase, the ML needs to recover from disturbances caused by turbulence effects that emerged during the filling of the settling column [12]. Instantaneously after the startup of the test, four regions are noticeable at increasing depth in the tank. At t_2, it can be seen the top region being the cleanest consisting of supernatants followed by regions where zone settling, transition settling and compression settling is taking place [9].

2.3.1 Hindered Settling Velocity

In a sedimentation process, the hindered settling velocity is crucial in determining the solids flux in a secondary settler. In general it is included at two different conditions, settling at low solid concentrations and settling at high solid concentrations. As mentioned earlier, the sludge blanket can be easily observed between the subsiding solids and clear supernatant which allows for easy determination of settling velocity with the help of batch settling tests for a set of measured initial concentrations [9]. During these tests a batch of RAS over a range of diluted concentrations (C) is settles under still conditions in a cylinder. The height of the sludge blanket is measured at predefined time instants. Subsequently, the settling velocity can be determined as the slope of the linear part of the settling curve [16]. In literature, mathematical expressions defining hindered settling velocity as a function of sludge concentration can be found [17-23]. The most commonly used are discussed below and are shown in Figure 2.7.

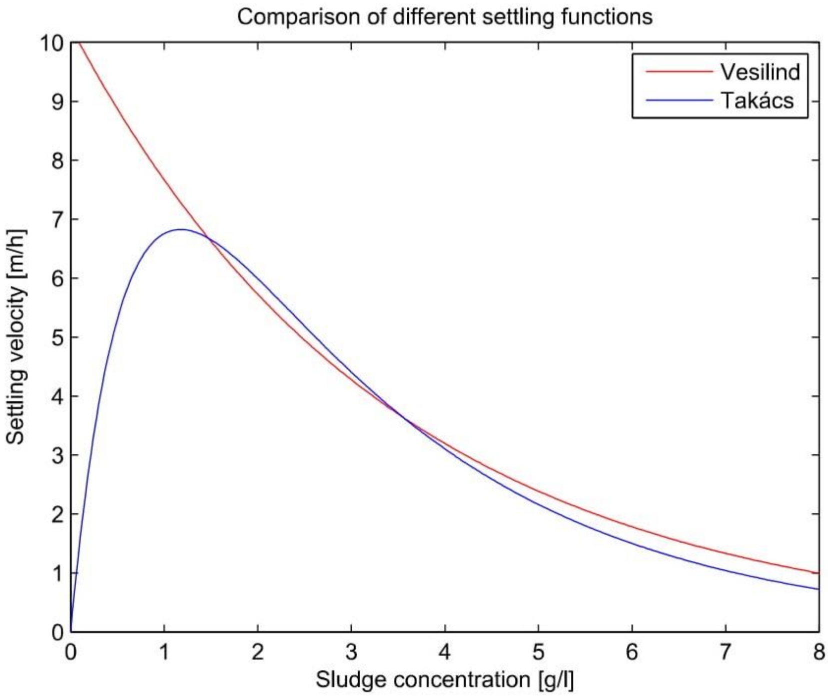

Figure 2.6 Comparison of different settling functions [16]

2.3.1.1 Vesilind settling function

In case of Vesilind settling function, an exponential decaying function is suggested to describe the relation between sludge concentration and hindered settling velocity (2.1). In this equation v_{hs} represents the settling velocity of the sludge, v_0 the maximum settling velocity, r_v a parameter model and C the solids concentration.

$$v_{hs}(C) = v_o(e^{-r_v C}) \qquad (2.1)$$

2.3.1.2 Takács settling function

As seen from the figure the settling velocity function of Vesilind will continue to increase as the solids concentration becomes small. This does not correspond to reality where very low concentrations will show much lower settling velocities. To account for this flaw, Takas et al. added another exponential term resulting in (2.3) [19]. In this equation r_h is the settling characteristic of the hindered settling zone, r_p is the settling characteristic of low solids concentration and C_{min} is the concentration below which the v_{hs} becomes 0. Even though Takács velocity model does account for lower concentrations but its predictability of settling is unreasonably random and difficult to calibrate [23].

$$v_{hs}(C) = \max\{\, 0, \min\{\grave{v}_0, v_0\big(\, e^{\,-r_h(C-C_{min})} - e^{\,-r_p(C-C_{min})}\big)\}\} \qquad (2.2)$$

2.3.1.3 Other settling functions

Cho et al. suggested an extension to the settling function of Vesilind. The settling function of Cho is given in (2.3). In this equation v_{hs} is the settling velocity, k and n are parameters for this relation and C the solids concentration [21].

$$v_{hs}(C) = \frac{k\ e^{-nC}}{C} \tag{2.3}$$

Settling velocity functions $v_{hs}(C)$ for 2-D and 3-D models have been proposed which takes into account the discrete settling of solid particles at lower concentrations [24]. However due to computational reasons, they are not extensively calibrated and not tested. Ramin proposed a better settling velocity functions which accounted for different settling regimes [22]. While Zhang proposed settling behavior based on RAS flow by validating a simple empirical model with measurable parameters (t_s and SVI) [25]. In this thesis, however, Vesilind settling function will be used for modelling for its simplicity and one local maximum for calculating Godunov flux which will be discussed in Section 3.4.

CHAPTER 3

MATHEMATICAL MODELLING OF SSTs

3.1 Introduction

Understanding the static and dynamic behavior of a system without the need of numerous practical experiments requires a mathematical model of the system. In practice, an experimental approach is quite tedious to implement as it often is barred with serious limitations [26]. In the development of a model for any system it consists of three main sources of information (Figure 3.1):

- a priori knowledge
- experimental data
- modelling objectives

The model structures within a methodology consisting of unidentifiable parameters are useless, and a priori identification analysis is compulsory [27]. In overview, the modelling of any system follows these steps, gaining a priori knowledge, designing the model as per the model objectives, an appropriate model for the desired application be it optimal control or designing purpose and followed by rigorous simulations of the designed model and if and only if the simulated data reaches the desired objective output it is termed as validated else it is required to reiterate the steps to the beginning of the model information. It must be noted that an efficient model for operation and control can be regarded as a simple model which supports for parameter update while functioning as a real complex process [27].

The secondary settling tanks are essentially the driving force for the efficient performance of activated sludge process based WWTPs [9]. However, the aeration tank has been much widely studied and researched compared to the settler tanks. This is partly due to the diversity and complexity of the nonlinearity involved in the settling process within SST [28]. SSTs maybe regarded as subsidiary to the entire wastewater treatment process but are in fact the central part of the activated sludge process. In theory, it's a separation process of solid sludge from fluid by gravity settling, and have two similarly distinct functions: clarification and thickening.

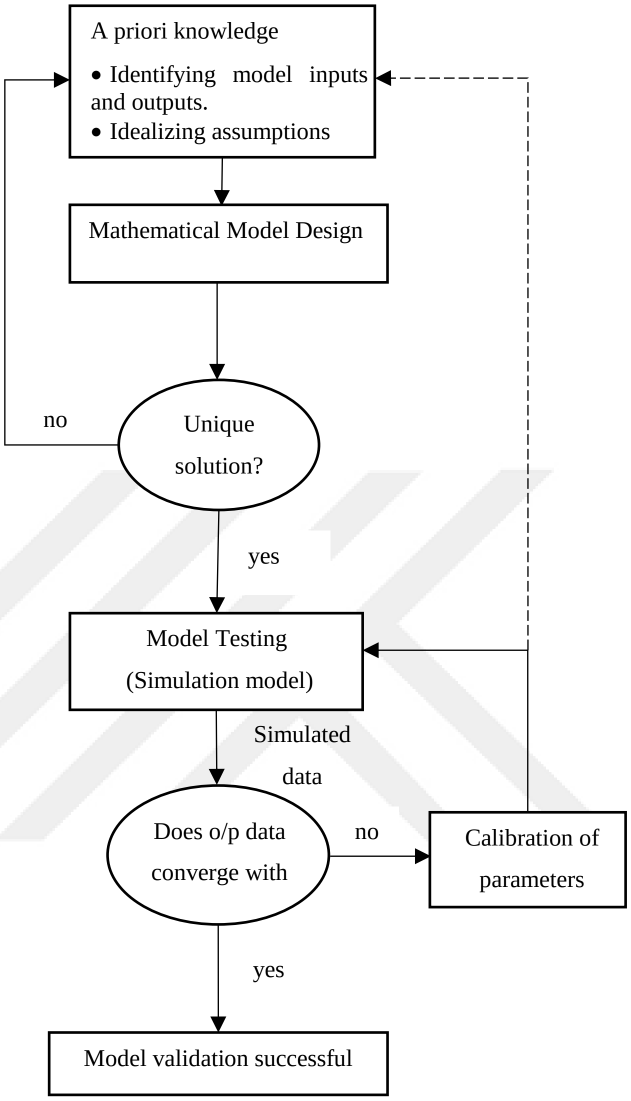

Figure 3.1 A stepwise flowchart in the modelling process

Clarification is the process of separation of finely distributed sludge from the liquid resulting in a low turbulent effluent; Thickening on the other hand is the increase in sludge concentration by flocculation in order for it to be recycled or disposed [29].

SST's primary function is to allow the suspended solids to settle in the lower zone/underflow zone while allowing the cleaner effluent to stay at the top/ effluent zone. Failing to these functions with either cases, the effluent flow will quickly deteriorate and an increase of suspended solids will be visible at the outlet.

Depending on the model objectives, a range of options in SST modelling are available. Complexity of SST models increases as the dimensions of the model increases, such as:

- Zero-dimensional (0-D) models: These models are representations of ideal splitters of solids and fluids, and are the simplest models with only one parameter, dependent upon only the amount of RAS fed back into the AS reactors. Furthermore, solids transport can also be plotted under state-point analysis [30,31]. Within these models, effluent concentration can be given as model input or a function of the flow rate through the SST.
- One-dimensional (1-D) models: 1-D are based on solid's flux theory proposed by [14]. These models function on the hydrodynamic behavior of the settling particles and its interaction with the flocs. The fluid flow is simplified in 1-D as upward/downward flow to simulate the effluent/under flow. They are mostly first or second order 1-D models, likely based on 1-D advection-dispersion PDEs [15,19,32] or recently proposed numerical integration methods [27,33].
- Two or three dimensional (2-D/3-D) models: Unlike 1-D models, 2-D/3-D models consider the hydrodynamics within the settler: flow patterns, density currents, temperature, non-symmetric features and internal configuration and visualization such as sludge blanket height [29, 34]. Its application is necessary for already established WWTPs and understanding bulking and flocculating behaviors of the solid concentration [16]. Computational Fluid Dynamics (CFD) are required in understanding and implementing 2-D/3-D models. Recently, flocculation-deflocculation models and even rheology of the activated sludge in the SSTs have been attempted [8, 36, 37, 38]. Due to their accuracy in flow pattern visualization they are widely studied for harsh weather conditions [35].

A combination of 2-D and 3-D models and bio-kinetic models tend to be extremely computational and demanding imposing difficulty in implementing the entire WWTP [9]. Therefore, in this thesis only 1-D models will be discussed, because of their simplicity in operation and control of SSTs and also they are easier to incorporate in models that simulate the entire WWTP.

3.2 1-D SST Modelling

The biological models typically involves ordinary differential equations (ODE), while settler models comprises of both time and space dependency resulting in a partial differential equation (PDE) [33].The modelling of secondary settlers is generally based on the solid flux theory using the state point analysis which are often referred to as 1-D models.

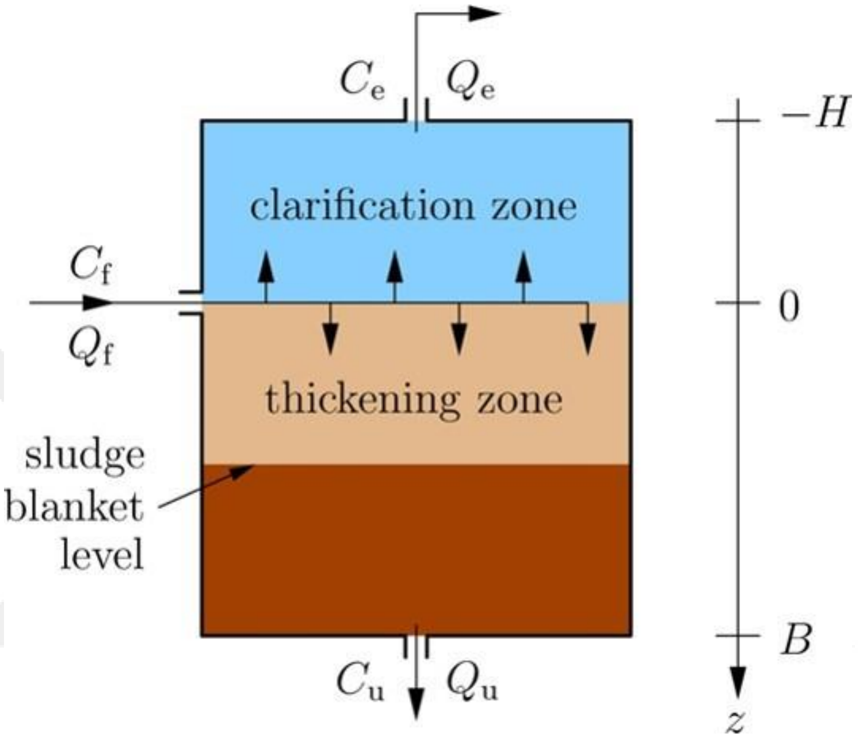

Figure 3.2 Schematic overview of 1-D SST [33]

Concurrently, nowadays current WWTP models often combine ASP models [39] with 1-D PDE equations. Generally the 1-D modelling is based on two different methodology, mass conservation law or mass momentum conservation law. The foundation of mass-momentum law based model is accurately identifying the forces acting on the particles, but it is also the most difficult stage [29]. While the mass conservation law is based on the assumptions of Kynch's theory.

According to Kynch's solid flux theory, the mass conservation law under steady state conditions must satisfy the conservation of flow and mass concentration within the SST [14].

$$Q_f = Q_e + Q_u \tag{3.1}$$

$$Q_f C_f = Q_e C_e + Q_u C_u \tag{3.2}$$

with Q and C as flowrate and sludge concentration respectively, and the subscripts f, e and u for feed, effluent and underflow. Accordingly, Kynch proposes the movement of particles are the result of a gravitational settling flux due to the settling property and a bulk flux due to the bulk movement. The total flux J_t consists of the bulk flux ($J_b = vC$) and the settling flux ($J_s = v_{hs}C$) and becomes

$$J_t = vC + v_{hs}C \tag{3.3}$$

where v_{hs} denotes the settling velocity of the sludge, v the vertical bulk velocity and C the sludge concentration. Mass balance equation of SST can be formed based on (3.3), in the form of a differential conservation equation described by a PDE:

$$\frac{\partial C}{\partial t} = -\frac{\partial v_{hs}C}{\partial z} - v\frac{\partial C}{\partial z} + \frac{Q_f(t)C_f(t)}{A}\delta(z) \tag{3.4}$$

with t as time and z as vertical coordinate with the origin at the feed, Q_f the feed flow rate, C_f the feed concentration, $\delta(z)$ the dirac delta distribution and A the surface area of the settler. When z is below the inlet, the vertical bulk velocity v_u is downward and is calculated by $v_0 = {}^{Q_u}\!/_{A}$, where Q_u is the recycle flow. When z is above the inlet, the vertical bulk velocity v_0 is upward and is calculated by $v_0 = {}^{Q_e}\!/_{A}$, where Q_e is the effluent flow. SSTs are also modelled as layered flux models, only when the settling model, and effluent and underflow concentration predictions affect the behavior of the plant [34].

A more sophisticated implementation of solids mass flux theory is the lumped parameter model [40]. To achieve this, the settling tank is divided into horizontal layers of constant thickness within which the concentration is assumed to be constant [9]. A mass balance is calculated across the boundaries of each layer. The lumped parameter model is often applied to understand, what effects does feed flow and suspended solids concentration have on the effluent and return sludge flows [40]. Since solving PDE equations is tedious and numerically difficult, PDEs are discretized into a set of ODEs which can be handled by ODE solvers in simulators, which can be realized by lumped parameter model layering approach.

In this approach, the downward and upward flux of a given layer j can be calculated as

$$J_{dn,j} = C_j v_{hsj} + C_j v_{hs} \tag{3.5}$$

$$J_{up,j} = C_j v_o \tag{3.6}$$

where C_j represents the sludge concentration in layer j, $J_{up,j}$,$J_{dn,j}$ the upward and downward fluxes on the layer j . This model is now widely used in 1-D modelling [19], the most commonly known is Takács model which follows a 10-layer model approach. In the following section current models based on Kynch theory and layering approach will be discussed.

3.3 Recent Advances in SST Models

The Takács model is used for many simulations under dry weather conditions with a 10-layered model approach. Takács model is based of Kynch solid flux theory and Vitasovic's model [41]. The model is principled around the division of SSTs into evenly spaced layers with constant thickness. Around each layer a mass balance for the solids is calculated which results in the prediction of the solids concentration in each layer. There are five groups of layers present in the model: the top layer, the layers above the feed point, the feed layer, the layers below the feed point and the bottom layer (Figure 3.3). However, due to several shortcomings within the model [33, 42] it is not numerically accurate. Takács model can hardly depict wet weather conditions accurately as the underflow concentration and sludge blanket height are affected by the limiting flux X_t (in 3.7). This empirical parameter in the solution scheme violates good modelling practice [33].

$$\mathrm{J}_{dn,j} = \begin{cases} \min\left(v_{s,j}X_j, or\ v_{s,j+1}X_{j+1}\right), & if\ X_{j+1} > X_t \\ v_{s,j}X_j, & if\ X_{j+1} \le X_t \end{cases} \tag{3.7}$$

The other drawbacks of Takács model were as the number of horizontally discretized layers were increased the predictability of the model decreased [42]. This method contradicts to the idea that a model's predictability matches the physical real model as the complexity of the model increases. The number of layers N, becomes an important parameter in changing the simulation outputs. This again is unconventional approach and the parameter can only be included during the construction of the mathematical model and not in the solution method [33,43,44].

Hamilton et al. first introduced the Fickian dispersion term instead of Takács limiting flux ($D\frac{\partial^2 C}{\partial z^2}$, where D is a dispersion coefficient, a constant) converted the PDE into a parabolic second-order PDE resulting in a smooth concentration graph, while applying Vesilind's velocity function [52].

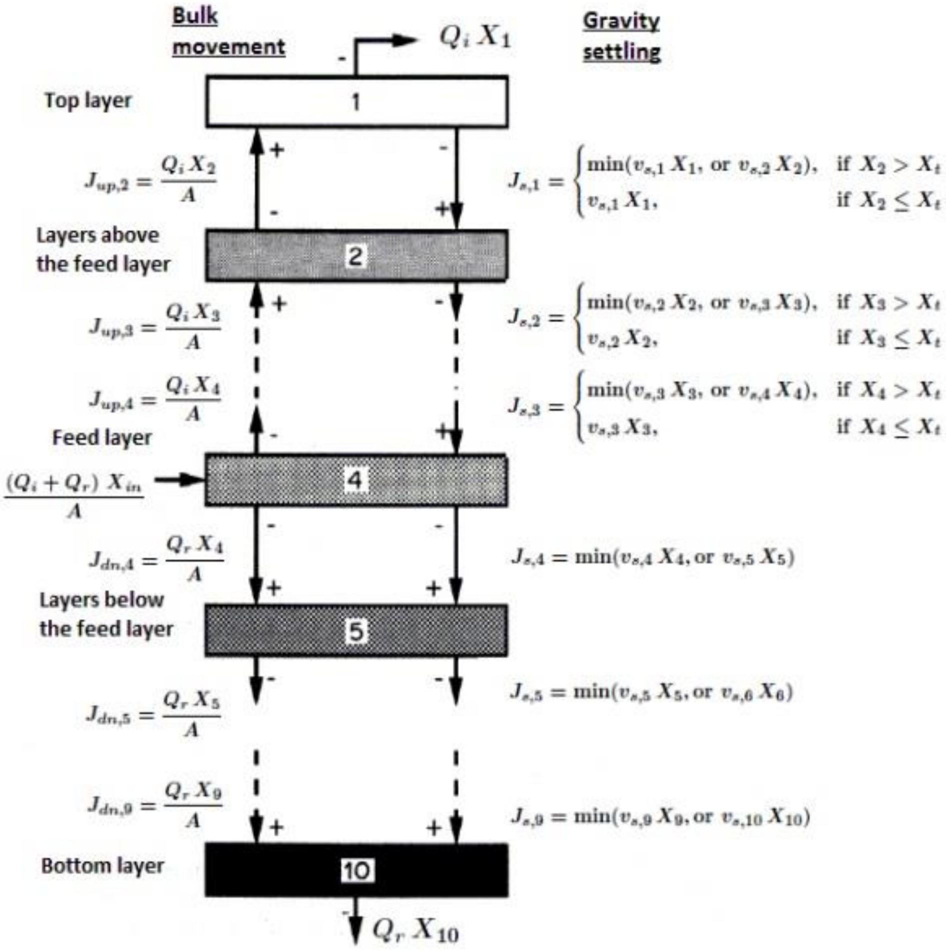

Figure 3.3 Takács layered model approach [19]

Watts et al., in their model, also included Fickian dispersion term instead of Takács limiting flux. Unlike Hamilton et al., they applied a varying dispersion term which depended on the layer concentration and feed flow rate while employing Takács velocity function and increasing the number of layers to 50 [53]. It resulted in better predictions than Takács model and a cross sectional area $A(z)$ was also introduced in the model. Watts et al. realized that the dispersion coefficient was a function of feed flow velocity and the inlet region was greatly affected because of the energy dissipation and turbulence effects. It also helped understand the processes that affect the sludge settling phenomenon [8].

Lee et al. modified Hamilton’s approach by applying Takács velocity function instead of Vesilind’s. Lee et al. realized the low load concentration results were inaccurate and inconsistent for the Hamilton model with Vesilind’s velocity function. Therefore, with Takács velocity he proposed two different terms: clarification zone- dispersion coefficient and thickening zone-dispersion coefficient [51]. In (3.8), z is the vertical axis, t the time and D is the dispersion coefficient as a constant for the overall SST domain.

$$\frac{\partial \phi}{\partial t} + \frac{\partial F(\phi)}{\partial z} - D\frac{\partial^2 \phi}{\partial z^2} = v_f \phi_f \delta(z) \tag{3.8}$$

De Clercq et al. proposed that Lee et al.’s approach is inconsistent with the flow pattern and cannot depend solely on feed flow, as the flow in the clarification zone is towards the effluent layer (upward) while in thickening zone is towards underflow layer (downward), resulting in upward and downward bulk flow [8].

Plósz et al. introduced an additional second order dispersion term. This term negates several factors effecting the model, such as turbulent diffusivity, dispersion, sludge removal procedure and errors introduced through numerical method [9, 32]. The model disregarded the limiting flux while considering Godunov flux for the overall flux calculation. The model produced superior clarification prediction by introducing a dispersion term as a function of the upward flow velocity. In recent studies, the dispersion term is assumed at various locations within a SST, mostly around the inlet region [24, 33, 45], the location of the dispersion term significantly affects the sludge bulking and concentration prediction.

Compression behavior is widely researched, introducing a correction function [46] which varies according to the location in the SST, few proposing distinction between microflocs and macroflocs in the model [47] and others introduced new settling velocity functions [48,49].

David et al. proposed a Method of Lines (MOL) approach to the modelling of secondary settling tanks [43]. The model was based on [50] for discretizing PDEs by presenting a simple model with boundary conditions which converts the parabolic form into a reduced-order model for optimization and control [43]. The model allowed for a better discretization strategy to the complex numerical computations [24].

All the 1-D models discussed above have tried to implement the dispersion and compression effects by adding a second-order term in their PDE but only by lumping it into one parameter [32,51-53]. The drawback to this technique is inaccurate representation of actual settler dynamics. The 1-D Bürger-Diehl model proposed a different approach, it accounted for all the dynamics within the SST be represented by an individual parameters for each property of dispersion, compression and flux, and no additional parameter be introduced in the numerical method itself [33].

3.4 Bürger-Diehl Model

Bürger-Diehl settling model accounts for various factors which were discarded by Takács et al. [33]. In its entirety, it ensures reliable solution for the governing PDE by consistent numerical methods and promises detailed description of the settling behaviors with the introduction of improved dispersion and compression expressions [54].

Takács model faced an unrealistic error due to the downward flux which BD model prevents in a modular way by equipping the model with Godunov flux. This approach was initially proposed by [27] and later proven mathematically correct by [45]. The Godunov flux does not make use of an empirical concentration and considers all the intermediate concentrations between the concentrations of layer j and layer $j+1$. The Godunov approach also ensures that the solution of the model converges to the substantially true solution when the number of layers is increased [45].

$$G_j = G_j(C_j, C_{j+1}) := \begin{cases} \min\limits_{C_j \leq C \leq C_{j+1}} f_{bk}(C) & if\ C_j \leq C_{j+1} \\ \max\limits_{C_{j+1} \leq C \leq C_j} f_{bk}(C) & if\ C_j > C_{j+1} \end{cases} \tag{3.9}$$

where j is layer within the SST, f_{bk} the bulk flux, C_j the concentration on j^{th} layer. This expression is particularly easy to evaluate if Vesilind velocity function is used because f_{bk} has precisely one local maximum at ($\hat{C}$).

The BD mathematical model is based on (3.8), while including discretization in both time (t) and space (z). Discretizing in space is done by dividing the SST into N layers. In contrast to other models proposed for SST, Bürger et al. proposes two extra layers at the top and bottom, respectively, representing individual effluent and underflow layers. These layers help in determining the correct concentrations of the effluent and underflow zones [33]. This denotes that in the underflow layer/last layer no settling will occur, which is not a good mathematical assumption [42]. Therefore, the effluent and underflow concentrations are present in -1 and $(N+4)^{\text{th}}$ layer (see Figure 3.4).

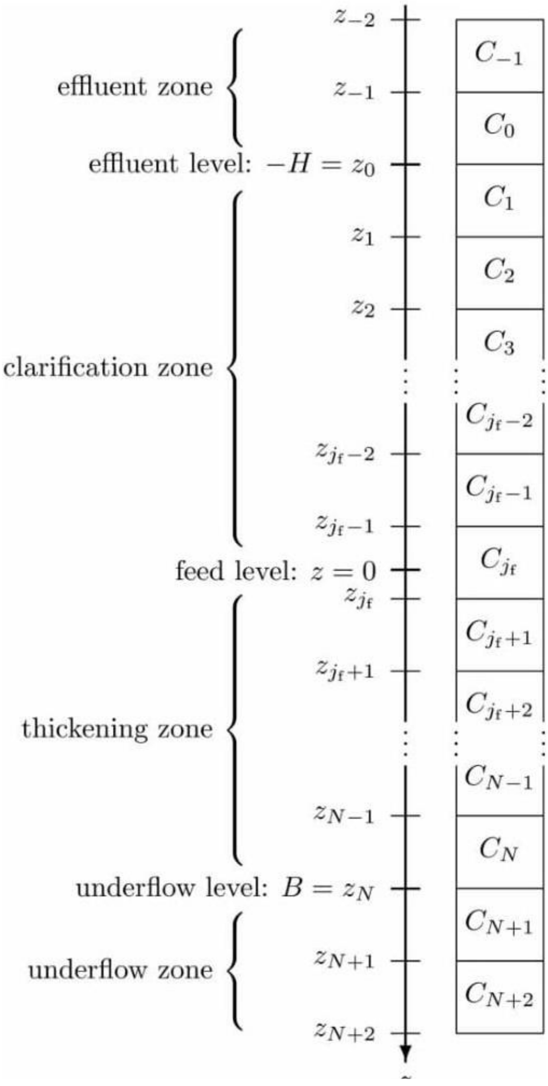

Figure 3.4 Layer Discretization with clarification zone denoted by H and Thickening zone by B [33]

Bürger et al. also included the stress function proposed by De Clercq [55]. It is known that when the concentration reaches critical condition the particles comes together and compression becomes active, the particles forming a mesh carry a certain stress, effective stress σ_e [55]. It is assumed that the concentration above the critical concentration is an increasing function of solids concentration while below it is zero, in (3.10), ρ_s is the density of the flocculated solids, ρ_f is the density of the fluid, g is the acceleration of gravity, α, β are the parameters in the solid stress function σ_e ,

$$\sigma_e(C) = \begin{cases} 0 & for\ C < C_c \\ \alpha \ln\left(1 + \frac{C - C_c}{\beta}\right) & for\ C \geq C_c \end{cases} \tag{3.10}$$

The model also included dispersion and compression functions which have been presented by many researchers in a single term [29]. These functions can be switched on or off by the user requirements enabling better calibration within the model. With the compression function (3.10), any settling velocity, Vesilind, Takács, Cho or any other velocity models, is extended with a compression term only when the concentration exceeds a certain critical concentration which is based on stress function given in (3.10),

$$d_{comp}(C) = \begin{cases} 0 \quad , & for\ 0 \leq C < C_c \\ \dfrac{\rho_s \alpha v_0 e^{-r_v C}}{g(\rho_s - \rho_f)(\beta + C - C_c)}, & for\ C \geq C_c \end{cases} \tag{3.11}$$

BD model originated on the basis of Kynch's theory, by considering most of the nonlinear dynamics of the model. The underlying mathematical model is formed by including the compression function and stress function described above and including a new dispersion function (in 3.13), the nonlinear PDE for the sludge concentration at $C(z,t)$, at depth z from the feed level and at time t is given by,

$$\begin{aligned} \frac{\partial C}{\partial t} = -\frac{\partial}{\partial z} F(C, z, t) + \frac{\partial}{\partial z}\left(\left\{\gamma(z) d_{comp}(C) + d_{disp}\left(z, Q_f(t)\right)\right\} \frac{\partial C}{\partial z}\right) \\ + \frac{Q_f(t) C_f(t)}{A} \delta(z) \end{aligned} \tag{3.12}$$

where the $F(C, z, t)$ the convective flux function which represents the hindered settling flux with bulk flows which is defined by Godunov's flux for numerical approximation [23], the $d_{comp}(C)$ and $d_{disp}\left(z, Q_f(t)\right)$ are the compression and dispersion terms, which accounts for compressive force acting on discrete sediments and the inlet mixing phenomena in the SST, respectively. $Q_f(t)$ is the time dependent feed flow rate and A is the constant cross-sectional area. Furthermore, the dispersion function is given by,

$$d_{disp}\left(z, Q_f\right) = \begin{cases} \alpha_1 Q_f \exp\left(\dfrac{z^2/\left(\alpha_2 Q_f\right)^2}{1-|z|/\left(\alpha_2 Q_f\right)}\right), & for|z| < \alpha_2 Q_f \\ 0 \qquad\qquad\qquad\qquad , & for\ |z| > \alpha_2 Q_f \end{cases} \tag{3.13}$$

where $\alpha_1\ and\ \alpha_2$ are parameters in the dispersion and z is sludge blanket height. It is assumed that d_{disp}, the dispersion coefficient, is a dependent function on two factors, the volumetric feed flow and inlet region where mixing occurs. Under different load conditions, simulations indicated that although dispersion occurs mainly around the inlet region of the SST it has an effect on overall sludge concentration within the tank, Burger et al. modelled this by including a modular dispersion term in the PDE as seen in (3.13). The term $\gamma(z)$ in (3.12) is equal to 1 while inside the SST and 0 when outside, since outside the settler only bulk movement occurs. Upon necessary spatial discretization of (3.12) it extends to a finite differential equation.

$$\frac{dC_j}{dt} = -\frac{F\left(C\left(z_j,t\right),z_j,t\right) - F\left(C\left(z_{j-1},t\right),z_{j-1},t\right)}{\Delta z} + \frac{J_{disp}\left(z_j,t\right) - J_{disp}\left(z_{j-1},t\right)}{\Delta z} + \frac{J_{comp}\left(z_j,t\right) - J_{comp}\left(z_j,t\right)}{\Delta z} + \frac{1}{\Delta z}\int_{z_{j-1}}^{z_j} \frac{Q_f(t)C_f(t)}{A}\delta(z)dx \tag{3.14}$$

Furthering the model equation in (3.14), to ensure the solution converges to the exact solution, numerical approximation method is applied [33]. The compressive and dispersive fluxes (J_{comp} and J_{disp}) are approximated with first order approximations and applying MOL (Method of Lines Strategy) discretization on the numerical approximation form of PDE (in 3.14) resulting in finite ODEs for each individual layer.

$$\frac{dC_j}{dt} = -\frac{F_j^{num} - F_{j-1}^{num}}{\Delta z} + \frac{1}{\Delta z}\left(J_{disp,j}^{num} - J_{disp,j-1}^{num} + J_{comp,j}^{num} - J_{comp,j-1}^{num}\right) + \frac{Q_f C_f}{A\Delta z}\delta_{j,j_f}, \quad j = -1, \ldots, N+2 \tag{3.15}$$

where $\delta_{j,j_f} = 1$ if $j = j_f$ and $\delta_{j,j_f} = 0$ otherwise. C_f is the concentration at the feed layer and Δz is the layer depth of each layer. The expressions F_j^{num} , $J_{disp,j}^{num}$, and $J_{comp,j}^{num}$ are all calculated according to [24].

A condition known as a CFL condition (named after Courant, Friedrichs, & Lewy) is a necessary condition to ensure stability of the numerical scheme [13]. This limit is imposed in the ODE solver for the upper limit to be within stable region. As seen from the expression (3.16), a finer discretization requires a smaller time step demanding for more computation power [24].

$$\Delta t \leq \left[\frac{1}{\Delta z}\left(\max_{0\leq t\leq T}\frac{Q_f(t)}{A} + \max_{0\leq C\leq C_{max}}\left|f'_{bk}(C)\right|\right) + \frac{2}{(\Delta z)^2}\left(\max_{0\leq C\leq C_{max}} d_{comp}(C) + \max_{-H\leq z\leq B, 0\leq t\leq T} d_{disp}\left(z, Q_f(t)\right)\right)\right]^{-1} \quad (3.16)$$

The layering approach followed by BD model is shown in Figure 3.5. Bürger discretized the model into N layers, with -1 as the effluent layer and $N+4$ as the underflow layer (after adding two extra layers for effluent and underflow). The simulations are carried out individually for each layer using the ODEs proposed using MOL strategy. The model is adequately feasible to apply control if needed, through directly controlling the output and inputs which are explicitly mentioned. Control strategy for the BD model will be discussed in detail in Chapter 4.

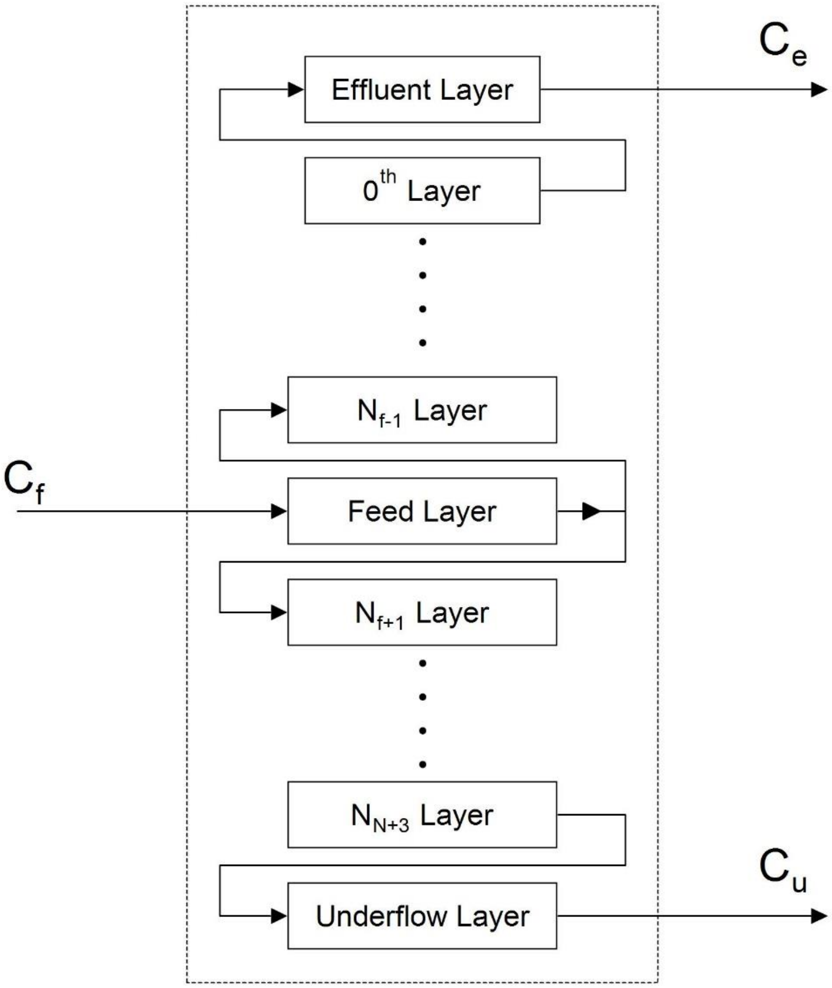

Figure 3.5 Block diagram of layering approach in BD model

3.5 Summary of Key Findings

The performance of the SSTs depend largely on the efficacy of the governing model equation. It is thus important to have a good model which relays the dynamics of the secondary settler tanks at different weather conditions. A bad prediction of the underflow/effluent flow and concentration will result in poor performance of the WWTP model and an insufficient control feedback once implemented. The other models, such as Takács model even widely accepted has several shortcomings, the velocity model’s unpredictability and the empirical flux parameter resulting in inconsistent modelling practice. The model doesn’t incorporate the compression functionality and is held back by the number of layers for finer detailed description of SST. Bürger et al. proposed a numerically well-thought model considering Godunov flux for the downward flux a provision to include higher number of layers and presenting a dispersion function as well as a compression function for better predictability. In the following chapter, Bürger model will be used to simulate for different weather conditions and a control model will be proposed.

CHAPTER 4

SIMULATION RESULTS

4.1 Data Collection

For the validation of the model, data was taken from the Oğuzeli Wastewater Treatment Plant in Oğuzeli district (Gaziantep, Turkey). Oğuzeli WWTP has a biological capacity of 40.000 inhabitant equivalents [62], and this facility was chosen because of its accessibility and easy commutable distance. The incoming influent is mostly carrying domestic waste, the raw wastewater is directed towards the first preliminary treatment: mechanical operations like screens, sedimentation processes. The wastewater is then flown into the primary clarifier where the initial sludge settling process takes places (anaerobic process). Subsequently, the wastewater is transferred to the aerobic tanks/aeration tanks where oxidation, nitrification, de-nitrification and phosphorous removal processes takes place. The mixed liquor collected from the tank is passed through a pump into the sedimentation tanks (secondary settling tanks). According to the inflow rate, either two or one secondary settlers are made operative (see Figure 4.1). As part of the sedimentation process, the sludge settled in the tanks, is pumped into the sludge dewatering station, where the sludge is subjected to centrifugal pressure to achieve maximum liquid from the thickened sludge. The excess sludge from the station is dumped into the dumping ground. Also, the central feed system directs a measured amount of settled sludge back to aeration tanks along with the RAS from the sludge dewatering station. Accordingly, in each settling tanks, a scum removal system along with mechanical scraper is present to remove the standing sludge within the SSTs. The SSTs also are equipped with an effluent weir on the top layer of the tank discharging clean effluent to be released into the Sacır River.

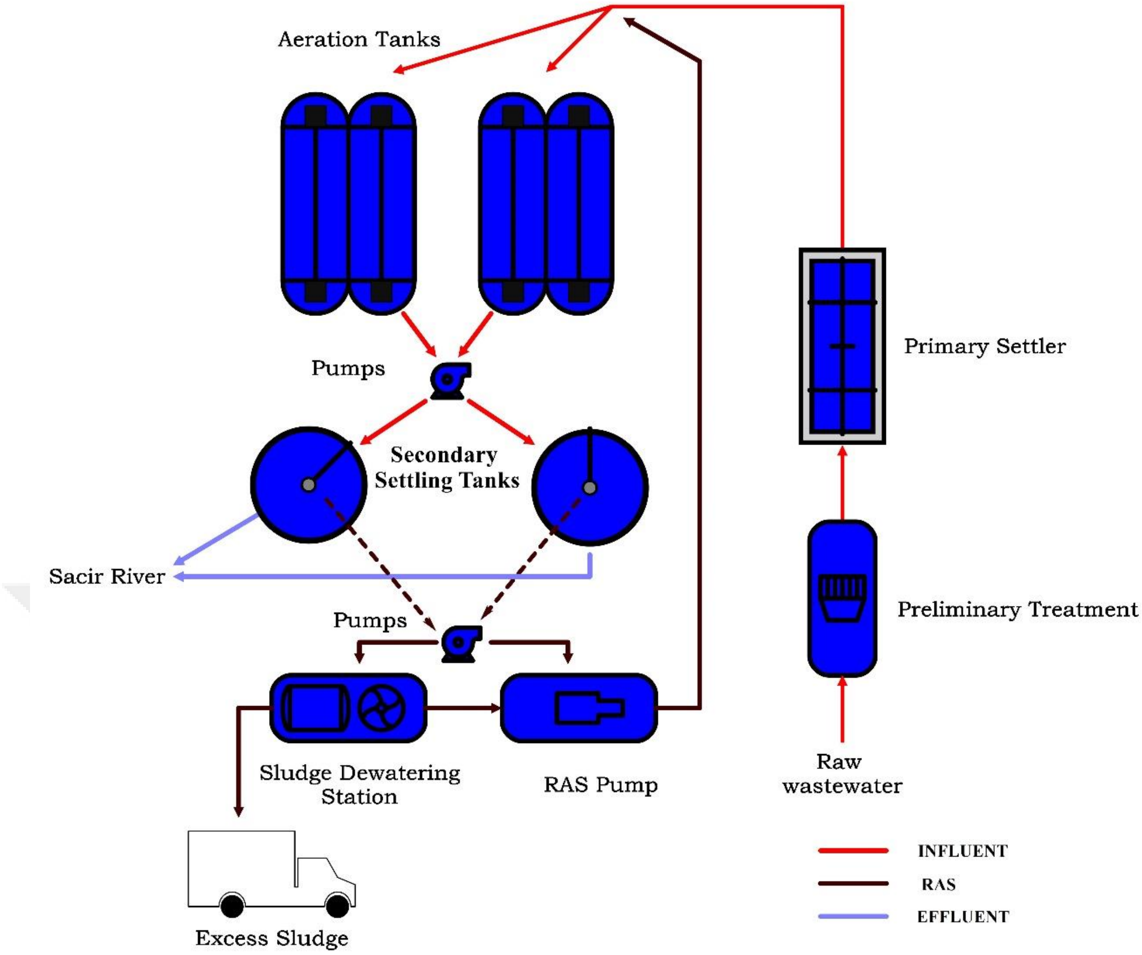

Figure 4.2 Overview of Oğuzeli Wastewater Treatment Plant

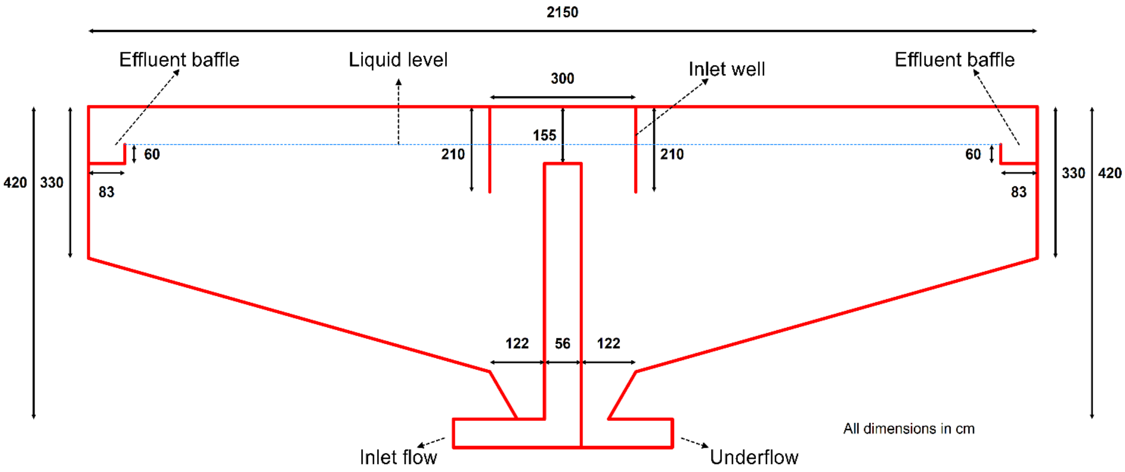

Figure 4.1 The geometry of the SST (in cm) at Oğuzeli WWTP

The Oğuzeli WWTP is constructed with a total inflow rate of 8000m^3/day and currently it treats 4000m^3/day of wastewater. A data collection was carried out for a period of 6 months each season (summer and winter). The inflow rate along with inflow concentration, RAS flow rate and effluent concentration were measured (Table 4.1).

Table 4.1 Summary of operational values (Average values)

	Inlet discharge of SST (m^3/h)	Q_{RAS} flow rate (m^3/h)	Feed Concentration (mg/L)
Summer Term	269.3	132.6	224
Winter Term	232.6	142.6	188

4.2 Assumptions and Methods

After theoretical calculations and attaining the SST model, rigorous simulations under different weather conditions is required. But firstly, before simulating the Bürger-Diehl model a few assumptions about the model are taken. Since Chapter 2, the discussion on settler models have solidified the hypothesis on which modern settler models are based, Kynch's theory. It proposes that the settling velocity of a particle is subject to the local solids concentration which however, can only be explained in the hindered settling region [56]. Kynch mentioned in his research, "Until the details of the forces on the particles can be specified, it is impossible to state when our hypothesis is valid, even for a dispersion of identical particles [14]. Thus, in order to overcome the uncertainties in the flux theory which leads to inaccuracies in the determination of SST functioning, as a result few assumptions are considered:

- The solid particle concentration within SST is uniform in only one dimension (vertical z-direction);
- The hydraulic flow pattern is insignificant (no density currents or wind effects) and no temperature or incompressible flow, and laminar flow effects are considered;
- The SST isn't affected, by any biological reaction, and chemical reactions;

- Settling process is uniform without being affected by mechanical sludge scraper movement;
- Hindered settling velocity is dependent only on the local particle concentration.
- All internal disturbances are ignored, wall effects and friction forces due to scraper;
- Velocity at C_{max} (end of settling) tends to zero as C increases;
- The inlet flow of the SST tank creates a radial flow pattern, an evenly distributed flow is observed and only radial cross-sectional area of the tank is considered for calculation.

In this thesis, MATLAB® and SIMULINK® are used to simulate the mentioned model, for solving the ODEs the ODE solver requires initial values which are predefined in an m-script in MATLAB® and ran once before the start of simulation. Within the initialization script a few precomputations are also performed to speed up the simulation. The pseudo code to the scripts is given in the Appendix section.

MATLAB® is developed by Mathworks and is an interactive environment for numerical computation, visualization and programming [57]. It has a lot of built-in functions. MATLAB® actually means MATrix LABoratory and performs matrix manipulations [57].

4.3 Results and Discussion

For solving the ODEs, the solver needs initial values for all states and defined values for all the parameter values in the model.

Table 4.2 Parameter values in BD model

Settling vel.	Value	Compression	Value	Dispersion	Value
v_o[m/h]	4.1	α[Pa]	4	α_1[m^{-1}]	0.0028
r_v[m^3/kg]	0.46	β[kg/m^3]	4	α_2[h/m^2]	0.0032
		C_{crit}[g/L]	6		

Accordingly, we have used the following data: $H = 1m,\ B = 3m,\ A = 400m^2$ and the hindered settling velocity is described by the Vesilind formula (Table 4.2) and other parameters are chosen as, $\rho_s = 1{,}050\ kg/m^3$, $\Delta\rho = 52\ kg/m^3, g = 9.81\ m/s^2$ and $C_{max} = 20\ g/L$. At time $t = 0$, we assume that the SST is full of sludge at a concentration of $C = 2\ g/L$, and let the number of internal layers (within the SST) be $N = 30$ (i.e. a total of 34 layers for the numerical method). It should be noted that higher the number of layers higher the efficiency.

For the dispersion function, values are chosen for the dispersion to cover a sludge height of $|z| < 1\ m$ within the feed flow region for a uniform concentration profile.

The simulations are carried out for various weather conditions, the above given values will be kept constant throughout the simulations. The volumetric flows and feed concentration will be varied according to the weather conditions. The scope of this research covers the simulation for recreating real data and will not divulge in optimization of the model.

4.3.1 Simulation 1: Constant influent

When a constant influent flow rate and feed concentration is introduced with $Q_f = 250\ m^3/h$ and $C_f = 3.5\ g/L$, as shown in the Figure 4.3, a clear and constant steady effluent and underflow concentration is observed (with a constant $Q_u = 80 m^3/h\ and\ Q_e = 170 m^3/h$). It should be noted that even with discontinuity present in the model, the steady state values of concentration within the settler follow the mass conservation law which is given by $Q_f C_f = Q_e C_e + Q_u C_u$. The steady state values (Figure 4.4, Figure 4.5) are, $C_u = 10.8\ g/L$ and $C_e = 65\ mg/\ l$, which satisfies the mass conservation law. The simulation (in figure 4.5) represent a clear effluent with negligible sludge concentration. Feed concentration shows discontinuity due to sludge bulking around sludge blanket height which can be corrected by tuning dispersion and compression parameters (Figure 4.6). Concentrations for individual layers validates the increasing concentration within the SST (Figure 4.7).

4.3.2 Simulation 2: Rain influent

In order to simulate a stormy weather condition, we choose the values as shown below

$$(Q_f, C_f) = \begin{cases} 270\ m^3/h, 5.0\ g/L, & 0 \le t < 50m, \\ 250\ m^3/h, 3.1\ g/L, & 50 \le t < 100m, \\ 320^3/h\ , 5.5\ g/L, & 100 \le t < 150m. \end{cases}$$

The volumetric underflow and effluent flow were kept same as in Simulation 1. For each set of feed flow and concentration, the model constantly managed to regulate the flow accordingly satisfying the mass conservation law (Figure 4.8). A 3-D model of the simulation shows the relation of varying time with the sludge blanket height. Around the feed layer a directly affected concentration is observed.

4.3.3 Simulation 3: Extreme influent

We also simulated the model for an extreme high influent condition, with influent flow rate and feed concentration $Q_f = 870m^3/h$ and $C_f = 5g/L$. The volumetric flows $Q_u = 200m^3/h \: and \: Q_e = 300m^3/h$ were increased to higher flow rate value, we managed to assess the model's robustness to different volumetric flow rates (Figure 4.10). The model was able to represent the effect of high concentration and high inflow rate to the effluent concentration. It should be noted that the settling velocity and initial concentration of the SST greatly effects the effluent and underflow concentrations.

The results of the simulation were significantly matching the data from literature [24, 33]. The model also partially satisfies data from [58].

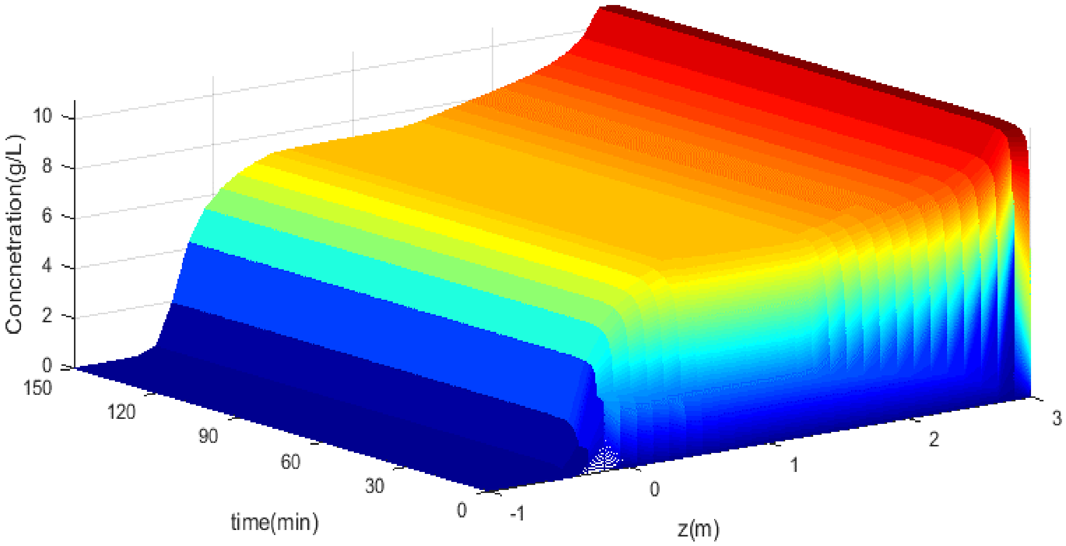

Figure 4.3 Constant influent: 3D model of all layers

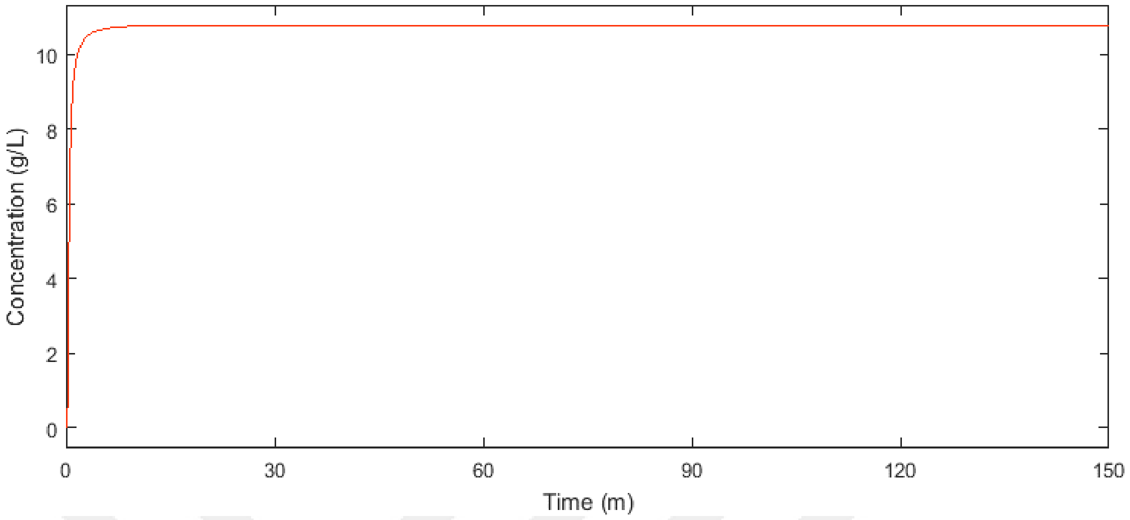

Figure 4.4 Underflow Concentration in Constant Influent

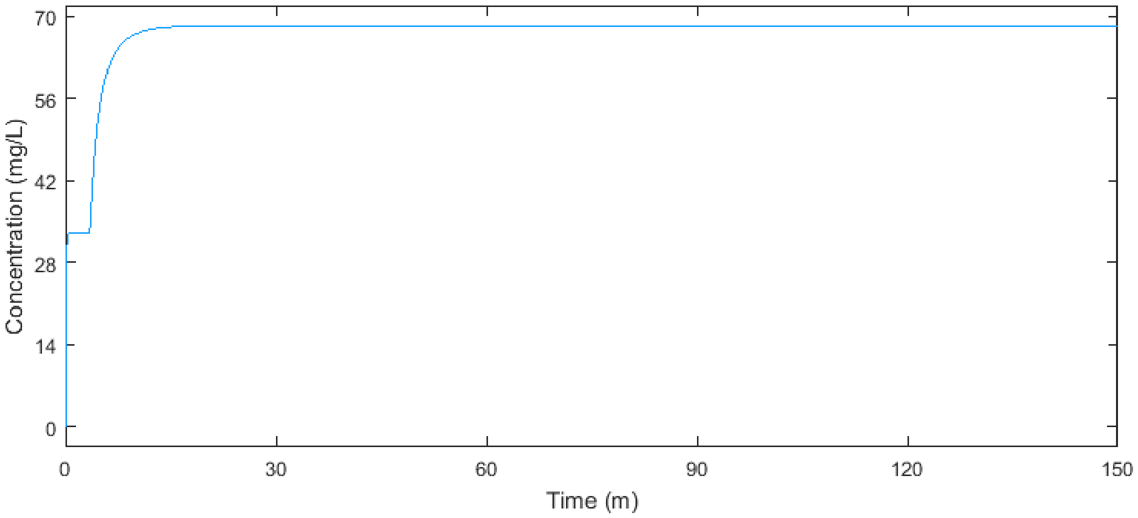

Figure 4.5 Effluent Concentration in Constant Influent

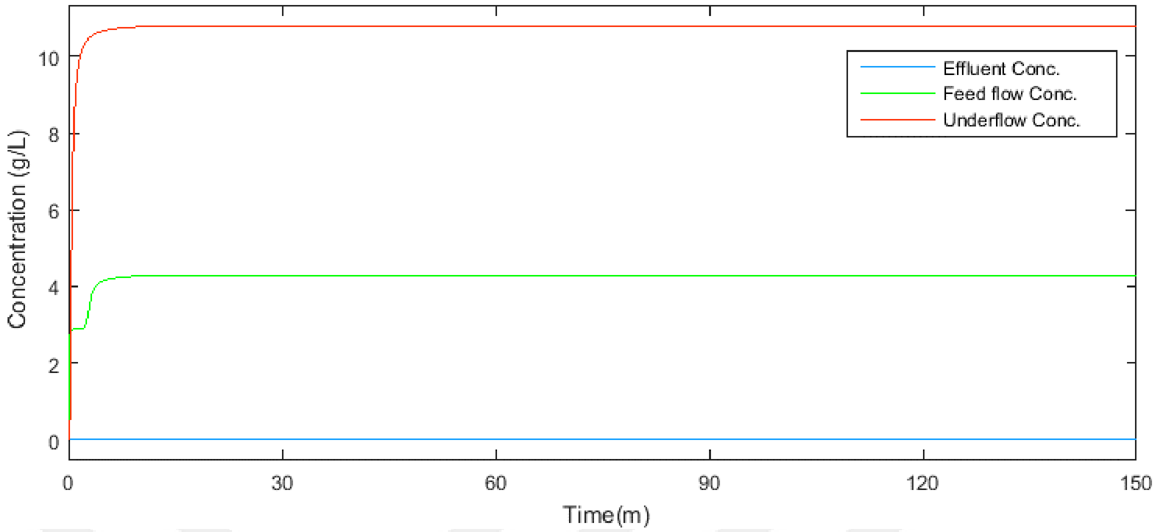

Figure 4.6 Volumetric Flows in Constant Influent

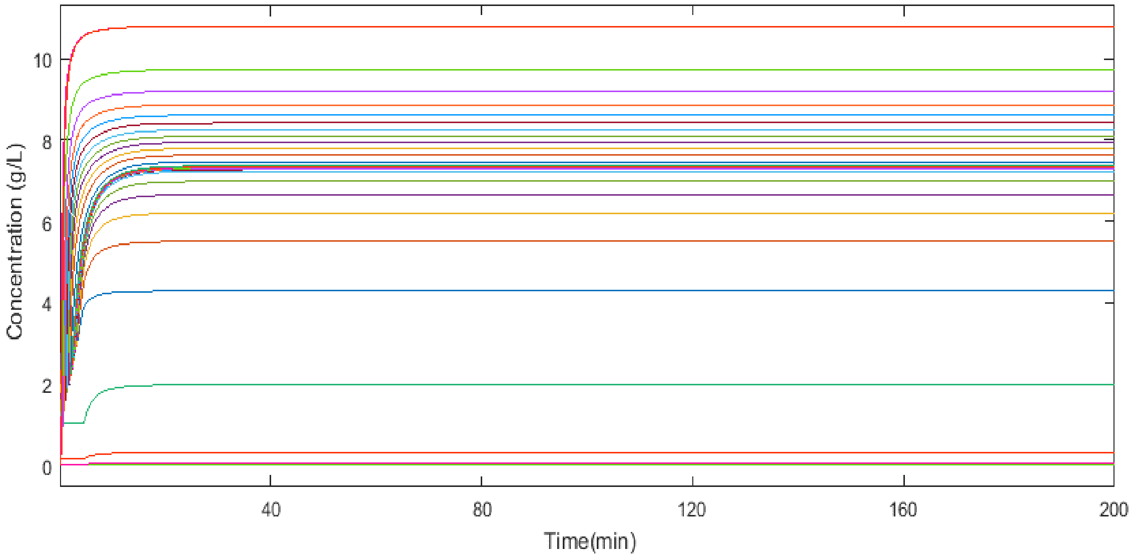

Figure 4.7 Constant Influent: 2D graph of concentration of all layers within SST

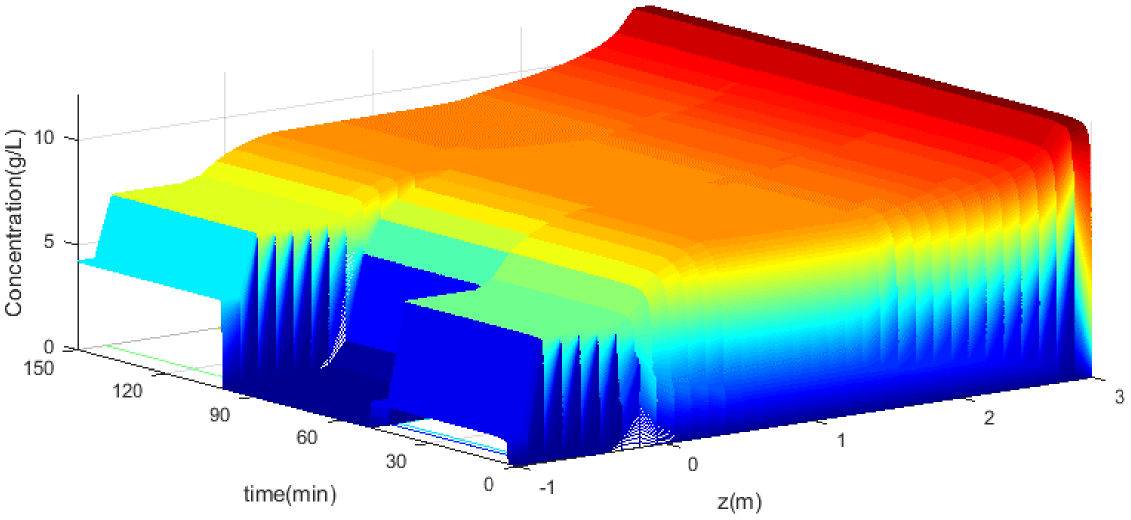

Figure 4.8 Rain influent: 3D graph of all layers within SST

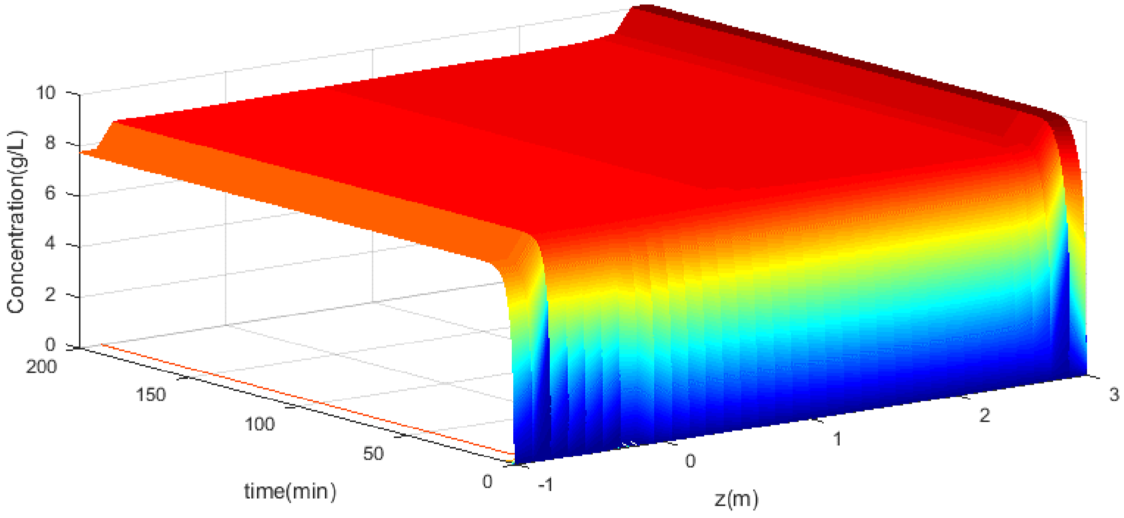

Figure 4.9 Extreme Influent: 3D model of all layers within SST

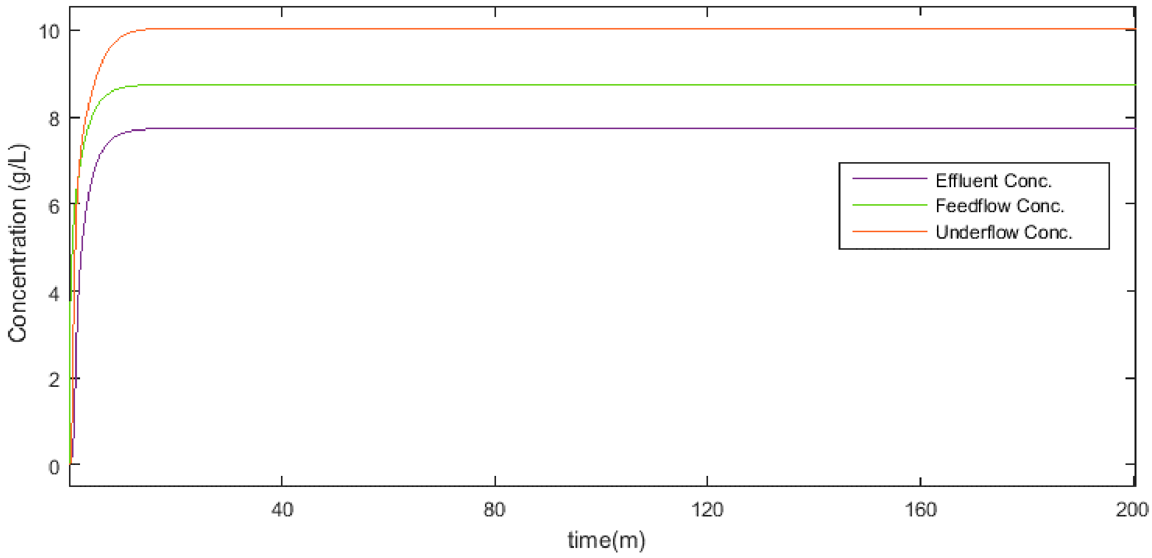

Figure 4.10 Volumetric flows in Extreme Influent

4.3.4 Simulation 4: Oğuzeli WWTP –Summer Term

Simulations were carried out for a 6 month period (April-September), for summer term. The geometry of the SST was considered and radial cross-section of the plant was assumed ($A = 363\ m^2$). The initial values were provided as per the above simulations with the settling velocity and other flow rates fed according to the real plant data. The influent flow rate, feed concentration, effluent and underflow rate used were $Q_f = 269.3 m^3/h$, $C_f = 0.224\ g/L$, $Q_e = 271\ m^3/h$ and $Q_u = 132.6\ m^3/h$ respectively. Table 4.3 compares the values achieved in the simulation to the real data observed.

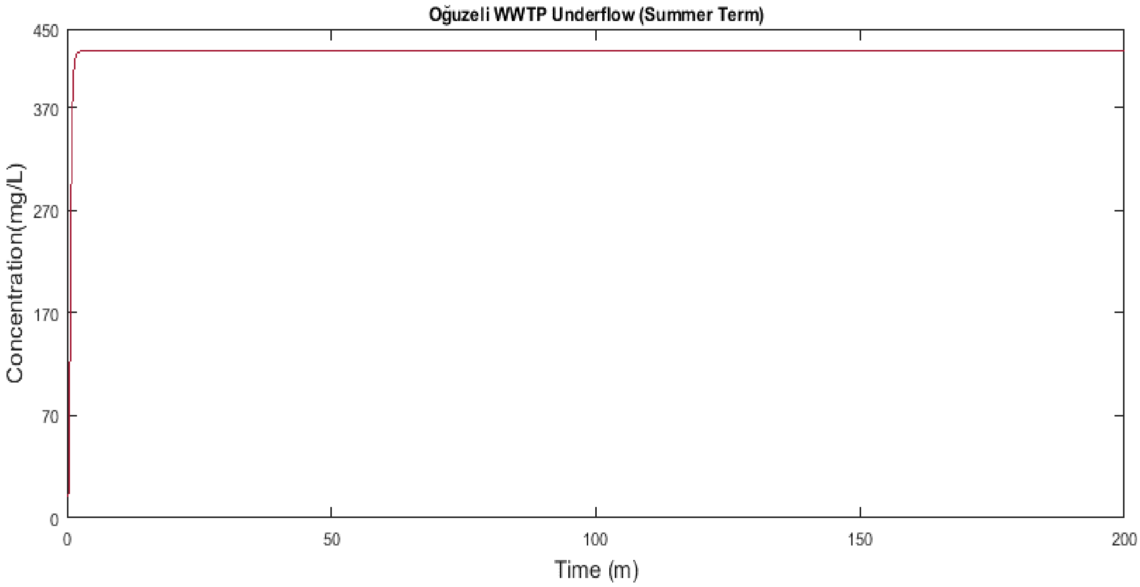

Figure 4.11 Underflow Concentration in Summer Term

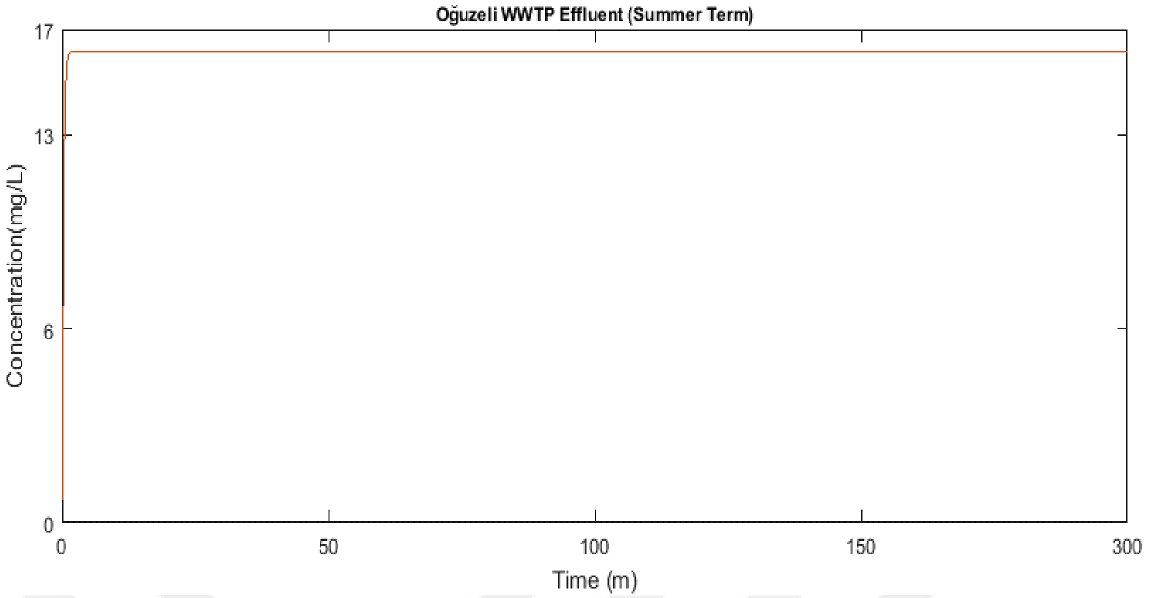

Figure 4.12 Effluent Concentration in Summer Term

4.3.5 Simulation 5: Oğuzeli WWTP –Winter Term

Simulations were carried out for a 6 month period (October-March), for winter term. The initial values were provided similar to the summer term and other flow rates fed according to the real plant data. The influent flow rate, feed concentration, effluent and underflow rate used were $Q_f = 232.6 m^3/h$, $C_f = 0.188\ g/L$, $Q_e = 228.4 m^3/h$ and $Q_u = 142.6\ m^3/h$ respectively. Table 4.3 compares the values achieved in the simulation to the real data observed.

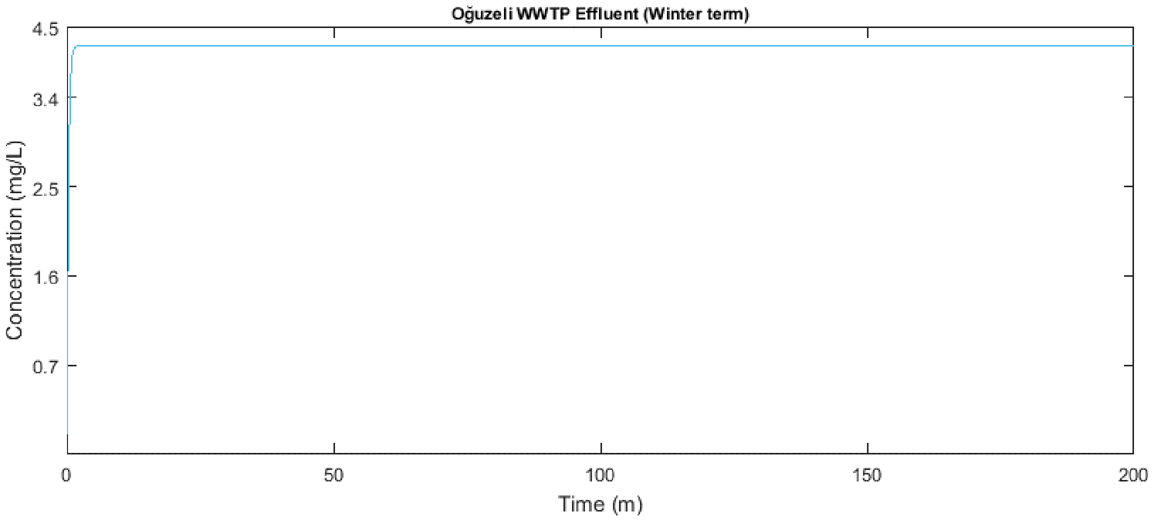

Figure 4.13 Effluent Concentration in Winter Term

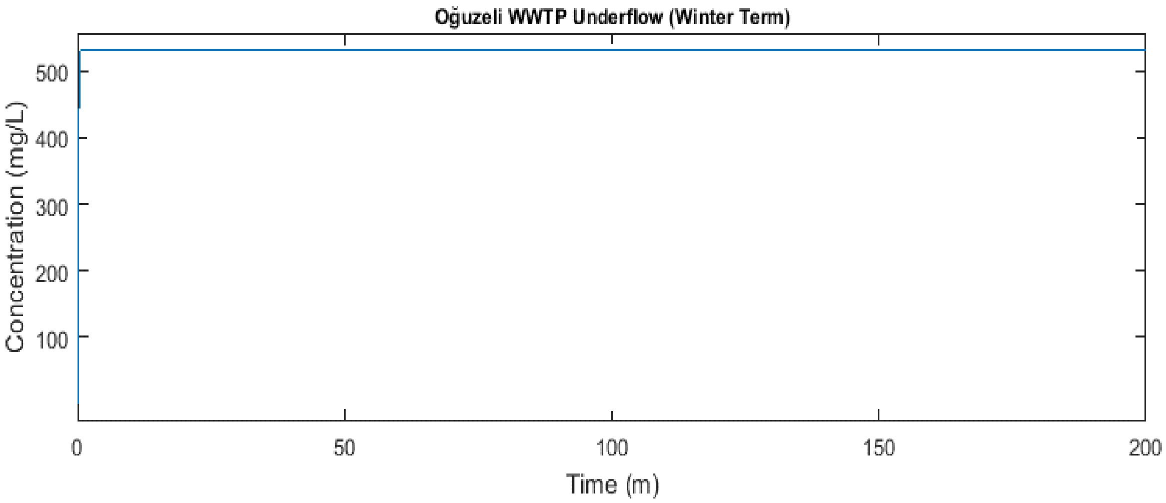

Figure 4.14 Underflow Concentration in Winter Term

Table 4.3 Effluent Concentrations of Simulated and Measured Data

Time period	Measured Values	Model Values
Summer Term	16 mg/L	16.4 mg/L
Winter Term	4mg/L	4.4 mg/L

From the Table 4.3, it is proven that the model behaves expectedly within the acceptable norms. The underflow sludge is however, not measured at the Oğuzeli WWTP, the simulated data presented were $C_u = 435\ mg/L$ and $C_u = 513\ mg/L$ for summer and winter term respectively. These values were almost able to satisfy the mass conservation law presented by Bürger et al. validating 80% accuracy of the model. It is also observed that the model struggles with representing low load conditions appropriately due to bulking inaccuracy which can be a possible future research discussed in Chapter 5.

4.4 Proposed Control Method

Wastewater treatment plants relies on four building blocks for control implementation (see Figure 4.15); understanding of the plant dynamics and an appropriate model; transducers/sensors help provide output data and disturbances; applicable control strategies for control; actuators to realize the control methodology.

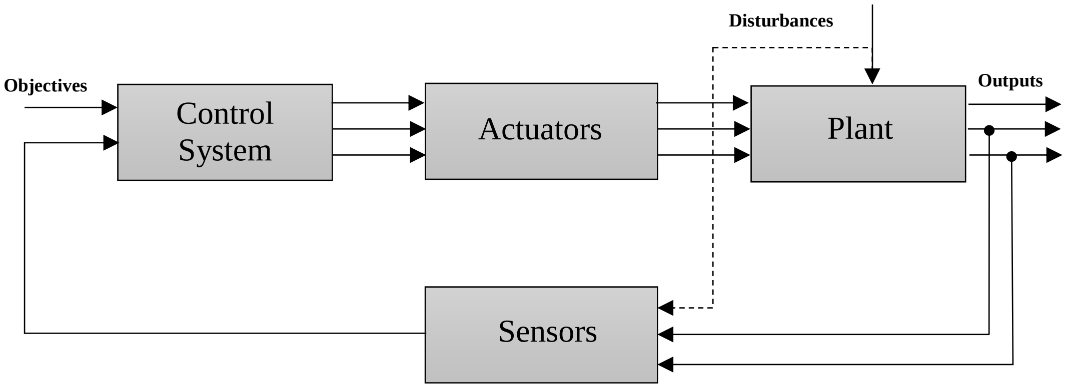

Figure 4.15 Schematic diagram of control implemented in WWTP [61]

It is understood that the most critical phase in providing with a control technique is complete understanding of the dynamics which can only be inferred from a good mathematical model. Moreover, the control quality of the system depends significantly on the designer’s understanding of the process dynamics and limitations. The bio-kinectical process’s complexity is still unparalleled in the process control industry. Thus, all the environmental disturbances affecting the model is extremely difficult to consider [27].

Although Bürger model can be used as a loose interpretation of the secondary settling process as the model on its own has few drawbacks. As seen in the simulation results, the rain influent and extreme fluent does create an unwanted increase in the solid profile concentration in the effluent flow, we proposed three different modes of control which if implemented may achieve acceptable outputs. For the control structures to be fitted, a block diagram as well as a P&I diagram with the proposed control model is presented (see Figure 4.16).

Controlling of secondary settler tanks can be achieved in two different methods, firstly, by controlling the recycled activated sludge flow (RAS) which is carried by Q_r. The RAS-flow which is fed back continuously to the aeration tank through the SST can be monitored. As RAS-flow eventually affects the influent flow Q_f, controlling the flow at various levels may help achieve a low sludge concentration at the effluent output.

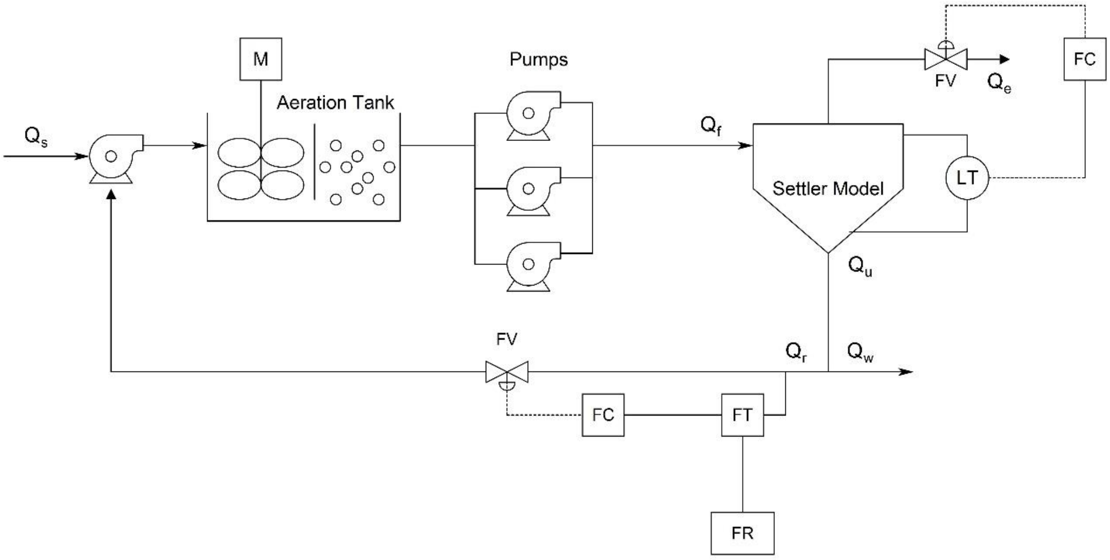

Figure 4.16 P&I diagram of the control model with settler tank

Another control strategy that is a bit difficult to implement and often not encouraged is controlling the effluent flow rate Q_e with respect to the sludge blank height. This technique presents an inversely proportional relationship with the hydraulic load on the secondary settler.

If implemented, it can be helpful in two different ways, firstly, and most importantly, the effects of surface load on the clarifier is minimized (Figure 4.17). At high loads, the effluent flow is minimized leading to a much clearer effluent and vice versa.

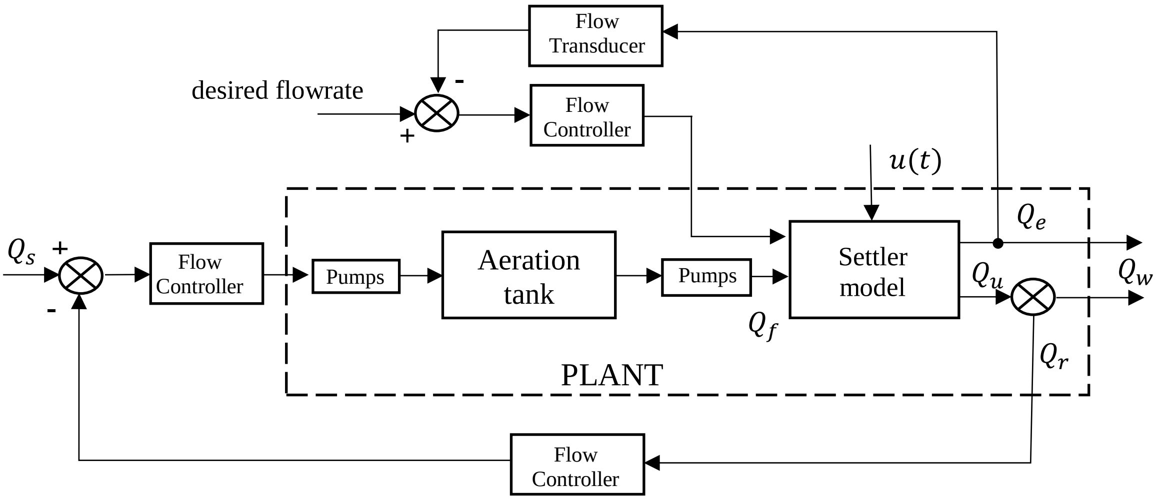

Figure 4.17 Block diagram of the control model

Secondly, controlling effluent flow would provide for a better sludge bulking at the bottom of the settler, and if the underflow flow is monitored a better Sludge Volume Index can be achieved.

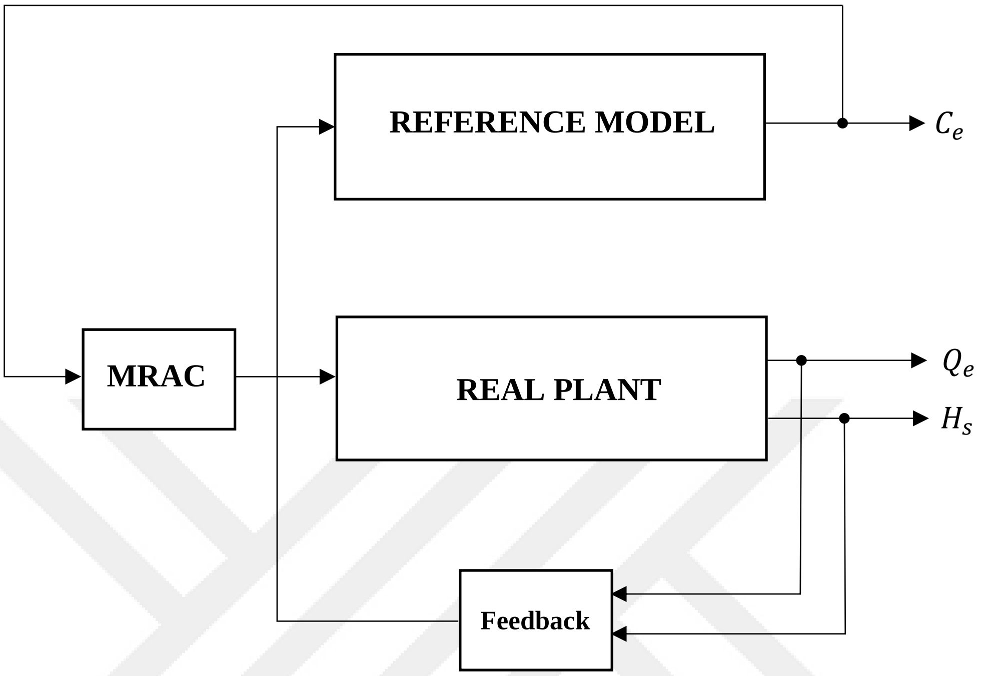

Figure 4.18 Adaptive control model for SST

In the third strategy, we propose an adaptive control strategy (Figure 4.18), whereby the reference model is employed to provide with online effluent concentration. The sludge blanket height and effluent flowrate of the real model are taken as input to the simulated model and through proper adaptive techniques such as MRAC the output of the simulated model (C_e) can be used to provide a set point for the real plant model.

CHAPTER 5

CONCLUSIONS AND FUTURE RESEARCH

Nowadays, biological complex processes are commonly defined in terms of partial differential equations. Although a lot of research has been done in the field of activated sludge process seldom has there been a perfect mathematical model describing the dynamics of secondary settling tank, partly due to the complexity in the field of settling theories and fluid mechanics. Among the different models proposed over the years, Takács model has been widely appreciated for its predictability but with restricted boundaries and insufficient expressions, the model fails to predict the effluent quality under changing weather conditions (example rainy/stormy weather). Hence, more research with regard to effluent predictions in settling secondary tank is required. The main aim of the thesis, to provide with an easily computable and user adaptable mathematical model has been studied. The Bürger model includes the necessary dispersion and compression functions to better understand the settleability of the solid sludge particles.

The introduction of Godunov flux facilitated in better understanding the downward settling flux within the settling tank. Through literature review and experimental data Vesilind velocity function proved to be a better match compared to Takács velocity model for Bürger-Diehl model, although many experiments have been conducted using the latter. The Bürger model's efficacy was tested through different climate conditions and the results were discussed thoroughly in Chapter 4. Often termed as the bottleneck of the activated sludge process, the highly complex process, its simulated model data was compared with real data from the Oğuzeli wastewater treatment plant. With different conditions it was understood the model can be used to predict in different load conditions. However, due to the numerical approximations the model does lack the feasibility to be used as a daily simulation driver. The highly computational requirement, CFL condition proposed by Bürger et al. makes it impractical for extensively long simulations.

The model was implemented on a familiar simulated environment in order for it to be easily accessible by future researchers. In the simulations, the results were presented for a constant, rainy and extreme influent cases in simulations 1-3, the model presented with a reasonable output which was cross referenced with literature data. Simulations 4 and 5 were implemented considering an actual WWTP in Oğuzeli district. The results were satisfactory and proved the efficacy of the plant by achieving effluent concentration close to the measured values. A pseudo code explaining the steps taken to understand the complexity of the process was given, including a step-wise process as a flowchart. The final objective, to present the model from a control engineer's perspective providing with explicitly describing the necessary inputs and outputs in a manner that control strategies can be easily implemented. Therefore, the model brought possibility for process control and provided a starting point for classical, adaptive, neural or fuzzy-logic based control. The proposed P&I diagram propel chemical engineers to look in the direction of WWTP research and provide a fresh perspective in optimization or control of SST models. The secondary settler can be regarded as a continuous stirred tank reactor and with necessary assumptions and conditions a mathematical model can be achieved. At its entirety, a model which is rather easily computable and with promising results compared to other 2-D and 3-D models with greater efficacy and possible control structures was presented.

This research can be further improved by considering the application of a better control strategy for uneven loading conditions. The model's accuracy depends greatly upon the settling velocity and layering approach, if settling velocity models can be improved with respect to the low sludge concentrations and better settling profiles unlike the Vesilind or Takács models, existing settler models can easily be benefited. The designed model considered only the radial cross-sectional area of the SST, which can be broadened by implementing a varying cross-sectional area, a more practical model of real WWTPs. Moreover, research in the Bürger model's compression function is also advisable, as in its present form it still lacks the accuracy in predicting the sludge blank height during bulking process.

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APPENDIX

PSEUDO CODE

```
%Bürger-Diehl secondary settler model %Vesilind velocity function is used.
%Copyright Syed Fouzan Ishaqui @ Gaziantep University

%INITIALIZATION M-FILE
%requesting user input on model type
PROMPT user input for type of model (Constant, Stormy, and Extreme)
%initializing all parameter data
GET all required parameters: maximum theoretical velocity ($v_o$), Vesilind parameter ($r_v$), solid density ($\rho_s$), density difference ($\rho_d$), acceleration constant (g), $\alpha$ and $\beta$ parameters in solid stress, $\alpha_1$ and $\alpha_2$ parameters from Bürger dispersion model.
GET cross sectional area(A), length of clarification(H) & thickening zone(B), number of layers(n), critical concentration($C_{cr}$), maximum concentration($C_{max}$), effluent flowrate($Q_f$), underflow rate ($Q_u$),     %All values are in SI units

%calculation of pre-computation data
total height(T) ← B+H
Total layers including extra underflow and effluent zone(N) ← n+4
Layer depth ($\Delta z$) ← T/n
layer boundaries(z) ← equally distributed (-H-2*dz,B+2*dz,n+5)
Z ← equally distributed (-2*dz, (B+H)+2*dz, N);     %For mesh of settler
initial concentration (x) ← user defined
```

```
%Compression function
Define $dcomp_{1xN}$
$M \leftarrow$ square of n %Factor to reduce error
Define $NCf_{1xM}$          %pre-numerical approximation compression function
$\Delta C \leftarrow (C_{max}-C_{cr})/M$
$dcomp_1 \leftarrow dcomp(C_{cr})$
$NCf_1 \leftarrow 0$

%Algorithm 1
FOR all the values of M starting from 2 do
    $dcomp_i \leftarrow dcomp(C+i\Delta C)$
    $NCf_i \leftarrow NCf_{i-1} + \Delta C/2*dcomp_{i-1+}dcomp_i$
END FOR

%Calculation of bulk flux and one local maximum
$\hat{C} \leftarrow 1/r_v$
Calculate bulk flux ($f_{bk}$) for one local maximum ($\hat{C}$)

%Calculation of CFL condition
Define equally distributed concentration values from 0 to $C_{max}$
$f_{bk}' \leftarrow$ differentiation of bulk flux
Calculate maximum value for $f_{bk}'$ , $d_{comp}$ , $D_{disp}$ for maximum value of $Q_f$ as 2000
Calculate for CFL condition

%SIMULINK SETTLER FUNCTION
Define main function settler dx for all parameter values initialized in the m-file
Define Gudonov flux $G_{1xN}$          %initialization of Gudonov flux G
Define $DCnum_{1xN}$          %initialization of numerical compression function
Define $Ddisp_{1xN}$          %initialization of numerical dispersion function
```

```
Define $dx_{1xN}$                    %initialization of dx concentration
Define $v_{hs}$                      %Vesilind Settling Velocity
Define $f_{bk}$                      % bulk flux

%DispersionFunction
Define first and last $D^{disp}$ values as zero
FOR all the values of N-1 from 2 do
    IF      z less than $\alpha_2 * Q_f$
            Calculate $D^{disp}$
    ELSE
            $D^{disp} \leftarrow 0$
            Increment counter
    END IF
END FOR

%Algorithm 2 Compression function
Define $D^{num}$ first and last value to be zero
FOR all the values of N from 2 do
    IF      concentration is less than equal to $C_{crit}$
            $D^{num} \leftarrow 0$
    ELSE
            $j \leftarrow (x_i - C_{crit}/\Delta C)$
            $D^{num}_i = NCf_j + (NCf_{j+1} - NCf_j) * ((x_i - C_{crit}/\Delta C) - k)$
            Increment counter
    END IF
END FOR

%Godunov Convective flux
Define Godunov convective flux $G_{1xN}$
```

```
FOR all the values of N-2 from 2 do
    IF  cuurent concentration is less than equal to next concentration
        $G_i \leftarrow$ minimum of $f_{bk}(C_j)$, $f_{bk}(C_{j+1})$
    ELSEIF
        $(\hat{C} - x_i)*(\hat{C} - x_{i+1}) < 0$
        $G_i \leftarrow f_{bk}(\hat{C})$;
    ELSE
        $G_i \leftarrow$ minimum of $f_{bk}(C_j)$, $f_{bk}(C_{j+1})$
        Increment counter
    END IF
END FOR

%%CALCULATION OF CONCENTRATIONS FOR EACH LAYER%%
%Layers in Effluent zone
$dx_1 \leftarrow Q_e/A*\Delta z*(x_2 - x_1)$
$dx_2 \leftarrow Q_e/A*\Delta z*(x_3 - x_2) - G_2/\Delta z + (D^{num}_3 - D^{num}_2/\Delta z^2)$

%Layer 1 in SST
$dx_3 \leftarrow Q_e/A*\Delta z*(x_4 - x_3) - (G_3 - G_2/\Delta z) + (D^{disp}_3*(x_4 - x_3) + D^{num}_4 - 2*D^{num}_3 + D^{num}_2/\Delta z^2)$

%Layers from 2 to N-3
FOR all the values of N-3 from 4 do
    IF  Layers before Feedlayer
        $dx_i \leftarrow Q_e/A*\Delta z*(x_{i+1} - x_i) - (G_i - G_{i-1}/\Delta z) + (D^{disp}_i*(x_{i+1} - x_i) - D^{disp}_{i-1}*(x_i - x_{i-1}) + D^{num}_{i+1} - 2*D^{num}_i + D^{num}_{i-1}/\Delta z^2)$
    ELSEIF
        Layers after Feedlayer
        $dx_i \leftarrow -Q_u/A*\Delta z*(x_i - x_{i-1}) - (G_i - G_{i-1}/\Delta z) + (D^{disp}_i*(x_{i+1} - x_i) - D^{disp}_{i-1}*(x_i - x_{i-1}) + D^{num}_{i+1} - 2*D^{num}_i + D^{num}_{i-1}/\Delta z^2)$
```

```
        ELSE
                Feedlayer
                $dx_i \leftarrow - Q_u+Q_e /A*\Delta z*x_i - (G_i-G_{i-1}/\Delta z)+(D^{disp}_i*(x_{i+1}-x_i)-D^{disp}_{i-1}*(x_i-x_{i-1}) +D^{num}_{i+1} -2* D^{num}_i + D^{num}_{i-1}/\Delta z^2) + Q_f* C_f / A*\Delta z$
                Increment counter
        END IF
END FOR
%Layer below the thickening zone
$dx_i \leftarrow - Q_u /A*\Delta z*(x_{N-2} - x_{N-3}) - (G_{N-2}-G_{N-3}/\Delta z)+(D^{disp}_{N-3}*(x_{N-2}-x_{N-3})+D^{num}_{N-1} -2*D^{num}_{N-2}+ D^{num}_{N-3}/\Delta z^2)$

%Layers in Underflow zone
$dx_{N-1} \leftarrow - Q_u /A*\Delta z*(x_{N-1} - x_{N-2}) - (G_{N-2}/\Delta z) + (D^{num}_{N-1} -D^{num}_{N-2}/\Delta z^2)$
$dx_N \leftarrow - Q_u /A*\Delta z*(x_N - x_{N-1})$
```