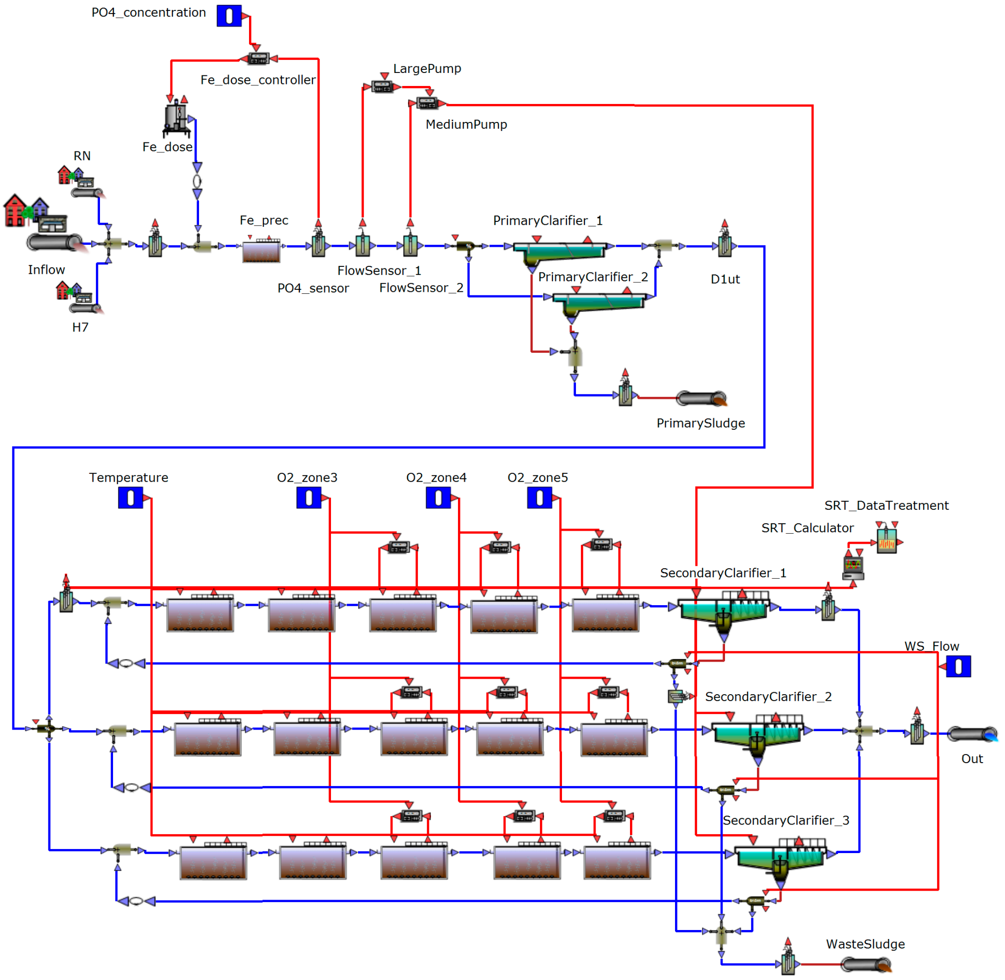
# Modelling the COD Reducing Treatment Processes at Sjölunda WWTP



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Water and Environmental Engineering
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# Modelling the COD Reducing Treatment Processes at Sjölunda WWTP

## Increased load and its effect on biogas production

by

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Front picture: Graphical layout of the wastewater treatment model created. All displayed items are an excerpt from the WEST template (DHI, 2014b).

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# Preface

This master thesis was carried out at Water and Environmental Engineering, Department of Chemical Engineering at Lund University with the support of VA SYD.

First of all I would like to thank my supervisor Jes la Cour Jansen and co-supervisor David Gustavsson for their constant support. Jes always had informative and quick answers and always valued the greater picture, aiding me to move forward when I got lost or stuck. I wish I had more time for this thesis, allowing me to incorporate all the interesting and splendid ideas presented by David who was always keen on discussing and finding the best solutions.

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I was gratefully given the opportunity to do my opposition on Marco Fezzi’s master thesis (A Pragmatic Approach to Wastewater Treatment Modelling, The Källby Wastewater Treatment Plant as a Case Study) and Marco was doing similar research as mine using WEST. I therefore found Marco’s work very inspiring and educational which I am very thankful for.

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A huge thanks to the DHI for providing me with a license for WEST, making the entire thesis possible. Enrico Remigi should also have a special thanks for providing me with fast and well formulated answers to all my questions in the WEST forum.

A very special thanks goes to VA SYD and everyone situated at Sjölunda WWTP where most of my time was spent. I thank for the technical information that everyone were keen on sharing and for making the time spent as pleasant and illuminating as it was.

My final and most important thanks go to my family and partner for their unlimited support and for making each day count.

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# Summary

The main focus of this thesis was to evaluate the possibility of establishing a wastewater treatment model for the main COD removal parts in the water line of Sjölunda Wastewater Treatment Plant (WWTP) located in Malmö, in southern Sweden. The finalised model was used to simulate an increased load of on average 5,000 population equivalents (P.E.) per year due to population growth in Malmö. The aim was to investigate for how long the present configuration of Sjölunda WWTP can handle the increased load without deteriorating water quality or enlarging the plant. The third aim was to investigate a possible increase in biogas production due to the increased load.

The construction, calibration and simulation of the wastewater treatment model were executed using the DHI software product WEST. The flow and concentration data used was provided by online measurements and lab analysis at Sjölunda WWTP. The four main sections modelled were the iron-based pre-precipitation with pre-settling, the primary clarifiers, the activated sludge lines and the secondary clarifiers. No parts of the waste sludge treatment processes were modelled, instead, the biogas production was analysed using simplified calculations.

The calibrated result indicates that it is highly possible to create a wastewater treatment model for the main COD removal parts in the water line for Sjölunda WWTP. The calibrated result for the primary sludge and the waste sludge were difficult to evaluate due to both lack of data from Sjölunda WWTP and data of low quality. The greatest calibration complication was to keep high concentrations for total suspended solids (TSS) and phosphorus ($PO^{3-}_4$-P) in the activated sludge, extensive effort was therefore directed towards solving this complication. The calibrated results for the overflow from the primary clarifiers and the concentrations for total Kjeldahl nitrogen (TKN) and COD in the overflow from the secondary clarifiers were considered good calibration results.

The results from the increased load simulations indicate that it is only possible to operate Sjölunda WWTP for an additional nine years without deteriorating effluent quality from the secondary clarifiers or enlarging the plant. The total yearly biogas production during year 0 (before the increased load started) was 800,000 $Nm^3$. The total yearly production was on average increased by 47,000 $Nm^3$ each year until the ninth simulation year where the total yearly production had reached a value of 1,220,000 $Nm^3$.

It was proposed for future work to continue the development of the wastewater treatment model of Sjölunda WWTP since it was proved to be possible to create a model. Especially well-conducted measuring campaigns were proposed to improve the model significantly and a biogas production study was proposed in order to improve and evaluate the calculations for the biogas production.

# Sammanfattning

Examensarbetets huvudsakliga syfte var att utvärdera möjligheten att skapa en avloppsreningsmodell för de reningssteg som involverar COD-reduktionen på Sjölunda avloppsreningsverk i Malmö. Den färdigkalibrerade modellen användes för att simulera ett ökat inflöde motsvarande det av ca 5000 personekvivalenter (pe) per år p.g.a. befolkningstillväxt i Malmö. Syftet var att undersöka hur många år den nuvarande konfigurationen av Sjölunda avloppsreningsverk klarar att hantera det ökade inflödet utan att försämra vattenkvalitén eller utvidga verket. Det tredje syftet var att undersöka en potentiell ökning av biogasproduktionen p.g.a. det ökade inflödet.

Modelleringen, kalibreringen och simuleringen av avloppsreningsmodellen gjordes i programvaruprodukten WEST, skapad av DHI. Värden på flöden och koncentrationer erhölls av onlinemätningar och labbanalyser från Sjölunda avloppsreningsverk. De fyra huvudsektioner som modellerades var den järn-baserade förfällningen, försedimenteringen, aktivslamanläggningen och eftersedimenteringen. Inga sektioner av slamhanteringen modellerades, istället analyserades biogasproduktionen genom att använda förenklade beräkningar.

Det kalibrerade resultatet visar att det är fullt möjligt att skapa en avloppsreningsmodell för de sektioner på Sjölunda avloppsreningsverk som är fokuserade på COD-reduktion. Det kalibrerade resultatet för primär- och överskottslammet var svårt att utvärdera då det både saknades data från Sjölunda avloppsreningsverk samt att viss data var av låg kvalité. Den största kalibreringskomplikationen var att behålla en hög koncentration av total mängd suspenderat material (TSS) och fosfatfosfor ($PO^{3-}{}_4$-P) i aktivslammanläggningen. Mycket tid spenderades därför på att försöka lösa denna komplikation. Det kalibrerade resultatet för flödet från försedimenteringen samt koncentrationerna för totalt Kjeldahlkväve (TKN) och COD i flödet från eftersedimenteringen visade på goda kalibreringsresultat.

Simuleringen av ett ökat inflöde visade att det endast är möjligt att driva Sjölunda avloppsreningsverk i ytterligare nio år utan att försämra vattenkvalitén i utflödet från eftersedimenteringen eller genom att utvidga anläggningen. Den totala årliga biogasproduktionen under år 0 (innan flödesökningarna startade) var 800 000 $Nm^3$. Den totala årliga produktionen ökade med i genomsnitt 47 000 $Nm^3$ per år fram till det nionde året då den totala årliga produktionen nådde upp till 1 220 000 $Nm^3$.

Framtida fokus bör läggas på att vidareutveckla avloppsreningsmodellen för Sjölunda avloppsreningsverk eftersom resultaten tydde på att det var fullt möjligt att skapa en modell. Väl genomförda mätningskampanjer bör genomföras för att förbättra modellen. Även studier av biogasproduktionen bör genomföras för att förbättra de förenklade beräkningarna som användes i detta arbete.

# Table of abbreviation

| | |
|---|---|
| ASM1 | Activated sludge model No. 1 |
| ASM2d | Activated sludge model No. 2d |
| BOD | Biochemical oxygen demand |
| COD | Chemical oxygen demand |
| $COD_S$ | Soluble COD |
| $COD_X$ | Particulate COD |
| EBPR | Enhanced biological phosphorus removal |
| F/M | Food-to-microorganism ratio |
| FF | Flow factor |
| IAWQ | International Association on Water Quality |
| MBBR | Moving bed biofilm reactor |
| MF | Mass factor |
| MLSS | Mixed-liquor suspended solids |
| $Nm^3$ | Normal $m^3$ (gas volume at standard temperature (0°C) and pressure (1 atm)) |
| NTF | Nitrifying trickling filter |
| P.E. | Population equivalent |
| PAO | Phosphorus accumulating organisms |
| SBR | Sequencing batch reactor |
| SF | Seasonal factor |
| SRT | Solids retention time |
| TKN | Total Kjeldahl nitrogen |
| TP | Total phosphorus |
| TSS | Total suspended solids |
| VS | Volatile solids |
| WWTP | Wastewater treatment plant |

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# 1 Introduction

Sjölunda Wastewater Treatment Plant (WWTP), located in Malmö, in southern Sweden treats wastewater corresponding to almost 300,000 population equivalents (P.E.) (considering 70 g $BOD_7$/person·d) (VA SYD, 2014). Some parts of Sjölunda WWTP are designed to handle a load corresponding to 550,000 P.E. (Hanner *et al.*, 2003). Malmö is expected to increase by on average 5,000 inhabitants per year in the following 10 years (Stadskontoret, 2014) which will increase the load on Sjölunda WWTP. It is important for engineers and operators to be able to predict these kinds of future changes but also to be able to understand how it will affect their WWTP. A well-developed wastewater treatment model of the plant facilitates the understanding of how changes in inflow and composition will affect the plant and the effluent quality.

In the 80s, the International Association on Water Quality (IAWQ, formerly IAWPRC) task group on mathematical modelling for design and operation of biological wastewater treatment had an aim to create a wastewater treatment model for nitrogen-removal activated sludge processes. Their work resulted in the Activated Sludge Model No. 1 (ASM1) in 1987 (Henze *et al.*, 2000). Since then, simulations of wastewater processes have been more common and a widely accepted tool (Coen *et al.*, 1997). The created models have been found to be useful on many levels, especially concerning optimisation, design and upgrading of the WWTP studied.

Sjölunda WWTP treats both domestic and industrial wastewater. It is composed of iron-based pre-precipitation with pre-settling and a high-loaded activated sludge with focus on COD-removal (Hanner *et al.*, 2003). The following steps are focused on nitrogen removal starting with nitrifying trickling filters (NTFs) followed by moving bed biofilm reactors (MBBRs). Final particle separation is done in a dissolved air flotation plant before the treated water is discharged in the Öresund strait. The produced waste sludge is digested anaerobically creating biogas while parts of the digested sludge may be used as fertilizer.

## 1.1 Aim

The main aim is to assess the possibility of establishing a wastewater treatment model for the main COD removal parts in the water line of Sjölunda WWTP. An increased understanding of WEST is therefore necessary to be able to choose the most favourable way of action while constructing Sjölunda WWTP in the modelling program. The goal is to assess the models ability to mimic and evaluate Sjölunda WWTP's ability to handle an increased load in order to guide in developing further wastewater treatment models that may improve the operation and extension of the WWTP.

## 1.2 Limitations

A wastewater treatment model is a simplification of reality and therefore, several limitations, assumptions and simplifications were made.

With the data available, the best course of action was considered to only define five of the 18 components in the inflow characterization, thus allowing WEST to do the rest of the fractionation. In case of missing data (occasional measurements or entire time series), interpolation and simple equations where used to fill out the gaps.

Only one of two parallel sections at Sjölunda WWTP was studied and in order to facilitate the modelling process, only half of this section was modelled. Some simplifications were made trying to mimic the design of some structures.

As the calibrated model had been finalized, changes were made in order to generalize the model to be able to use it while simulating the increased load. The $O_2$ concentrations and the temperature in the activated sludge were set to a fixed value and a fixed average temperature curve. The sub-model controlling the iron dose for the pre-precipitation and the sub-model controlling the solids retention time (SRT) were altered to follow a fixed value.

The increased load simulation was simplified to be simulated as a yearly step-wise increase. The additional flow depends on the catchment area but due to simplification, a generalized value was chosen.

No parts of the waste sludge treatment processes were modelled in WEST, instead, biogas production was analysed using simplified calculations.

# 2 Wastewater treatment

The sections of Sjölunda WWTP studied were the iron-based pre-precipitation with pre-settling, the primary clarifiers, the activated sludge, the secondary clarifiers and the biogas production. This chapter is therefore focusing on the wastewater treatment processes dealt with in those sections.

## 2.1 Wastewater composition

Wastewater from households is divided into blackwater and greywater. Blackwater is composed of urine, faeces and toilet paper while greywater comes from sinks, showers, washing machines and dishwashers. Naturally, the composition of these wastewater fractions differs and Jönsson *et al.* (2005) have conducted a study where the composition of these fractions has been developed.

The data from Jönsson *et al.* (2005) is developed for Swedish conditions and stormwater and industrial wastewater is not accounted for. The concentrations for the parameters studied in this thesis; flow ($H_2O$), total Kjeldahl nitrogen (TKN), chemical oxygen demand (COD), total suspended solids (TSS) and total phosphorus (TP) are visible in Table 2.1 with the unit g/(P.E.·d). The parameters are divided into the fractions blackwater, greywater and the total household wastewater. Concentrations for TKN were calculated according to Equation 2.1 since TKN was not directly available in Jönsson *et al.* (2005). The $H_2O$ fraction within total greywater is dependent on the technology and habits of the studied area. A default value for this fraction, 130,000 g/(P.E.·d) is proposed by Jönsson *et al.* (2005) which was used in this thesis.

$$TKN = N_{tot} - NO_{2,3}\text{-}N \qquad \text{Equation 2.1}$$

*Table 2.1. Concentrations for $H_2O$, TKN, COD, TSS and TP in blackwater, greywater and the total household wastewater in g/(P.E.·d) (Jönsson et al., 2005).*

| Parameter | Blackwater | Greywater | Household wastewater |
|---|---|---|---|
| **$H_2O$** | 1,597.6 | 130,000 | 131,597.6 |
| **TKN** | 12.5 | 1.52 | 14.02 |
| **COD** | 72.6 | 62.4 | 135.0 |
| **TSS** | 48.76 | 17.6 | 66.36 |
| **TP** | 1.4 | 0.68 | 2.08 |

## 2.2 Chemical phosphorus removal

Iron-based precipitation is a very effective way of reducing the phosphate ($PO^{3-}_4$) concentration in wastewater (Hammer and Hammer, Jr., 2012). The precipitation can take place in several locations in the plant but this study investigates pre-precipitation (the iron is added before the primary clarifiers). The added iron acts as a coagulant by reducing the electrical charges that allows particles to be detained in the solution. The process is complex and not completely understood but it is believed that the iron is combined with the $PO^{3-}_4$ allowing the phosphate to be precipitated. An example from Hammer and Hammer, Jr (2012) using iron chloride can be seen in Equation 2.2.

$$FeCl_3 \cdot 6H_2O + PO_4^{3-} = FePO_4 + 3Cl^- + 6H_2O_3 \qquad \text{Equation 2.2}$$

The most common iron salt used is the iron sulphate ($FeSO_4$) and it is also the least expensive (Hammer and Hammer, Jr., 2012). The reaction presented in Equation 2.2 indicate the molar ratio between Fe and P to be 1 to 1, the same ratio goes for the reaction between $FeSO_4$ and $PO^{3-}_4$. But there is another competing reaction, the one for natural alkalinity (the reaction using $FeCl_3$ can be seen in Equation 2.3), which means that a higher dosage of $FeSO_4$ must be added in order to precipitate sufficient amount of $PO^{3-}_4$.

$$FeCl_3 \cdot 6H_2O + 3HCO_3^- = Fe(OH)_3 + 3CO_2 + 3Cl^- + 6H_2O \qquad \text{Equation 2.3}$$

## 2.3 Primary clarifiers

Clarifiers are design to keep the wastewater as motionless as possible in order to favour gravitational separation of particulate material from the solution (Hammer and Hammer, Jr., 2012). The settled particles are removed from the clarifier as sludge while the solution is continuing as overflow. The amount of biochemical oxygen demand (BOD) removed via sludge also depends on the characteristics on the raw wastewater. A high content of soluble BOD in the incoming water may resolve in less than 20 % BOD removal while some industrial wastewater may add more settleable solids which can increase the removal up to 60 %.

## 2.4 Activated sludge system

The activated sludge system is a biological treatment system and it is the most efficient way of removing organic matter from wastewater (Hammer and Hammer, Jr., 2012). Bacteria present in the activated sludge decompose colloidal and dissolved organics present in the raw wastewater, thus removing them from the solution. By doing so, they consume oxygen while creating new mass and carbon dioxide ($CO_2$). The microorganisms in the system are in need of sufficient oxygen, reasonable temperature and pH, biological food and growth nutrients. A commonly used concentration for dissolved oxygen is 2.0 $g/m^3$, but concentrations down to 0.5 $g/m^3$ have still been proved to be enough. Normal temperature ranges are between 8-10 °C up to 20-25 °C depending on the natural climate. A high temperature favours biological activity and chemical reactions but it also increases the oxygen demand. pH may vary in the range between 6.5 to 8.5 in order to favour the aerobic treatment. The theoretical ratio for BOD:nitrogen:phosphorus (BOD:N:P) in aerobic treatment systems is 100:5:1. The system must be carefully managed by controlling the outflow and ensuring a large enough recirculation flow not to lose the wanted biological culture that are responsible for treating the water.

The activated sludge system is normally followed by a secondary clarifier where the biological flocs are settled by gravity and removed as secondary sludge. Part of the removed sludge is recirculated to the activated sludge while the excess microorganisms are removed as waste sludge. The amount of active sludge recycled depends on the food-to-microorganism ratio, F/M which is a way of analysing the amount of food present in relation to the amount of microbial mass expressed as mass BOD per mass MLSS (mixed-liquor suspended solids). Another way of analysing the amount of recirculated sludge is by defining the SRT (also defined as the sludge age) and this is the method used in this thesis. The SRT is calculated according to Equation 2.4.

$$SRT = \frac{MLSS \cdot V}{SS_e \cdot Q_e + SS_w \cdot Q_w} \qquad \text{Equation 2.4}$$

SRT is calculated in terms of days where MLSS (g/m$^3$) is the microbial growth in the activated sludge, V is the volume of the aeration tank (m$^3$), $SS_e$ and $SS_w$ are suspended solids in effluent and waste sludge (g/m$^3$) and $Q_e$ and $Q_w$ are flows in effluent and waste sludge (m$^3$).

## 2.5 Secondary clarifiers

Secondary clarifiers are over all very similar to primary clarifiers and their main purpose is to separate the biological flocs from the solution (Hammer and Hammer, Jr., 2012). This is done by gravitational settling and the most common design is to allow large scrapers to accumulate the sludge towards the middle where it is removed. Part of the removed sludge is recirculated to the activated sludge and the excess sludge is removed as waste sludge. Biological flocs are harder to settle by gravity than the particles in the primary clarifiers since the biological production generates gas bubbles that decrease the particles settling capacity. Secondary clarifiers are often designed to be deeper than primary clarifiers partly in order to handle the increased sludge volume. Due to the decreased settleablity, the overflow rate is lowered and the detention time is normally around two to three hours.

## 2.6 Biogas production

The produced waste sludge can be sent to anaerobic digesters where biogas is produced. The organic matter in the sludge is digested in several steps creating products that are altered into methane ($CH_4$) (Davidsson, 2007). An anaerobic digestion process is hard to initiate since the archaea that is responsible for the methane production only exists in very small concentrations in incoming wastewater. It is also slow growing and sensitive to environmental factors (Hammer and Hammer, Jr., 2012).

In the first stage, the large organic material is converted into organic acids and some $CH_4$, $CO_2$ and a very small amount of hydrogen sulphide ($H_2S$) (Hammer and Hammer, Jr., 2012). The second stage is conducted by acid-splitting methane-forming bacteria that are very sensitive to environmental conditions concerning temperature (normally around 35 °C), pH and oxygen level (it has to be anaerobic conditions). The bacteria digest the organic acids and forms $CH_4$ and $CO_2$. The function of an anaerobic digester is dependent on the balance between the two stages.

# 3 Sjölunda Wastewater Treatment Plant

Sjölunda WWTP, located in Malmö, in southern Sweden, treats wastewater corresponding to around 300,000 P.E. which yields an average flow of 1,140 L/s (VA SYD, 2014). Major parts of the plant are designed for 550,000 P.E., corresponding to a load of 1,650 L/s (Hanner *et al.*, 2003). Sjölunda WWTP was constructed in 1963 and has been upgraded several times, mainly due to more stringent effluent demands. It was upgraded in 1998-1999 in order to introduce enhanced nitrogen removal, i.e. nitrification-denitrification. Sjölunda WWTP is composed of a high loaded activated sludge with focus on BOD removal followed by nitrification in NTFs and denitrification in MBBRs.

Sjölunda WWTP is divided into two separate and parallel sections, D1 and D2. Only D1 was studied and is therefore the one described in this chapter. D1 is composed of four primary clarifiers, six activated sludge lines with two secondary clarifiers per line. D1 and D2 are joined together before entering the nitrogen removal section that is composed of two NTFs and three MBBRs. A flow chart of Sjölunda WWTP is seen in Figure 3.1.

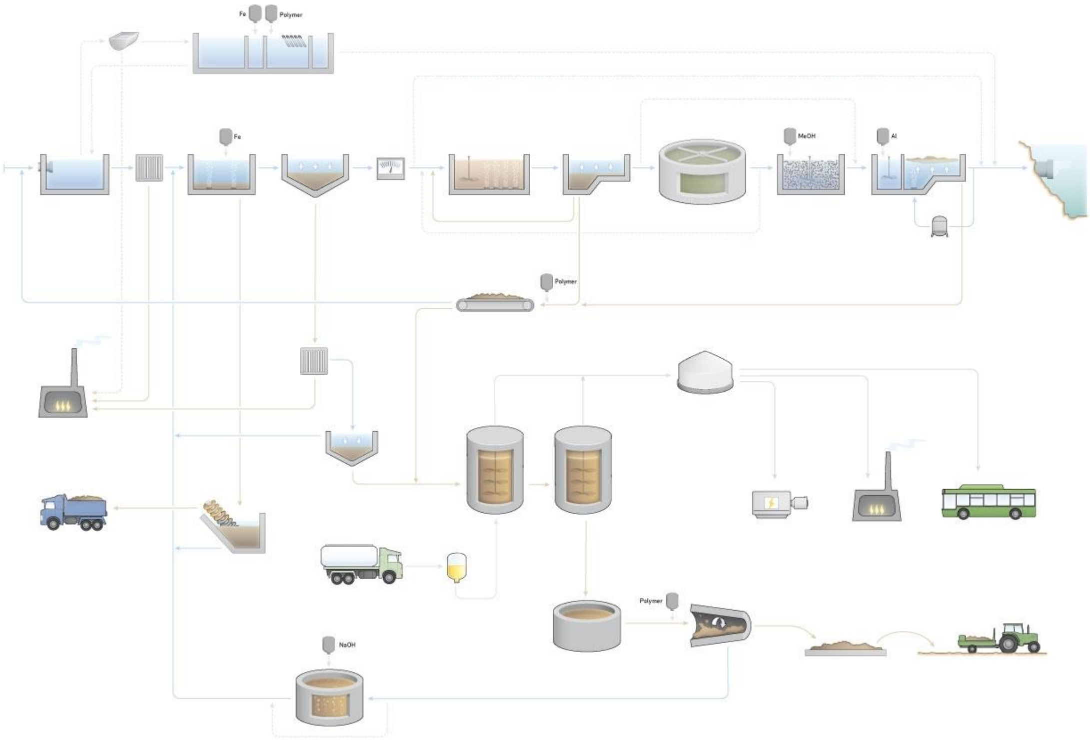


*Figure 3.1 The flow chart of Sjölunda WWTP (VA SYD, 2014, with kind permission).*

Prior to 2008, the occasion of overflows at Sjölunda WWTP was more common. Overflows occur when inflow is higher than the capacity at the plant allowing excess water to be discharged without treatment. But in 2008, a wet weather overflow plant was constructed at Sjölunda WWTP. Part of the high flow (at wet weather occasions) is pumped to this facility where the wastewater is partly treated before it is discharged in to the Öresund strait.

The first treatment step at Sjölunda WWTP is screening where larger particles are removed and combusted for energy extraction. This is followed by an aerated grit removal chamber where heavier particles such as sand sinks to the bottom and are removed. The grit is washed to remove organic material in order to be able to use it in soil construction. Phosphorus removal is conducted at Sjölunda WWTP by adding iron as a pre-precipitation step in aerated chambers. This is conducted prior to the four primary clarifiers where particles sink to the bottom and are removed as primary sludge. The primary sludge is led to a gravity thickener before entering the digesters, while the water phase is recirculated to the inlet of the plant (this recirculated flow is further denoted as H7).

The primary clarifiers are followed by the six activated sludge lines denoted G1:1, G1:2, G2:1, G1:2, G3:1 and G3:2. Each line is constructed of two anaerobic zones followed by three aerated. The anaerobic zones are constantly stirred and it is by volume one fourth of the total activated sludge volume. The anaerobic zones are responsible for a minor denitrification as reject water is recirculated to the inlet of the plant. The three aerated zones are treated differently by adding a lower oxygen concentration in zone three, a higher in zone four and the highest in zone five. The activated sludge has a low SRT around 2.5 days. It is rich in heterotrophic bacteria that consume carbon, nitrogen and phosphorus thus creating a large volume of activated sludge. The activated sludge is removed from the system in the following secondary clarifiers where it is denoted secondary sludge.

Each sludge line has two secondary clarifiers where the activated sludge is removed. A larger part of the removed sludge is recirculated back to the inlet of the activated sludge in order to control the SRT, i.e. keep the sludge within the system. The other minor part of the removed activated sludge, denoted waste sludge, is transferred to a filter belt thickener. The waste sludge then enters the anaerobic digesters while the water phase is recirculated to the inlet of the plant.

The water phase leaving the secondary clarifiers enters the NTFs where nitrification takes place. The large towers are packed with folded plastic material where the wastewater is sprinkled on the top allowing it to move by gravity through the tower being naturally aerated.

At the bottom of the NTFs, the wastewater is extracted and transferred to the MBBRs where the post-denitrification takes place in constantly stirred basins. Methanol is added as external carbon source which allows the microorganisms to grow on the carriers, consuming the methanol and nitrate allowing the nitrogen to leave the system as nitrogen gas.

The final step is the flotation basin where small air bubbles enter at the bottom of the basin, adhere to remaining particles and brings them to the surface where the sludge is scraped off. The sludge is brought to the same mechanical thickening filter belt as the waste sludge while the treated water is transported about 3 km out in to the Öresund strait where it is discharged.

The thickened sludge from the gravity thickener and the filter belts are transported to the digesters where it is anaerobically digested at 35 °C. Some organic material is degraded by microorganisms creating biogas composed of methane and carbon dioxide. The biogas can be stored and then converted into electricity and heat used to power the WWTP or to be distributed to the central heating network. The total biogas production during 2013 was 5,330,000 $Nm^3$. The digested sludge is transferred to a buffer tank and then dewatered where the water phase is rich in ammonium-nitrogen ($NH^+_4$-N). The water phase is moved to a sequencing batch reactor (SBR) where the $NH^+_4$-N is converted into nitrite-nitrogen ($NO^-_2$-N) by nitritation and then recirculated to the inlet of the plant (this recirculated flow is further denoted as RN). The recirculated nitrogen is then removed in the anaerobic zones of the activated sludge. The dewatered sludge that is rich in nutrient is stored by month to ensure high quality and traceability. The sludge is controlled and if quality permits, the sludge is distributed on agricultural land.

# 4 Dynamic modelling in WEST

The modelling program WEST is a software product by the DHI that incorporates different wastewater treatment models. The four main sections of Sjölunda WWTP modelled were the iron-based pre-precipitation with pre-settling, primary clarifiers, the activated sludge lines and the secondary clarifiers. The primary clarifiers are based on the primary Takács clarifier and the secondary clarifiers are based on the Takács SVI (which is an extension of the Takács model) (Takács, Party and Nolasco, 1991). The activated sludge lines are based on the Activated Sludge Model No. 2d (ASM2d, Henze *et al.* (2000)). ASM2d is a more comprehensive model than the first ASM constructed, ASM1. More processes and components are included which makes the model more complex. The major differences between the two models are that biomass can be defined as inert and the process of biological phosphorus removal can be simulated in ASM2d (Henze *et al.*, 2000). ASM2d was chosen since it is desired to study phosphorus and ASM2d is the only ASM that takes it into account. The model category used for creating the model was ASM2dModTemp. Biogas production is studied as a part of this thesis but none of the sludge treatment steps are modelled in WEST. These sections are instead investigated using simple calculations.

Sjölunda WWTP was constructed in WEST where the flows and processes are graphically displayed as lines and blocks. Each block is a pre-programmed model like the ASM2d, Primary Takács and Takács SVI containing different processes. Other blocks are also available like controllers, sensors, calculators etc.. There are several components present in ASM2dModTemp that defines the composition of the wastewater. The constructed model needs to be fed with an input file characterizing the incoming wastewater before the simulations can start. The input file contains flows and concentrations of certain components over time. After and during the simulations, graphs and tables can be constructed after choice presenting the results of the simulations.

## 4.1 Model processes

ASM2d use stoichiometric and kinetic parameters and process rate equations to simulate the different processes (Henze *et al.*, 2000). The main processes are: growth of biomass (heterotrophic, autotrophic and phosphorus accumulating organisms (PAO)), decay of biomass, hydrolysis of particulate organics, nitrification processes and chemical precipitation of phosphorus. Growth of biomass is assumed to exclusively rely on readily biodegradable material for substrate. Decay of biomass leads to the creation of inert particulate material and slowly biodegradable material. The slowly biodegradable substrates cannot be consumed by the organisms, the substrate has to undergo hydrolysis where the material is converted into readily biodegradable material. Inert particulate material is assumed not to take part in any more processes. The nitrifying processes are growth and decay of autotrophic biomass. The nitrification is simplified to only include one step, from ammonium to nitrate. The PAO are involved in growth, storage and decay. Chemical precipitation of phosphorus is modelled to only precipitate $PO^{3-}_4$-P.

## 4.2 Model components

There are 19 model components that are divided into soluble components, S and particulate components, X (Table 4.1).

*Table 4.1. All components used in ASM2dModTemp (Henze et al., 2000).*

| Short name | Description | Unit |
|---|---|---|
| Dissolved components | | |
| **$S_O$** | Dissolved oxygen | g $O_2/m^3$ |
| **$S_F$** | Readily biodegradable substrate | g $COD/m^3$ |
| **$S_A$** | Fermentation products (acetate) | g $COD/m^3$ |
| **$S_{N2}$** | Dinitrogen | g $N/m^3$ |
| **$S_{NH}$** | Ammonium | g $N/m^3$ |
| **$S_{NO}$** | Nitrate and nitrite | g $N/m^3$ |
| **$S_{PO}$** | Phosphate | g $P/m^3$ |
| **$S_I$** | Inert, non-biodegradable organics | g $COD/m^3$ |
| **$S_{ALK}$** | Bicarbonate alkalinity | g $HCO^-_3/m^3$ |
| Particulate components | | |
| **$X_I$** | Inert, non-biodegradable organics | g $COD/m^3$ |
| **$X_S$** | Slowly biodegradable substrate | g $COD/m^3$ |
| **$X_H$** | Heterotrophic biomass | g $COD/m^3$ |
| **$X_{PAO}$** | Phosphorus accumulating organisms, PAO | g $COD/m^3$ |
| **$X_{PP}$** | Stored poly-phosphate of PAO | g $P/m^3$ |
| **$X_{PHA}$** | Organic storage products of PAO | g $COD/m^3$ |
| **$X_{AUT}$** | Autotrophic, nitrifying biomass | g $COD/m^3$ |
| **$X_{MEOH}$** | Ferric-hydroxide, $Fe(OH)_3$ | g $Fe(OH)_3/m^3$ |
| **$X_{MEP}$** | Ferric-phosphate, $FePO_4$ | g $FePO_4/m^3$ |
| **$X_{TSS}$** | Particulate material | g $TSS/m^3$ |

### 4.2.1 COD components

COD is fractionated into nine components in ASM2dModTemp and is divided into biodegradable, non-biodegradable and active biomass (Equation 4.1 and Figure 4.1).

$$COD_{tot} = S_F + S_A + S_I + X_I + X_S + X_{AUT} + X_H + X_{PAO} + X_{PHA} \qquad \text{Equation 4.1}$$

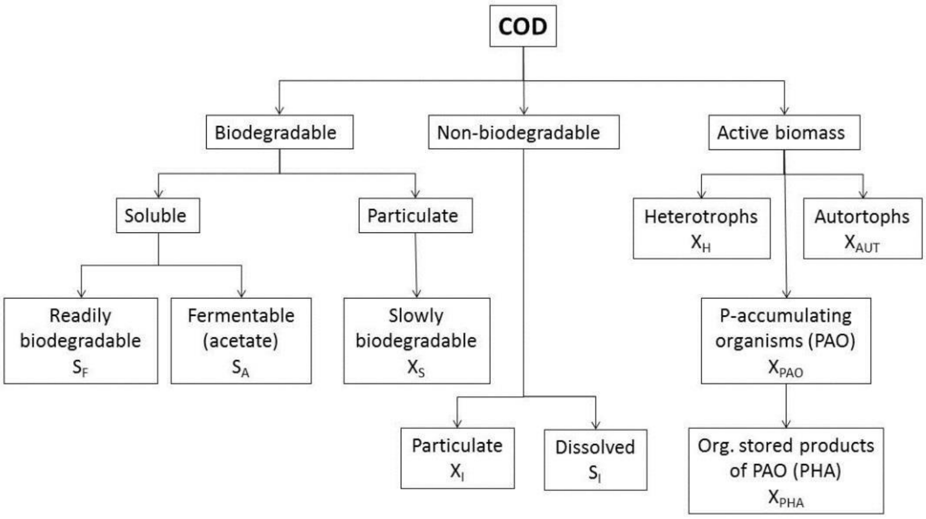


*Figure 4.1. COD components in ASM2dModTemp are divided into biodegradable, non-biodegradable and active biomass.*

***Biodegradable, COD components***

The biodegradable compounds are divided into readily biodegradable ($S_F$), fermentation products ($S_A$) and slowly biodegradable ($X_S$) (Henze *et al.*, 2000). To simplify the model according to the strategy presented in Henze *et al.* (2000), the readily materials are treated as soluble and the slowly biodegradable materials are treated as particulate. This is assumed a valid simplification since readily biodegradable materials often are simple molecules which are easy for the heterotrophic bacteria to degrade. The slowly degradable components are considered to be of high molecular weight and colloidal. They are assumed to flocculate directly in the activated sludge (thus leaving the suspension) where it is converted into readily material during hydrolysis to be available for degradation. Slowly biodegradable material is produced during decay of both heterotrophic and autotrophic bacteria. $S_A$ is the final product after fermentation and although many different products are produced, $S_A$ is considered to be acetate.

***Non-biodegradable, COD components***

Inert, non-biodegradable components are divided into soluble ($S_I$) and particulate ($X_I$) organic matter (Henze *et al.*, 2000). Both are assumed not to be part of any conversion processes and will therefore not be further degraded. The soluble fraction is therefore assumed to leave the activated sludge with the same concentrations as it had at the inlet. The particulate inert organics flocculate in the activated sludge and leaves the system by the waste sludge. Some particulate inert organics are also produced when biomass decay.

***Active biomass, COD-components***

The autotrophic biomass ($X_{AUT}$) is responsible for nitrification and in the ASM2dModTemp, it assumed that it converts ammonium-nitrogen ($S_{NH}$) directly into nitrate-nitrogen ($S_{NO}$), hence no nitrite exists (Henze *et al.*, 2000). Autotrophic bacteria only grow in aerobic environments. The heterotrophic biomass ($X_H$) consume readily biodegradable substrates ($S_F$) and grow (slow or fast) in both aerobic and anoxic environments, but are assumed not to grow during anaerobic conditions. Heterotrophic biomass is also needed during hydrolysis of slowly biodegradable substrate ($X_S$). Both heterotrophic and autotrophic biomasses are lost during decay.

### 4.2.2 Phosphorus components

During enhanced biological phosphorus removal (EBPR), phosphorus accumulating organisms (PAO) are responsible for the uptake of phosphorus (Henze *et al.*, 2000). The COD component $X_{PAO}$ is assumed to include all poly-phosphate-accumulating organisms in the model. PAO is divided into three components: $X_{PAO}$, $X_{PP}$ and $X_{PHA}$. $X_{PAO}$ is assumed only to represent the “true” biomass while $X_{PP}$ and $X_{PHA}$ (stored poly-hydroxy-alkanoate) describe other parts of PAO. $X_{PHA}$ is the internal storage of PAO organisms but it is not included in their biomass in this model. $X_{PHA}$ is a necessary component for ASM2dModTemp but it is not comparable to measured PHA. The final phosphorus component is the inorganic soluble phosphorus, $S_{PO4}$ that is primarily considered to be ortho-phosphates.

### 4.2.3 Nitrogen components

There are four nitrogen components studied in ASM2dModTemp, dinitrogen ($S_{N2}$), ammonium-nitrogen ($S_{NH4}$) and nitrate- and nitrite-nitrogen ($S_{NO3}$) (Henze *et al.*, 2000). It is assumed that dinitrogen is the only nitrogenous product after denitrification. Nitrite does not exist as a separate component and all $S_{NO3}$ is therefore assumed to be nitrate.

### 4.2.4 Iron components

The two iron components $X_{MeOH}$ and $X_{MeP}$ are important when conducting iron precipitation (Henze *et al.*, 2000). $X_{MeOH}$ is assumed to be $Fe(OH)_3$ and is responsible for the phosphorus binding capacity. Phosphate and $X_{MeOH}$ react and create $X_{MeP}$ (Equation 4.2). $X_{MeP}$ can then be precipitated thus removing phosphate from the system via the sludge.

$$X_{MeOH} + S_{PO} \rightarrow X_{MeP} \qquad \text{Equation 4.2}$$

### 4.2.5 Other components

TSS is obtained from the component $X_{TSS}$ (g TSS/$m^3$) and is a measurement of the amount of particulate material (Henze *et al.*, 2000). The alkalinity of the water is expressed as the component $S_{ALK}$ (g $HCO^-_3$/$m^3$) and the oxygen concentration is obtained by $S_O$ (g $O_2$/$m^3$).

# 5 Model setup

The construction, calibration and simulation of the wastewater treatment model were executed using the DHI software product WEST (DHI, 2014b). In WEST, the WWTP is first constructed graphically followed by data insertion. WEST is in need of design data such as tank volumes and temperatures but it is also in need of data that defines the composition of the incoming wastewater and other concentrations and flows. Once the model setup is complete, simulations are run and the calibration process begins.

The four main sections of Sjölunda WWTP modelled were the iron-based pre-precipitation with pre-settling, the primary clarifiers, the activated sludge lines and the secondary clarifiers. The clarifiers are based on the models presented by Takács, Party and Nolasco (1991) and the activated sludge lines were modelled using the Activated Sludge Model No. 2d (ASM2d, Henze *et al.* (2000)). The model category used for creating the model was ASM2dModTemp.

The data presented by Sjölunda WWTP were produced by online measurements and lab analyses. No additional measuring campaign was carried out. The time frame chosen to study was 2013.01.01 to 2014.10.31. The calibration period used data from 2013 and the validation used data from 2014.01.01 to 2014.10.31. It is only possible to compare and calibrate WEST results were the same data is available for Sjölunda WWTP. Flow measurements are available for most sections of the plant but the occurrence of lab data is less frequent. Hence, the flow lines and sections compared with data for Sjölunda WWTP were: outflow and sludge flow from the primary clarifiers, TSS and $PO^{3-}_4$-P concentrations in zone 5 in the activated sludge and outflow and waste sludge flow from the secondary clarifiers.

Two models were created, the first was calibrated using Sjölunda WWTP data from 2013 and the second is a generalized model. The calibrated model used inputs with time series for parameters like temperature, oxygen concentration in the activated sludge, flowrate of waste sludge etc. gathered from 2013. The aim was to mimic Sjölunda WWTP during 2013 as good as possible. Once calibration was finished, the generalized model was created using the calibrated model as a base. Some of the input series (with data from 2013) were converted into fix values or fix time series to be able to use the model while simulating the increased load scenario.

Sjölunda WWTP is composed of two sections, D1 and D2 and only D1 was studied. In order to further simplify and enhance the modelling process, only half of D1 was modelled.

## 5.1 Modelling strategy

During model setup and simulation, the entire model was constructed piece by piece to facilitate the modelling process. The inflow data was added to the sub-model and model parameters were set before simulation started. The simulated outflow and its concentrations were compared with the known data from Sjölunda WWTP. When the sub-model provided reasonable results, the next section was added to the growing model. When the model was complete and delivered reasonable results, the calibration process was started. The process started with a sensitivity analysis where the different parameters, model mechanisms, inflow fractions etc. were set to unreasonable high and low values in order to study their behaviour. This was followed by fine tuning of several parameters, mechanisms, fractions etc. in order to reach a result as close to Sjölunda WWTP data as possible. The strategy of the iterative procedure was similar to the one presented by Rieger *et al.* (2013) where simulation was followed by evaluation of the results. If the results were considered acceptable, the next section was studied. If results were considered non-acceptable, the following parameters were studied/changed in the following order: hydrodynamics, influent and recycle stream characteristics, settling parameters, aeration model parameters and finally biokinetic parameters.

## 5.2 Inflow characterisation

WEST is in need of data that defines the composition of the incoming wastewater. This is introduced by creating an input file composed of certain components and their concentrations over time. Flow measurements are available for most sections at Sjölunda WWTP for 2013, but the occurrence of lab data is less frequent. Lab measurements have on average been conducted once a week and Sjölunda WWTP has data for the following components: $BOD_7$, $BOD_{7,\ filt}$, COD, $COD_{filt}$, $P_{tot}$, $P_{tot,\ filt}$, $NH^+_4$-N, $NO_{2,3}$-N, $NO^-_2$-N, $N_{tot}$, alkalinity ($HCO^-_3$), SS and VSS (Table 5.1). The series for the components must be complete, i.e. no gaps can exist. Since inflow concentration data from Sjölunda WWTP is partly incomplete, the series of interest were interpolated in order to fill out the gaps.

*Table 5.1. Sjölunda WWTP has data for the following components.*

| Component | Description | Unit |
|---|---|---|
| **$BOD_7$** | Biochemical oxygen demand, 7 days | $g/m^3$ |
| **$BOD_{7,filt}$** | Biochemical oxygen demand, 7 days (filtered) | $g/m^3$ |
| **COD** | Chemical oxygen demand | $g/m^3$ |
| **$COD_{filt}$** | Chemical oxygen demand (filtered) | $g/m^3$ |
| **TP** | Total phosphorus | $g/m^3$ |
| **$TP_{filt}$** | Total phosphorus (filtered) | $g/m^3$ |
| **$N_{tot}$** | Total nitrogen | $g/m^3$ |
| **$NH^+_4$-N** | Ammonium nitrogen | $g/m^3$ |
| **$NO_{2,3}$-N** | Nitrite and nitrate nitrogen | $g/m^3$ |
| **$NO^-_2$-N** | Nitrite nitrogen | $g/m^3$ |
| **Alkalinity ($HCO^-_3$)** | Alkalinity as a measurement of $HCO^-_3$ | $g/m^3$ |
| **SS** | Suspended solids | $g/m^3$ |
| **VSS** | Volatile suspended solids | $g/m^3$ |
| **Flow** | Water flow | $m^3/d$ |

The incoming wastewater can be characterised in ASM2dModTemp in many different ways depending on the data available. The incoming wastewater in ASM2dModTemp is composed of 19 components (Table 5.2). One way is to present time series for each component or to present time series for the larger components such as TKN, COD and TSS and allow ASM2dModTemp to do the fractionation. A third possibility is to do something in between and that is what was done in this thesis.

*Table 5.2. All components used in ASM2dModTemp (Henze et al., 2000).*

| Short name | Description | Unit |
|---|---|---|
| Dissolved components | | |
| **$S_O$** | Dissolved oxygen | g $O_2/m^3$ |
| **$S_F$** | Readily biodegradable substrate | g COD/$m^3$ |
| **$S_A$** | Fermentation products (acetate) | g COD/$m^3$ |
| **$S_{N2}$** | Dinitrogen | g N/$m^3$ |
| **$S_{NH}$** | Ammonium | g N/$m^3$ |
| **$S_{NO}$** | Nitrate and nitrite | g N/$m^3$ |
| **$S_{PO}$** | Phosphate | g P/$m^3$ |
| **$S_I$** | Inert, non-biodegradable organics | g COD/$m^3$ |
| **$S_{ALK}$** | Bicarbonate alkalinity | g $HCO^-_3/m^3$ |
| Particulate components | | |
| **$X_I$** | Inert, non-biodegradable organics | g COD/$m^3$ |
| **$X_S$** | Slowly biodegradable substrate | g COD/$m^3$ |
| **$X_H$** | Heterotrophic biomass | g COD/$m^3$ |
| **$X_{PAO}$** | Phosphorus accumulating organisms, PAO | g COD/$m^3$ |
| **$X_{PP}$** | Stored poly-phosphate of PAO | g P/$m^3$ |
| **$X_{PHA}$** | Organic storage products of PAO | g COD/$m^3$ |
| **$X_{AUT}$** | Autotrophic, nitrifying biomass | g COD/$m^3$ |
| **$X_{MEOH}$** | Ferric-hydroxide, $Fe(OH)_3$ | g $Fe(OH)_3/m^3$ |
| **$X_{MEP}$** | Ferric-phosphate, $FePO_4$ | g $FePO_4/m^3$ |
| **$X_{TSS}$** | Particulate material | g TSS/$m^3$ |

While analysing the data available, the best way of action was considered to be to only define five components; flow, TKN, COD, TSS and TP and then allow ASM2dModTemp to do the rest of the fractionation using a fractionation scheme (Figure 5.1). The default fractionation scheme in Figure 5.1 represents input components with left pointing arrows and output components with right pointing arrows. Water, TKN, COD, TSS and TP are all presented as input variables while the minor fractions (presented in Table 5.2) are visible as output components. Soluble and particulate COD ($COD_S$ and $COD_X$, denoted S_COD and X_COD in Figure 5.1) are marked with a V that indicates a variable. Two boxes are marked with 1 which means that the fractions for the output components connected to these blocks are set to fixed values. Between each component box, a label is visible that indicates the name or value of the fraction. WEST holds default values for these fractions but they are possible to change as a part of the calibration process.

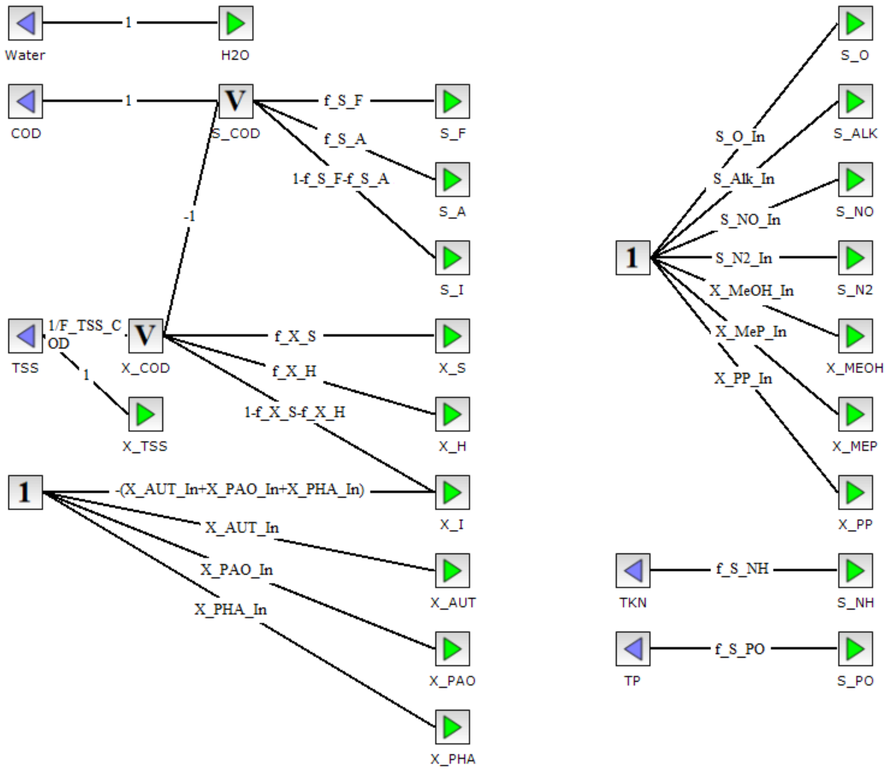


*Figure 5.1. Default fractionation scheme for incoming wastewater in ASM2dModTemp where the left and right pointing arrows indicate input and output components. S_COD and X_COD (soluble and particulate COD) are presented with V which indicates a variable. Two boxes are marked with a 1 that indicates fixed values on the fractions for the output components connected to the box (All displayed items in this figure are an excerpt from the WEST template (DHI, 2014b).*

The fractionation scheme used had the default fractionation scheme as a base while changes were made in order to receive a more suitable model (Figure 5.2). Two changes were made concerning the way COD, COD$_X$, COD$_S$ and TSS were connected. In the default fractionation, the amount of COD$_X$ is directly dependent on the amount of TSS and the fraction between them (Equation 5.1). The input component COD is divided into COD$_X$ and COD$_S$ (Equation 5.2) which together with Equation 5.1 forms Equation 5.3.

$$\frac{TSS}{COD_X} = 0.75 \qquad \text{Equation 5.1}$$

$$COD = COD_X + COD_S \qquad \text{Equation 5.2}$$

$$COD = \frac{TSS}{0.75} + COD_S \qquad \text{Equation 5.3}$$

By studying Equation 5.3, it is seen that in case of high TSS values and a low value on the fraction, COD$_S$ risk becoming negative since COD is unaffected as an input component. This was also what happened during simulation and it was the reason to why COD$_X$ were changed to no longer be dependent on TSS. Instead, COD$_X$ and COD$_S$ were changed to only depend on a fraction between themselves and that value were found during calibration.

The input component TKN is not directly available from Sjölunda WWTP data. Therefore, it was calculated according to Equation 5.4 where it is the difference between total nitrogen and the sum of nitrate and nitrite nitrogen.

$$TKN = N_{tot} - NO_{2,3}\text{-}N \qquad \text{Equation 5.4}$$

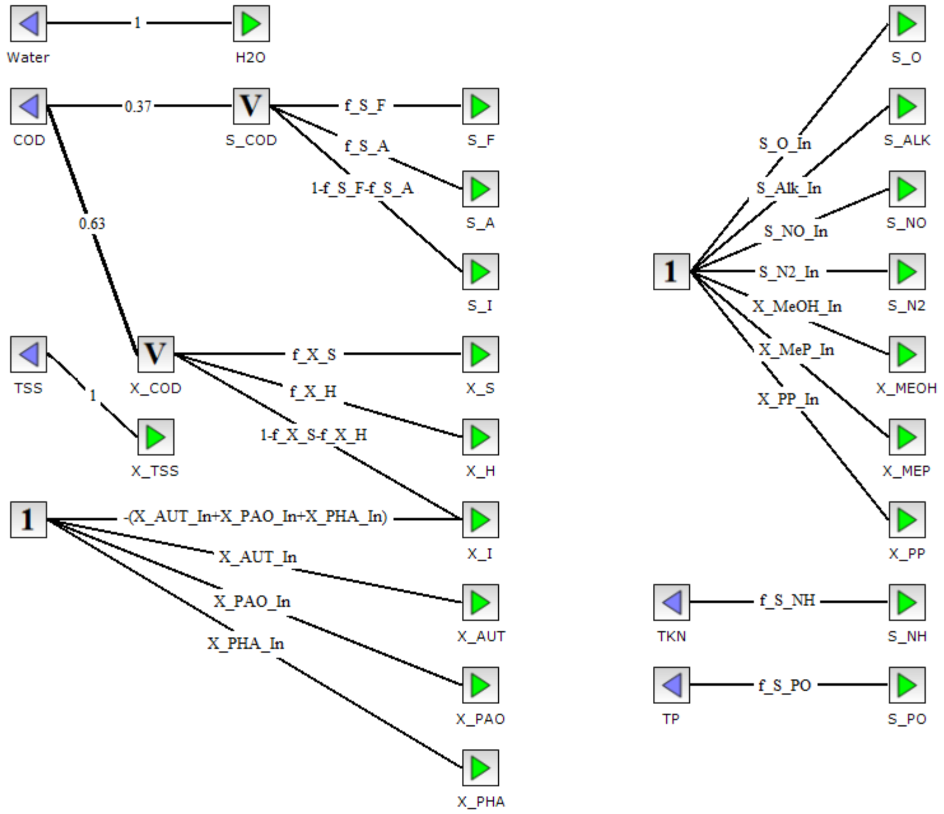


*Figure 5.2. Fractionation scheme used in this thesis for the ASM2dModTemp category. $COD_X$ is no longer dependent on TSS but is governed by the fraction between itself and $COD_S$ (All displayed items in this figure are an excerpt from the WEST template (DHI, 2014b).*

### 5.2.1 Fractions in the inflow characterisation

In order to improve the model, some fractions were calculated, others were estimated and most were left with their default values (Table 5.3).

*Table 5.3. The fractions used to characterize the incoming wastewater together with their default values (DHI, 2014b).*

| Fraction | Description | Default value |
|---|---|---|
| **f_S_F** | Fraction of $COD_S$ that exist as readily biodegraded substrate ($S_F$) | 0.375 |
| **f_S_A** | Fraction of $COD_S$ that exist as fermentation product ($S_A$) | 0.25 |
| **f_X_S** | Fraction of $COD_X$ that exist as slowly biodegradable substrate ($X_S$) | 0.69 |
| **f_X_H** | Fraction of $COD_X$ that exist as heterotrophic biomass ($X_H$) | 0.17 |
| **f_S_NH** | Fraction of TKN that exist as $NH^+_4$-N ($S_{NH}$) | 0.6 |
| **f_S_PO** | Fraction of TP that exist $PO^{3-}_4$-P ($S_{PO}$) | 0.6 |

Sjölunda WWTP has values for TP and $TP_{filt}$. It was assumed that $TP_{filt}$ is comparable to the amount of phosphate ($PO^{3-}_4$-P) which is an output component in the default fractionation in ASM2dModTemp, $S_{PO}$ (denoted S_PO in Figure 5.2). With the data provided by Sjölunda WWTP, the fractions $PO^{3-}_4$-P/TP, denoted f_S_PO and $NH^+_4$-N/TKN, denoted f_S_NH were calculated. Each pair were plotted together where a line was drawn indicating the inclination, hence the fraction (Figure 5.3 and Figure 5.4). The result shows that 43 % of TP exist as $PO^{3-}_4$-P and that 57 % of TKN is $NH^+_4$-N.

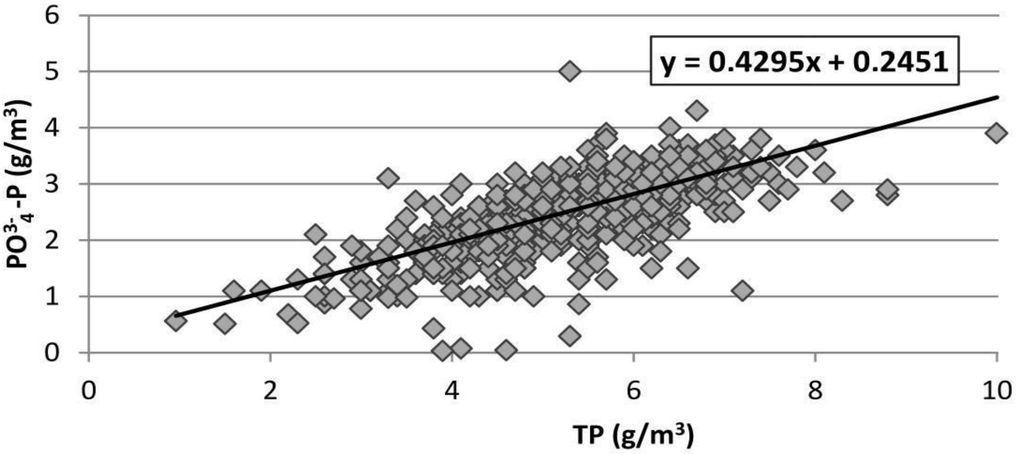


*Figure 5.3. Development of the fraction between TP and $PO^{3-}_4$-P denoted f_S_PO which yielded a value of 0.4295. Hence, approximately 43 % of TP exist as $PO^{3-}_4$-P.*

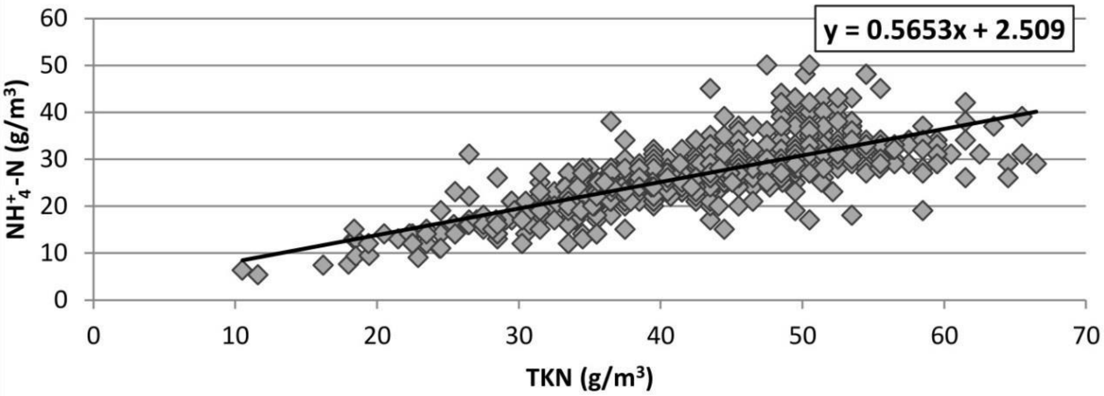


*Figure 5.4. Development of the fraction between TKN and $NH^+_4$-N denoted f_S_NH which yielded a value of 0.5653. Hence, approximately 57 % of TKN exist as $NH^+_4$-N.*

An example of typical wastewater composition according to Henze *et al.* (2000) can be seen in Figure 5.5. Figure 5.6 present the result of a study executed by Martinello (2013) showing the composition average after one day of hourly measurements. Note that the WEST category used was ASM1 instead of ASM2dModTemp, hence $S_H$ was not part of the study and $S_S$ is a generic term for $S_F$ and $S_A$. By using the two calculated fractions f_S_NH and f_S_PO and studying both Martinello (2013) and Henze *et al.* (2000) composition diagrams, an initial inflow characterisation was made.

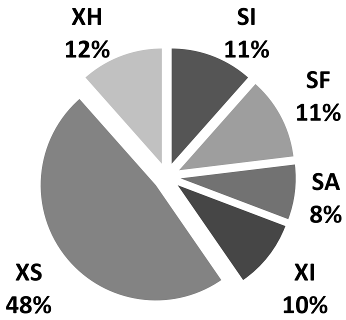


*Figure 5.5. Typical wastewater composition concerning the different components in percent (Henze et al., 2000).*

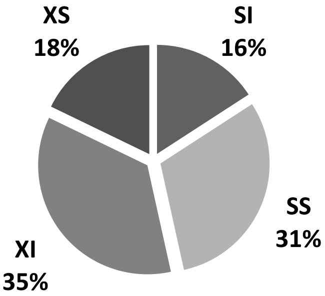


*Figure 5.6. Wastewater composition in percent at Sjölunda WWTP during a study in 2013 (Martinello, 2013).*

## 5.3 Recirculated flows

There are three recirculated flows that connect to the mainstream prior to the iron-based pre-precipitation. They come from the waste sludge thickener, primary sludge thickener (denoted H7) and sludge liquor treatment (denoted RN). The two recirculated flows H7 and RN were modelled in WEST but the recirculated flow from the waste sludge thickener is connected at the inlet of Sjölunda WWTP and is therefore included in the measured incoming flow.

Flow and concentration data are available for H7 and RN. They were therefore modelled as input blocks (just as the inflow block) since it is possible to construct an input file containing flow, TKN, COD, TSS and TP. The data for the recirculated flows are partly incomplete, just as for the inflow. The missing values were therefore replaced by values found through interpolation. Both RN and H7 lack concentration data for COD. As discussed in section 5.2, there is a fraction between TSS and $COD_X$ in the default fractionation for ASM2dModTemp. This fraction was calculated for the incoming wastewater (Figure 5.7) and then used to calculate the COD in the RN and H7 flows according to Equation 5.5 and Equation 5.6. This is a simplification and since the flows for RN and H7 are low, on average 0.5 and 0.7 % of incoming wastewater, the risk for large errors are almost non-existent.

$$COD_{RN} = TSS_{RN} \cdot \frac{COD_{X_{inflow}}}{TSS_{inflow}} \qquad \text{Equation 5.5}$$

$$COD_{H7} = TSS_{H7} \cdot \frac{COD_{X_{inflow}}}{TSS_{inflow}} \qquad \text{Equation 5.6}$$

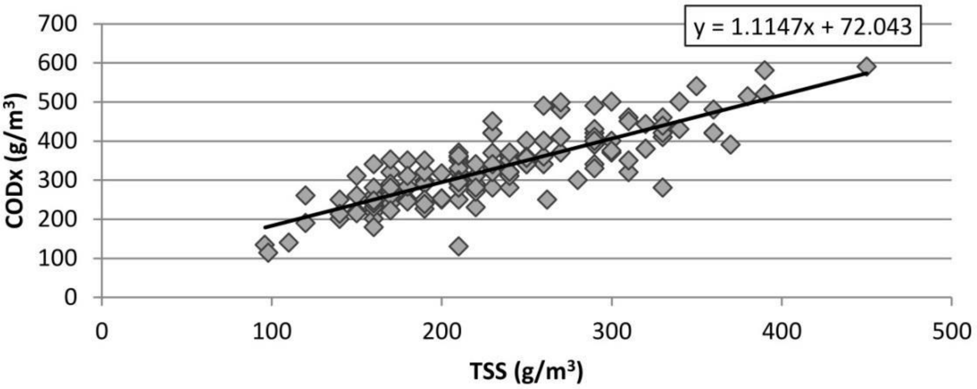


*Figure 5.7. The fraction $COD_X$/TSS for the incoming wastewater had a value of 1.1147 during 2013.*

There is no concentration data for nitrite and nitrate for H7 which is needed to calculate TKN according to Equation 5.4. This concentration was therefore assumed to be zero which was considered a valid assumption since H7 is the recirculated flow from the gravity thickener that treats primary sludge (concentrations for nitrite and nitrate are low to non-existent in primary sludge).

Sjölunda WWTP is divided into the sections D1 and D2 and over the years, the recirculated flows RN and H7 have been on and off between the two sections. During periods, the entire recirculated volume entered only D1 or only D2. The recirculated volume was therefore set to either 100 % or 0 % during these periods (100 % if the entire volume entered D1 and 0 % if the entire volume entered D2). During some periods, the flow was divided on both sections and for simplicity, it was assumed that the flow was divided equally between the two sections (i.e. D1 received 50 % of the flow).

The fractions used to characterize the recirculated water was for simplify set to default values (column three, Table 5.3).

## 5.4 Iron-based pre-precipitation

Pre-precipitation is conducted with iron sulphate ($FeSO_4$) and occurs prior to the primary clarifiers. During 2013 the amount of iron added in relation to incoming wastewater was 9.4 g Fe/m$^3$ wastewater (VA SYD, 2014). WEST precipitate only phosphate, so by studying the concentration of phosphate entering the activated sludge, i.e. after the pre-precipitation, it was possible to dose more iron automatically if the phosphate concentration was too high (Figure 5.8). The model setup contains the iron-dosing unit, a reaction tank, a $PO^{3-}_4$-P concentration sensor and a controller with an input. The $PO^{3-}_4$-P sensor informs the controller of the concentration. The controller compares the value with the value given by the input which is a time series of $PO^{3-}_4$-P concentrations from 2013. The controller informs the iron-dosing unit to add more or less iron by controlling the flow rate of the solution. Two parameters can be changed in the iron-dosing unit, flowrate of the solution and concentration of the solution. The concentration of the solution in the iron-dosing unit was set to a fix value of 450 kg/m$^3$ in order to assure that the dose was high enough.

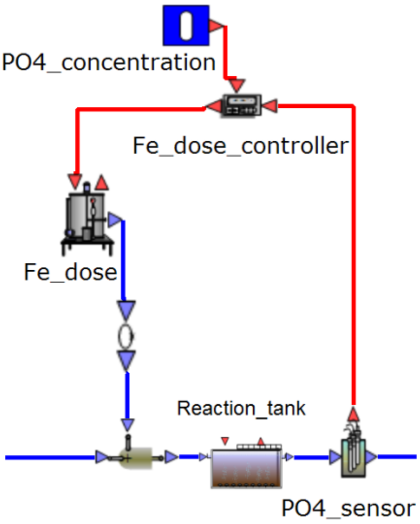


*Figure 5.8. The model setup for the iron-based pre-precipitation with the iron-dosing unit, the reaction chamber, the $PO^{3-}_4$-P sensor and the controller and its input (All displayed items in this figure are an excerpt from the WEST template (DHI, 2014b)).*

After calibration, as the generalized model was constructed, the input informing the controller of the actual $PO^{3-}_4$-P concentration was replaced by the fix value 0.84 $g/m^3$ which is an average of the input values from 2013 (Figure 5.9).

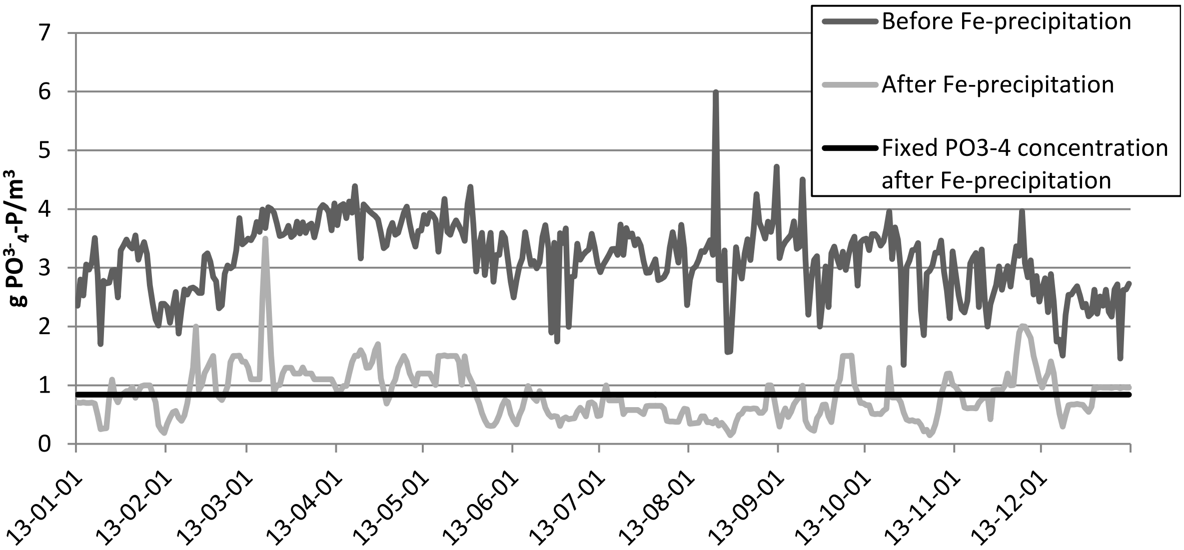


*Figure 5.9. The $PO^{3-}_4$-P concentration before (dark grey line) and after (light grey line) the iron-precipitation. After calibration, as the generalized model was constructed, the $PO^{3-}_4$-P concentration was set to a fixed value of 0.84 $g/m^3$ (black line).*

## 5.5 Primary clarifiers

The section studied (D1) contains four primary clarifiers. Since only half of D1 was studied, only two primary clarifiers were modelled (Figure 5.10).

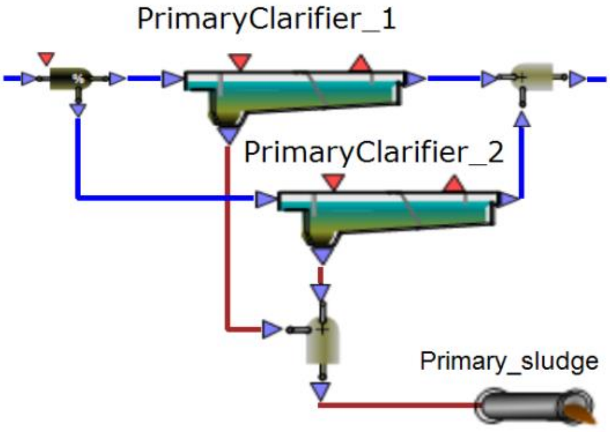


*Figure 5.10. The two modelled primary clarifiers with the primary sludge outtake (All displayed items in this figure are an excerpt from the WEST template (DHI, 2014b)).*

The radius of the basins (excluding inflow and outflow sections, see Figure 5.11) are 12.6 m which gives an active surface area of 498.8 $m^2$ per basin. The depth at the border is 0.74 m and the bottom has a gentle slope towards the middle (Sandström, u.d.) which was disregarded, thus the modelled depth was set to 0.74 m.

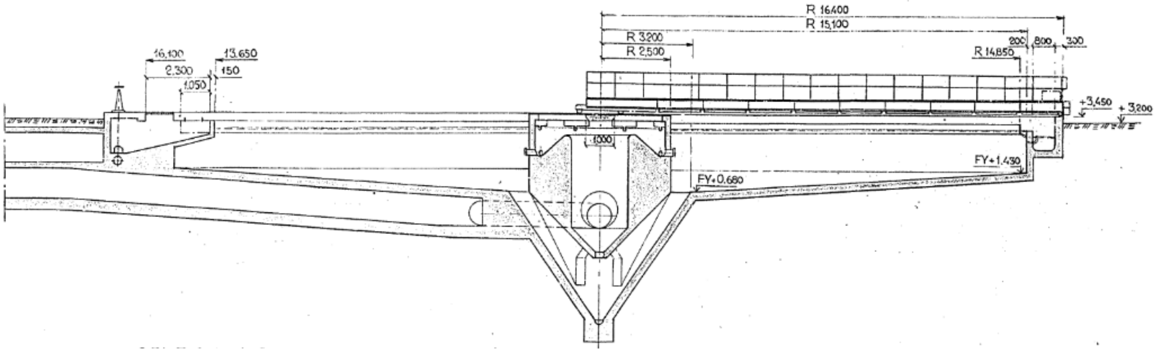


*Figure 5.11. Sketch of the primary clarifiers located at section D2, but the design for the clarifiers at D1 is similar but the depths differ. The flow enters in the middle which occupies 2.5 m in radius. The outflow occurs at the periphery of the basins in a flume that is 0.8 m wide. The radius available for sedimentation is 12.6 m (Sandström, u.d., with kind permission from VA SYD).*

The two primary clarifiers were designed and calibrated in the same way. The model used is called Primary Takacs (Takács, Party and Nolasco, 1991) and it was designed by adding a fixed sludge flow and calibrating the settling properties (Table 5.4). The Primary Takacs is a 10-layered settler model where the incoming solids are homogenously distributed over one of the middle layers called the feed layer. The settling flux is governed by the gravitational flux and the bulk flux. Gravitational flux is always moving downwards while the bulk flux is moving upwards in layers above the feed layer and downwards in layers below the feed layer. The two parameters v0 and v00 describes the maximum theoretical and practical settling velocity. The settling parameter (low concentration), r_P influence the settling velocity in the layers above the feed layer where the concentration is lower. A larger value on the settling parameter (hindered settling), r_H will slow down the settling velocity. A larger value on the non-seattleable fraction of suspended solids, f_ns will hinder some of the suspended solids from settling, thus leaving the clarifier at the overflow (DHI, 2014a).

*Table 5.4. Model parameters for the primary clarifiers and their default values (DHI, 2014b).*

| Parameter | Description | Unit | Default value |
|---|---|---|---|
| **Q_Under** | Primary sludge flow (underflow) | $m^3/d$ | - |
| **v0** | Maximum theoretical settling velocity | m/d | 96 |
| **v00** | Maximum practical settling velocity | m/d | 45 |
| **r_P** | Settling parameter (low concentration) | $m^3/g$ | 0.0007 |
| **r_H** | Settling parameter (hindered settling) | $m^3/g$ | 0.00019 |
| **f_ns** | Non-settleable fraction of suspended solids | - | 0.0024 |

The sludge flow (Q_Under) was calculated as inflow minus outflow from the clarifiers since these two flows are known. An average of these flows were calculated and set as a fixed value for the sludge flow. Sjölunda WWTP cannot provide any concentration data for the primary sludge. The concentrations for TKN, COD, TSS and TP were therefore calculated as mass entering minus mass leaving the primary clarifiers in g/d, divided by the sludge flow in $m^3/d$. An example using TSS is seen in Equation 5.7, the method is the same for TKN, COD and TP.

$$TSS_{primary\ sludge} = \frac{(TSS \cdot Q)_{entering\ clarifier} - (TSS \cdot Q)_{leaving\ clarifier}}{Q_{primary\ sludge}} \qquad \text{Equation 5.7}$$

## 5.6 Activated sludge lines

There are six activated sludge lines in section D1 which means that only three were modelled (since only half of D1 was modelled). The different inflows to G1, G2 and G3 are known and since only half was modelled, the sum of the three inflows was divided by two and split evenly on the three modelled sludge lines. Each sludge line is composed of five zones with different environments and volumes (Table 5.5). Zone 3, 4 and 5 are all aerated with an increasing oxygen concentration from zone 3 to zone 5 (Figure 5.12). The temperature of the wastewater was varying between 10-21 °C in 2013 (Figure 5.13).

*Table 5.5. The five zones in each activated sludge line have different volumes and are either aerobic or anaerobic.*

| Zone | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| **Volume ($m^3$)** | 187 | 196 | 417 | 422 | 385 |
| **Aerobic/anaerobic** | Anaerobic | Anaerobic | Aerobic | Aerobic | Aerobic |

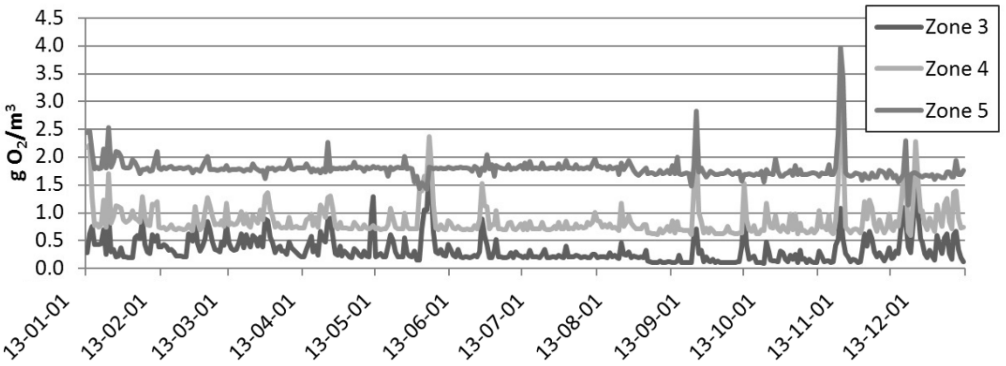


*Figure 5.12. Oxygen concentration (g/m$^3$) in the three aerated zones of the activated sludge during 2013. The concentration is on average 0.4, 1.0 and 1.9 g/m$^3$ in zone 3, 4 and 5.*

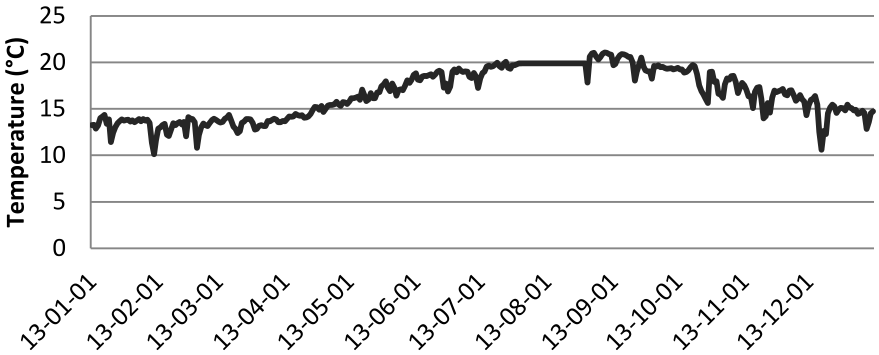


*Figure 5.13. Wastewater temperature (°C) during 2013. The temperature varies approximately between 10-21 °C and had an average of 17 °C.*

All three sludge lines were modelled and calibrated in the same way. The oxygen setup was modelled by allowing an input (containing the oxygen concentrations during 2013) to inform a controller of the concentration which in turn governs the oxygen concentration in the activated sludge unit (Figure 5.14). Each of the aerated zones has its own input since oxygen concentration varies between them. The temperature is the same in all zones which was modelled by allowing an input, containing the temperature curve for 2013, to control all zones (Figure 5.14).

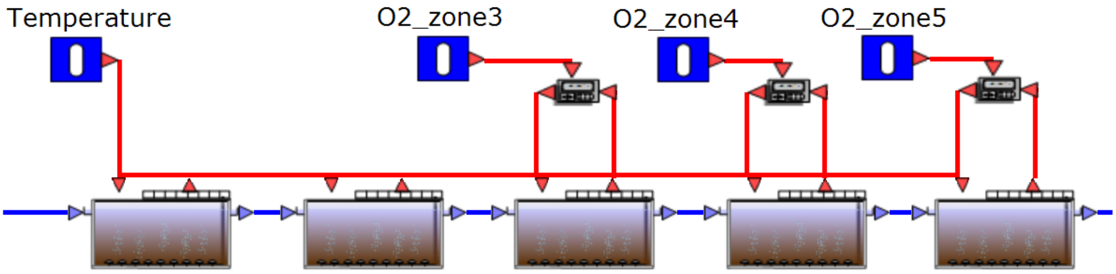


*Figure 5.14. The oxygen concentrations in the three activated sludge zones were controlled separately by an input and a controller. The temperature was controlled in each zone by one input. (All displayed items in this figure are an excerpt from the WEST template (DHI, 2014b)).*

The activated sludge model was calibrated by changing parameters that affect rates for growth, decay, hydrolysis etc. (Henze *et al.*, 2000). All sludge units were modelled in the same way (except for volume and oxygen) and the parameters of greatest interest and those that were changed from default are presented in Table 5.6. The hydrolysis rate constant, k_h governs at what rate the $X_S$ components are hydrolysed into $S_F$. The rate constant for lysis and decay, b_H controls the rate at which $X_H$ is lost, generating $X_S$ and a smaller fraction of $X_I$. The saturation coefficients for $COD_X$, $S_F$, $S_A$, $S_{NH4}$ and $S_{PO}$ (K_X, K_F, K_A, K_NH and K_P) are controlling the concentration available for different processes, a high value allows less to be available and vice versa. mu_H governs the maximum growth rate for $X_H$ on substrate. The yield for $X_H$ is depended on the value on Y_H, a higher value increases the amount for $X_H$ and vice versa.

*Table 5.6. Model parameters for the activated sludge units and their default values (DHI, 2014b).*

| Parameter | Description | Unit | Default value |
|---|---|---|---|
| **k_h** | Hydrolysis rate constant | g COD/(g COD·d) | 3 |
| **K_X** | Saturation coefficient for $COD_X$ | $g/m^3$ | 0.1 |
| **mu_H** | Maximum growth rate on substrate | $d^{-1}$ | 6 |
| **b_H** | Rate constant for lysis and decay | $d^{-1}$ | 0.4 |
| **K_F** | Saturation/inhabitation coefficient for growth on $S_F$ | $g/m^3$ | 4 |
| **K_A** | Saturation coefficient for $S_A$ (acetate) | $g/m^3$ | 4 |
| **K_NH** | Saturation coefficient for $S_{NH4}$ (nutrient) | $g/m^3$ | 0.05 |
| **K_P** | Saturation coefficient for $S_{PO}$ (nutrient) | $g/m^3$ | 0.01 |
| **Y_H** | Yield for $X_H$ | g COD/g COD | 0.625 |

After calibration, as the generalized model was constructed, the inputs informing the controllers of the correct oxygen concentration in the different activated sludge zones were removed. The controllers were instead fed with the fix values 0.3, 0.8 and 2.0 $g/m^3$ in zone 3, 4 and 5 respectively since these are the values currently used at Sjölunda WWTP. The temperature curves for the years 2011-2014 in the activated sludge were plotted together to create a standard, average curve in order to keep the seasonal variations that would have been lost if a fix value was used instead. Hence, the temperature curve for 2013 was replaced by this average temperature curve. The temperature curve from 2013 has the same average value as the created standard curve, i.e. 17 °C.

## 5.7 Secondary clarifiers

Each sludge line at Sjölunda WWTP is connected to its own two secondary clarifiers. To simplify the modelling procedure, the two clarifiers were modelled as one. Each clarifier has a surface area of 467 $m^2$ and a depth of 3.8 m, generating a volume of 1,783 $m^3$ (VA SYD, 2014).

The secondary clarifiers were modelled by using the Takacs SVI model (Takács, Party and Nolasco, 1991). They were designed by adding a sub-model for controlling the sludge flow (see further in section 5.7.1) and calibrating the settling properties, v0, v00, r_P and f_ns (Table 5.7). The Takacs SVI is an extension of the Primary Takacs that were used to simulate the primary clarifiers, as described in section 5.5. The difference is that it is possible to add information about the sludge volume index (SVI), either as a fixed value or as an input (DHI, 2014a).

*Table 5.7. Model parameters for the secondary clarifiers and their default values (DHI, 2014b).*

| Parameter | Description | Unit | Default value |
|---|---|---|---|
| **Q_Under*** | Secondary sludge flow (underflow) | $m^3/d$ | - |
| **SVI** | Sludge volume index | mL/g | 100 |
| **v0** | Maximum theoretical settling velocity | m/d | 474 |
| **v00** | Maximum practical settling velocity | m/d | 250 |
| **r_P** | Settling parameter (low concentration) | $m^3/g$ | 0.00286 |
| **f_ns** | Non-settleable fraction of suspended solids | - | 0.00228 |

* Q_Under is dependent on the inflow to the plant and is therefore varying (see further in section 5.7.1).

The concentrations provided by Sjölunda WWTP for TKN, COD and TP for the waste sludge during 2013 showed errors in the overall mass balance. The mass entering the activated sludge was not equal to the mass leaving the secondary clarifiers as overflow and sludge outtake. The masses in the waste sludge were highly overrated. The concentrations were therefore calculated in a similar manner as for the primary sludge (Equation 5.7). Hence, the concentrations were calculated as mass entering the activated sludge minus mass leaving the secondary clarifiers as overflow in g/d, divided by the waste flow in $m^3/d$. An example using TP can be seen in Equation 5.8, the method is the same for TKN and COD.

$$TP_{waste\ sludge} = \frac{(TP \cdot Q)_{entering\ activated\ sludge} - (TP \cdot Q)_{leaving\ clarifier}}{Q_{waste\ sludge}} \qquad \text{Equation 5.8}$$

It was not possible to make the same calculation for TSS since TSS is created within the activated sludge. The concentration data from 2013 provided by Sjölunda WWTP for TSS was therefore still used.

There is no data available for the flow leaving the secondary clarifiers. By using know data from Sjölunda WWTP, the flow was calculated as flow entering the activated sludge minus the flow of the waste sludge.

### 5.7.1 Waste sludge, recirculated sludge and SRT

The secondary sludge outtake (denoted Q_Under in WEST) is dependent on the volume of incoming water to the plant, a high inflow generates a high flow of return sludge. The return sludge flow at Sjölunda WWTP during 2013 varied between the different sludge lines so the flows presented here are average flows. The outtake is governed by up to three pumps (Table 5.8, data is presented as $m^3/d$ since WEST generates daily values). One pump is always active which yields a return sludge flow of 3,283 $m^3/d$. If the inflow increases above 38,880 $m^3/d$ a second pump starts which yields a return sludge flow of 6,048 $m^3/d$. The flow must then decrease below 25,920 $m^3/d$ before the system returns to operate with only one pump. If the inflow increases above 64,800 $m^3/d$ a third pump is activated generating a return sludge flow of 8,467 $m^3/d$. The flow must decrease below 51,840 $m^3/d$ before the system returns to operate with two pumps.

*Table 5.8. The return sludge flow from the secondary clarifiers is governed by the inflow. Dependent on the flow rate, one, two or three pumps are active which generates a lower or higher return sludge flow.*

| **No. of pumps active** | **Increasing inflow ($m^3/d$)** | **Decreasing inflow ($m^3/d$)** | **Return sludge flow ($m^3/d$)** |
|---|---|---|---|
| **3** | > 64,800 | > 51,840 | 8,467 |
| **2** | 38,880 < Inflow < 64,800 | 51,840 > Inflow > 25,920 | 6,048 |
| **1** | < 38,880 | < 25,920 | 3,283 |

The return sludge flow was modelled by introducing flow sensors in the beginning of the plant that inform two pumps of the flow (a simplified figure of the setup can be seen in Figure 5.15).

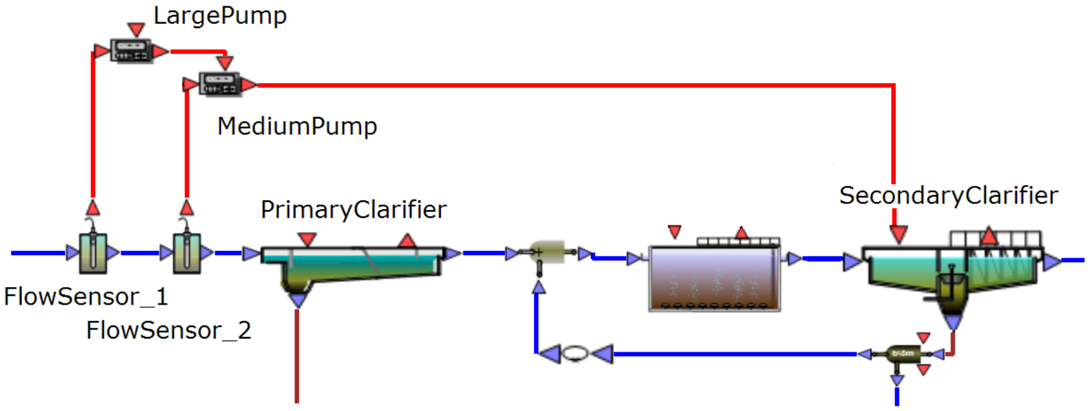


*Figure 5.15. A simplified model with the aim to illustrate how the flow sensors and pumps are controlling the sludge flow (Q_Under) of the secondary clarifiers (All displayed items in this figure are an excerpt from the WEST template (DHI, 2014b)).*

The two pumps co-operate by sending different outputs, i.e. information about the magnitude of the sludge flow to the secondary clarifiers dependent on the incoming flow rate (Table 5.9). The two pumps are so called "on-off" controllers and work in the following manner: if the flow is too low (lower than y_Min) the pumps output signal u_On is active. If the flow is too high (higher than y_Max) the pumps u_Off signal is active. So by operating two pumps parallel, allowing the larger pump to overwrite the medium pump's u_Off when inflows are larger than 38,880 $m^3/d$ it was possible to mimic Sjölunda WWTP's configuration.

*Table 5.9. Parameter values for the Medium pump and the Large pump according to Sjölunda WWTP. u_On and u_Off are output signals that controls the sludge flow in the secondary clarifiers. y_Min and y_Max are threshold values for during which inflows the pump is to be active.*

| **Parameters** | **Medium pump ($m^3/d$)** | **Large pump ($m^3/d$)** |
|---|---|---|
| **u_On** | 3,283 | 6,048 |
| **u_Off** | 6,048* | 8,467 |
| **y_Min** | 25,920 | 51,840 |
| **y_Max** | 38,880 | 64,800 |

* u_Off for the Medium pump is overwritten by the u_On of the Large pump.

It was possible to calibrate the sludge flow from the secondary clarifiers by comparing the simulated recirculated flow with available recirculated flow data from Sjölunda WWTP for 2013. This could be done since the waste sludge flow was both low and fairly constant.

The secondary sludge flow is split into waste sludge and recirculated sludge. This was modelled by allowing an input to control the splitter, feeding it with waste sludge flows from Sjölunda WWTP in 2013.

After calibration, as the generalized model was constructed, the input that controls the splitter between recirculated sludge and waste sludge flow was replaced by a sub model that controls the SRT (Figure 5.16). A calculation model was constructed that calculates the SRT by taking information from two sensors. The sensors are located at the outflow from the secondary clarifier and at the waste sludge. The calculated SRT (the total SRT is calculated, not the aerobic SRT) is delivered to a data treatment block that generates a smoother curve and makes it possible to recirculate the data without algebraic loops. The values are delivered to a controller where a fixed value on the SRT was entered. The controller can then control the splitter where the secondary sludge is split into recirculated sludge and waste sludge, hence analysing the amount of sludge leaving the system. If the calculated SRT is too low (lower than the fixed value), the waste sludge flow is lowered to keep the sludge within the system for a longer time. The SRT during calibration was on average 1.64 days which then was used as the fixed value in the controller, generating a waste sludge flow around 1,200 m$^3$/d.

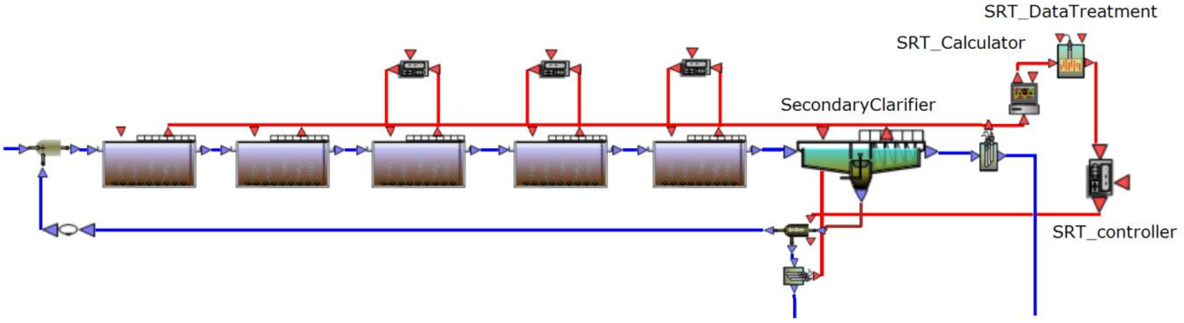


*Figure 5.16. After calibration, the SRT was controlled by using information from two sensors, an SRT calculator, a data treatment block and a controller that controls the splitter on the secondary sludge line (All displayed items in this figure are an excerpt from the WEST template (DHI, 2014b)).*

# 6 Increased load simulation

There are two main questions that were to be answered during this case study. The first regards the performance of the plant, i.e. for how many years can Sjölunda WWTP handle an increased load? The second regards the changes in biogas production, i.e. is the biogas production increased and by how much in that case? The increased load was simplified to be simulated as a yearly step-wise increase. The increased load was not implemented to the recirculated flows, H7 and RN in order to simplify the model, i.e., their flow and concentration values were unchanged during the simulations. No parts of the waste sludge treatment processes were modelled in WEST, instead, biogas production was analysed using simplified calculations.

## 6.1 Changes in flow and masses

Malmö is expected to increase with on average of 5,000 inhabitants per year which will increase the load on Sjölunda WWTP. The incoming flow and concentrations of TKN, COD, TSS and TP will therefore increase. Jönsson *et al.* (2005) provides data for the amount of $H_2O$, TKN, COD, TSS and TP that is produced in g/(P.E.·day) (column two, Table 6.1). These values were used to calculate the total extra amount of each component that an increase of 5,000 inhabitants would cause per day (column three, Table 6.1). These values are denoted mass factors (MF), since they are the addition factors the components are increased by in mass per day. The flow was further calculated into $m^3$/d and is therefore denoted a flow factor (FF) (column four, Table 6.1).

*Table 6.1. Column two present the mass in gram produced per P.E. and day according to Jönsson et al. (2005). The mass produced by 5,000 P.E. and day can be seen in column three where the values are denoted mass factor (MF). In column four, the MF for the flow is presented as a flow factor (FF) in $m^3$/d.*

| **Parameter** | **g/(P.E.·d)** | **Mass factor (MF) g/(5,000 P.E.·d)** | **Flow factor (FF) $m^3$/d** |
|---|---|---|---|
| **$H_2O$** | 131,600 | $65.80 \cdot 10^7$ | 658 |
| **TKN** | 14 | 70,100 | |
| **COD** | 135 | 675,000 | |
| **TSS** | 66 | 331,800 | |
| **TP** | 2 | 10,400 | |

The increase of on average 5,000 inhabitants per year was simulated in WEST as a yearly step-wise increase. The input file created while modelling Sjölunda WWTP was in this case study modified to take the increased load into account. The daily values in the input file for the five components were all increased with their respective MF or FF. But the seasonal variations in the different concentrations were taken into account.

## 6.2 Seasonal variation for the different components

The concentrations for TKN, COD, TSS and TP for the year 2013 were plotted separately together with a straight line representing their average concentration. The concentration curve is occasionally above and occasionally below the average yearly curve which was assumed to be due to seasonal variations. In all four concentration curves, four periods were distinguished to be on average above, below or the same as the total yearly average. Figure 6.1 show an example of this using values for TKN. In period 1 (1 January-14 February), the curve is on average below the total average concentration. In period 2 (15 February-20 May), the curve is on average above, in period 3 (21 May-13 October), the curve is on average the same as the total average concentration and period 4 (14 October-31 December) has a curve on average below the total average concentration.

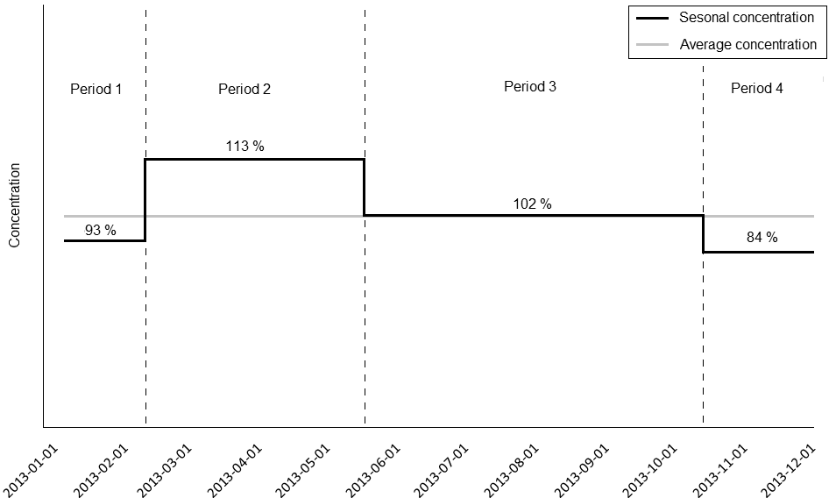


*Figure 6.1. An explanatory graph using the curves for TKN. The graph shows the average yearly concentration of TKN during 2013 (light grey curve) and the average concentration of TKN in the four time periods representing the seasonal change in concentration (black curve). During period 1, 93 % (the seasonal factor (SF) for TKN in period 1 (Table 6.2)) of the MF for TKN was added each day. During period 2, 113 % of the MF was added, in period 3, 102 % of the MF was added and during period 4 was 84 % of the MF added each day.*

The fluctuations in Figure 6.1 had to be taken into account when adding the extra load. For each component, the average concentration in each period was calculated and compared with the total yearly average. The difference in percent between the two values indicates how large proportion of the different components that was added in each period and is denoted the seasonal factor (SF) (Table 6.2). Table 6.2 indicate that the water flow did not follow the other components pattern. Water flow was high when the concentrations were low and the other way around.

*Table 6.2. The seasonal factors (SF) for each component during all four period.*

| Parameter | Period 1 | Period 2 | Period 3 | Period 4 |
|---|---|---|---|---|
| **Water** | 1.18 | 0.96 | 0.91 | 1.11 |
| **TKN** | 0.93 | 1.13 | 1.02 | 0.84 |
| **COD** | 0.89 | 1.18 | 1.00 | 0.83 |
| **TSS** | 0.91 | 1.14 | 1.05 | 0.77 |
| **TP** | 0.87 | 1.12 | 1.04 | 0.85 |

## 6.3 Input file

The input file created to simulate Sjölunda WWTP was used as a base in this case study and is further denoted as year 0. The population growth was simulated one year at a time, hence one input file was created per year, each using the values in year 0 as a base. The flow was calculated according to Equation 6.1 and the concentrations were calculated according to Equation 6.2 that uses TKN as an example. In both equations, $i$ is representing the year studied.

$$Flow_{Year\,i} = Flow_{Year\,0} + FF \cdot SF \cdot i \qquad \text{Equation 6.1}$$

$$TKN_{Year\,i} = \frac{TKN_{Year\ 0} \cdot Flow_{Year\,0} + MF \cdot SF \cdot i}{Flow_{Year\,i}} \qquad \text{Equation 6.2}$$

## 6.4 Model setup and simulation

During the increased load simulation, the second model created was used, the model called the generalized model.

The performance of Sjölunda WWTP was studied with regards to the number of years the plant could handle the increased load. The quality of the overflow from the secondary clarifiers was therefore continuously analysed during simulation in order to ensure the condition of the water. The treatment standard limits were kept constant concerning effluent quality from the secondary clarifiers that on Sjölunda WWTP enter the NTFs. Hence, the water quality has to favour the nitrifying process. Two parameters were therefore studied; concentration of total COD and the ratio between $PO^{3-}{}_4$-P and $NH^{+}{}_4$-N. A too high COD concentration entering the NTFs will favour the heterotrophs that will outcompete the nitrifiers, hence no nitrification will take place. The COD concentration leaving the secondary clarifiers was approximately 80 $g/m^3$ at Sjölunda WWTP during 2013. This value was therefore a benchmark during the simulation, i.e. the COD concentration leaving the model had to be equal to or below 80 $g/m^3$.

The ratio between $PO^{3-}{}_4$-P and $NH^{+}{}_4$-N has to be high enough in order to ensure autotrophic growth. This ratio is on average 0.02 at Sjölunda WWTP. In the calibrated model that used data from 2013, the ratio was 0.005, hence only a fourth of the actual value. In order to ensure the condition of the flow entering the NTFs, a modification was conducted to the generalized model before it was used in this case study. It is mentioned in section 5.4 that the allowed $PO^{3-}{}_4$-P concentration entering the activated sludge was set to the fixed value 0.84 $g/m^3$. This value was changed to 1.75 $g/m^3$ which then ensured a ratio of 0.02 between $PO^{3-}{}_4$-P and $NH^{+}{}_4$-N in the overflow from the secondary clarifiers.

Once the simulations started, modifications were made after each simulated year if the condition of the outgoing flow had deteriorated. The four parameters SRT, oxygen concentration in the activated sludge, allowed $PO^{3-}{}_4$-P concentration entering the activated sludge and the primary sludge flow were adjusted in order to meet the demands. Oxygen concentration in the activated sludge was not allowed to be increased more than 3 $g/m^3$ per section. The simulation was continued until changes of the four parameters could no longer guarantee the condition of the outgoing flow.

## 6.5 Effects on biogas production

Both the primary sludge and the waste sludge are sent to the anaerobic digester. Here, the organic material is digested in several steps into the final products methane ($CH_4$) and carbon dioxide ($CO_2$). The amount of biogas produced depends on the amount of biodegradable substrate present in the sludge and the following simplified estimations are based on the guidance of Carlsson (2015). The components contributing to biogas production of the primary sludge are readily biodegradable substrate ($S_F$), fermentation products ($S_A$), slowly biodegradable substrate ($X_S$) and heterotrophic biomass ($X_H$). The concentrations of $S_F$ and $S_A$ are almost zero in the waste sludge, hence, only $X_S$ and $X_H$ are contributing to the biogas production of the waste sludge. The production is also dependent on the yield, i.e. how much biogas is produced per amount of added COD. A study by Nyberg *et al.* (1994) at Sjölunda WWTP presents biogas production data for the primary sludge and for the waste sludge. The percent of volatile solids (VS) reduction was 44 % for the primary sludge and 43 % for the waste sludge. It was here assumed that the VS are the same as the biodegradable COD fractions. The amount of biogas produced for the primary sludge was 0.95 $Nm^3/(kg\ VS_{red})$ and the amount for the waste sludge was 0.82 $Nm^3/(kg\ VS_{red})$ (Nyberg *et al.*, 1994). The biogas production was therefore calculated according to Equation 6.3 and Equation 6.4. The biodegradable COD fraction in the primary sludge is composed of $S_F$, $S_A$, $X_S$ and $X_H$ while the same fraction for the waste sludge is composed of $X_S$ and $X_H$.

$$Biogas\ production_{primary\ sludge} = \frac{(S_F + S_A + X_S + X_H)\ kg\ VS}{dt} \cdot \frac{0.44\ kg\ VS_{red}}{kg\ VS} \cdot \frac{0.95\ Nm^3}{kg\ VS_{red}} \qquad \text{Equation 6.3}$$

$$Biogas\ production_{waste\ sludge} = \frac{(X_S + X_H)\ kg\ VS}{dt} \cdot \frac{0.43\ kg\ VS_{red}}{kg\ VS} \cdot \frac{0.82\ Nm^3}{kg\ VS_{red}} \qquad \text{Equation 6.4}$$

# 7 Results and discussion

## 7.1 Final model of Sjölunda WWTP

The final layout of the wastewater treatment model constructed of Sjölunda WWTP can be seen in Figure 7.1. The inflow is located in the top left section of the figure together with the two recirculated flows, H7 and RN. They are followed by the iron-dosing unit and the chamber where the iron reacts with the phosphate. After the reaction chamber, the $PO^{3-}_4$-P concentration is measured by a sensor that informs a controller of the concentration that in turn notifies the iron-dosing unit if it should add more or less iron. The $PO^{3-}_4$-P concentration sensor is followed by two flow sensors that via two pumps control the sludge flow from the secondary clarifiers. The primary clarifiers and the primary sludge outtake are located just before the inflow to the three activated sludge lines that have a separate unit for each zone (five zones per line). The oxygen level is controlled for each line in zone 3, 4 and 5. Each sludge line is connected to a secondary clarifier and a recirculation flow. The waste sludge from each clarifier is connected before it leaves the system in the bottom right of the figure. The overflow from each secondary clarifier is connected before it leaves the system by the outflow. At Sjölunda WWTP, this outflow is connected to the NTFs that are not part of this model.

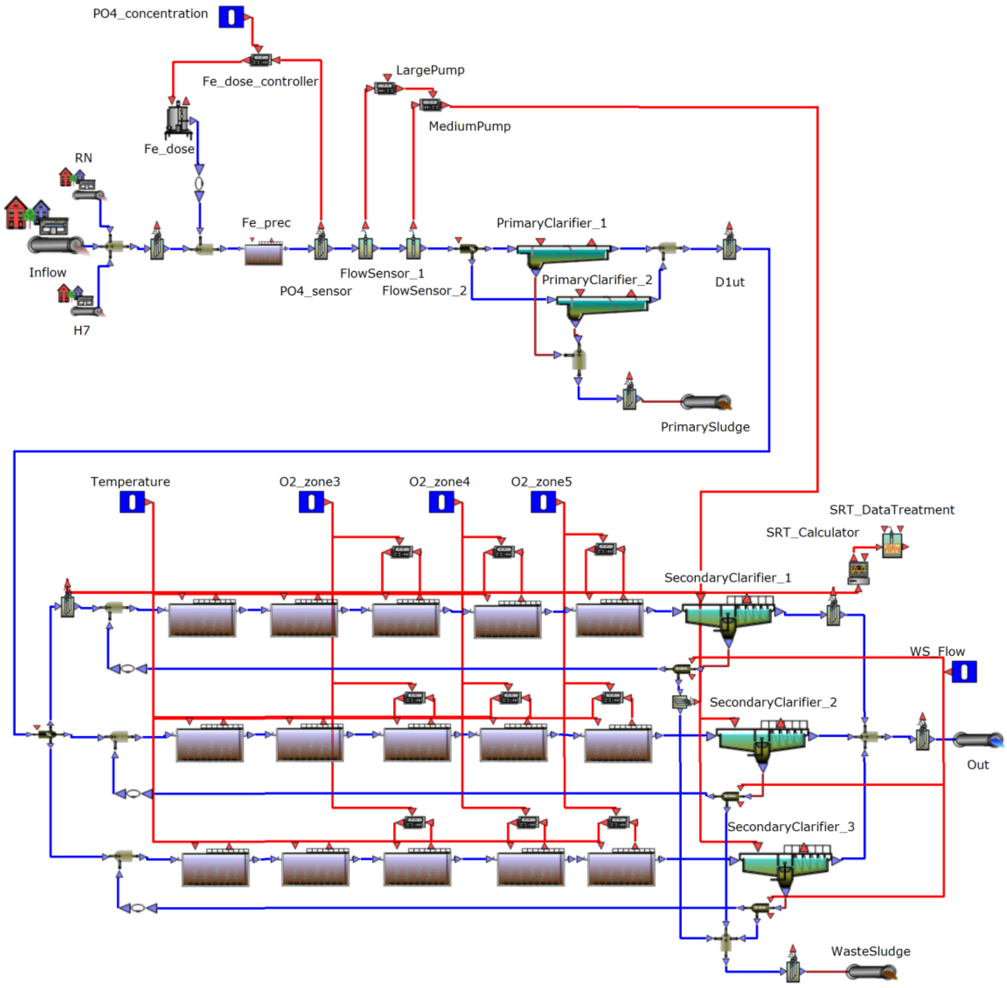


*Figure 7.1. The final layout of the calibrated model of Sjölunda WWTP. (All displayed items in this figure are an excerpt from the WEST template (DHI, 2014b)).*

### 7.1.1 Modelling process for the incoming wastewater fractionation

By using the two calculated fractions f_S_NH and f_S_PO presented in section 5.2.1 and studying both Martinello (2013) and Henze *et al.* (2000) composition diagrams, an initial inflow characterisation was done. This composition was changed back and forth during calibration and Figure 7.2 and Table 7.1 shows the final results for the wastewater composition and fractions. COD is divided into $COD_X$ and $COD_S$, the final calibration results indicates that 63 % were particulate and 37 % were soluble.

There were two larger difficulties during calibration; the concentration for TSS and $PO^{3-}_4$-P in the activated sludge and in the outflow that tended to be too low. The iterative process, trying to find a suitable incoming wastewater fractionation prioritised to solve these two difficulties.

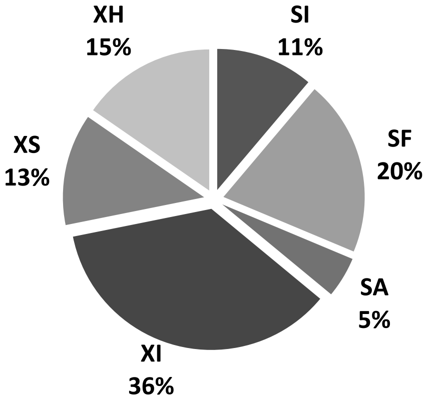


*Figure 7.2. The final calibrated wastewater composition for the inflow characterisation.*

*Table 7.1. The fractions used to characterize the incoming wastewater together with the default values for ASM2dModTemp (DHI, 2014b), the two calculated values for f_S_NH and f_S_PO and the final calibrated values.*

| Fraction | Description | Default value | Calculated value | Final value |
|---|---|---|---|---|
| **f_S_F** | Fraction of $COD_S$ that exist as readily biodegraded substrate ($S_F$) | 0.375 | - | 0.57 |
| **f_S_A** | Fraction of $COD_S$ that exist as fermentation product ($S_A$) | 0.25 | - | 0.22 |
| **f_X_S** | Fraction of $COD_X$ that exist as slowly biodegradable substrate ($X_S$) | 0.69 | - | 0.31 |
| **f_X_H** | Fraction of $COD_X$ that exist as heterotrophic biomass ($X_H$) | 0.17 | - | 0.2 |
| **f_S_NH** | Fraction of TKN that exist as $NH^+_4$-N ($S_{NH}$) | 0.6 | 0.5653 | 0.67 |
| **f_S_PO** | Fraction of TP that exist $PO^{3-}_4$-P ($S_{PO}$) | 0.6 | 0.4295 | 0.42 |

The amount of soluble COD was calibrated to just ensure growth of biomass in the activated sludge and to ensure the amount of COD leaving the system. $S_I$ was assumed to leave the system with approximately the same concentration as at the inflow. Hence, in case of low COD concentrations in the outflow, the fractions for $S_F$ and $S_A$ were decreased thus increasing the fraction for $S_I$. The continuous difficulty to increase the TSS concentration in the activated sludge was aided by the increase of the $X_I$ fraction, hence decreasing the fractions for $X_S$ and $X_H$. The concentrations for $NH^+_4$-N and $PO^{3-}_4$-P were constantly surveyed in the outgoing flows and as mentioned, the $PO^{3-}_4$-P concentration tended to be too low. A too low concentration could partly by aided by increasing their fractions; $S_{NH}$ and $S_{PO}$.

### 7.1.2 Modelling process for the iron-based pre-precipitation

The continuous difficulty to increase the $PO^{3-}_4$-P concentration was partly related to the iron-based pre-precipitation. The phosphate concentration in the activated sludge was almost around zero even though the concentration entering the activated sludge was assumed to be correct. Different possible solutions were investigated such as too active heterotrophs, possible bio-P activity and too much biodegradable COD which shifts the ratio between biodegradable COD, nitrogen and phosphorus. It was found to be no bio-P activity but the phosphate concentration was found to be the limiting factor for biomass production. The amount of iron entering the activated sludge was studied and found to be very high. The volume of the pre-precipitation reaction tank was increased to 3,100 m$^3$ and the concentration of the solution in the iron-dosing unit was lowered to 300 kg/m$^3$. This increased both the TSS and $PO^{3-}_4$-P concentration in the activated sludge. Hence, the problem was that the iron was continuing to precipitate $PO^{3-}_4$-P in the activated sludge.

### 7.1.3 Modelling process for the primary clarifiers

The continuous difficulty with too low TSS concentration in the activated sludge was partly aided by the chosen calibration method of the primary clarifiers (Table 7.2). The primary clarifiers were calibrated to sediment less than the default clarifier in order to allow more TKN, COD, TSS and TP to enter the activated sludge, thus increasing the biomass production. The parameters changed were the maximum theoretical and practical settling velocity (v0 and v00), settling parameter (r_P) and non-settleable fraction of suspended solids (f_ns) (Table 7.2).

*Table 7.2. Model parameters for the primary clarifiers and their default values from ASM2dModTemp (DHI, 2014b) together with the final calibrated values.*

| Parameter | Description | Unit | Default value | Final value |
|---|---|---|---|---|
| **Q_Under** | Primary sludge flow (underflow) | m$^3$/d | - | 450 |
| **v0** | Maximum theoretical settling velocity | m/d | 96 | 90 |
| **v00** | Maximum practical settling velocity | m/d | 45 | 40 |
| **r_P** | Settling parameter (low concentration) | m$^3$/g | 0.0007 | 0.00068 |
| **r_H** | Settling parameter (hindered settling) | m$^3$/g | 0.00019 | 0.00019 |
| **f_ns** | Non-settleable fraction of suspended solids | - | 0.0024 | 0.0029 |

Figure 7.3 present the calibrated result for the outflow from the primary clarifiers. The four graphs represents the calibrated results for TKN, COD, TSS and TP (line) together with the data for Sjölunda WWTP from 2013 (scatter).

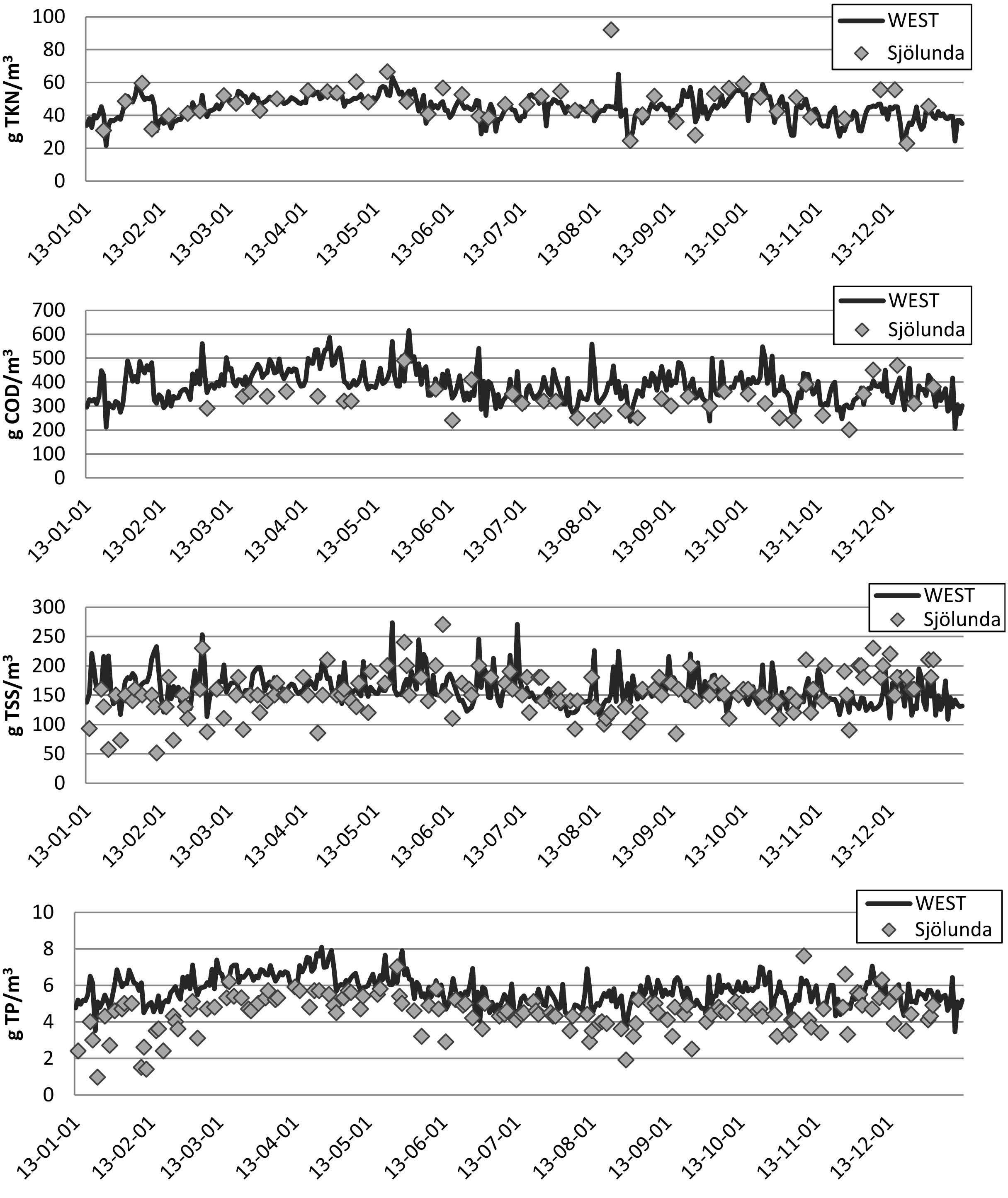


*Figure 7.3. The four graphs present the concentrations for TKN, COD, TSS and TP in the flow leaving the primary clarifiers for the calibrated model (line) together with the data for Sjölunda WWTP from 2013 (scatter).*

The overall calibration results presented in Figure 7.3 are considered to be good results. The concentration curves for both COD and TP are somewhat higher than the curves representing data from Sjölunda WWTP. It is assumed that only particulate material sediment in clarifiers. Since the TSS concentration seems reasonable, the conclusion was that it were the soluble fractions that were too high, hence $S_I$, $S_F$, $S_A$ and $S_{PO}$. By decreasing these in the inflow fractionation model, an improved calibration result was achieved for the primary clarifiers.

But the continuous difficulty with low TSS and $PO^{3-}_4$-P concentration in the activated sludge was of a greater priority, hence the higher concentrations for COD and TP leaving the primary clarifiers were kept.

Figure 7.4 present the calibrated result for the primary sludge flow. The four graphs represents the calibrated results for TKN, COD, TSS and TP (line) together with the data from Sjölunda WWTP during 2013 (scatter).

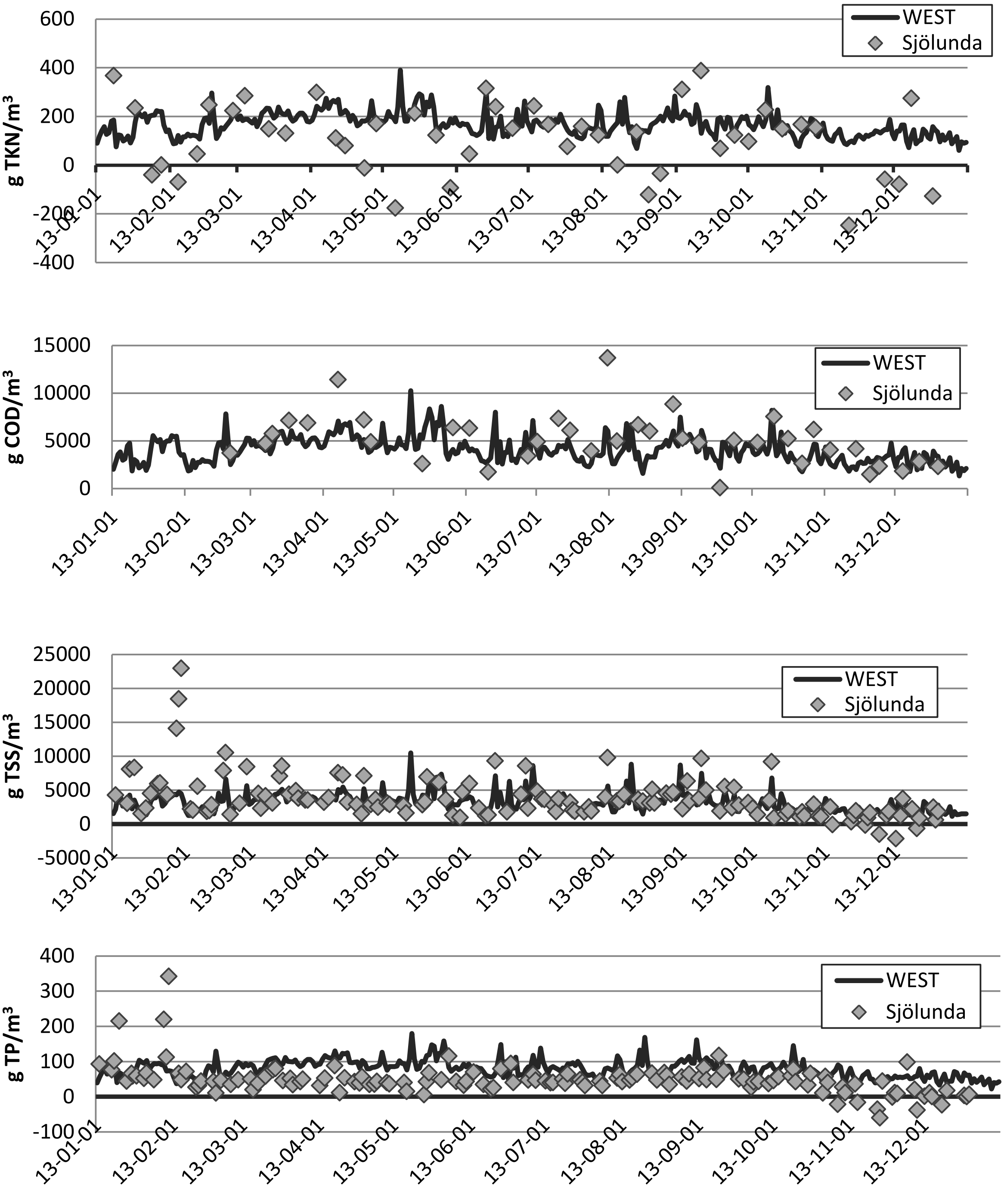


*Figure 7.4. The four graphs present the concentrations for TKN, COD, TSS and TP in the primary sludge for the calibrated model (line) together with the data for Sjölunda WWTP from 2013 (scatter).*

As discussed in section 5.5, there are no data available from Sjölunda WWTP concerning flows and concentrations for the primary sludge. Therefore, the scatters representing data for Sjölunda WWTP during 2013 in Figure 7.4 are calculated, not observed data. This is most likely the reason to why some data scatter points are negative. Improving the calibrated results for the primary sludge was not prioritised since the calculated data was not completely reliable.

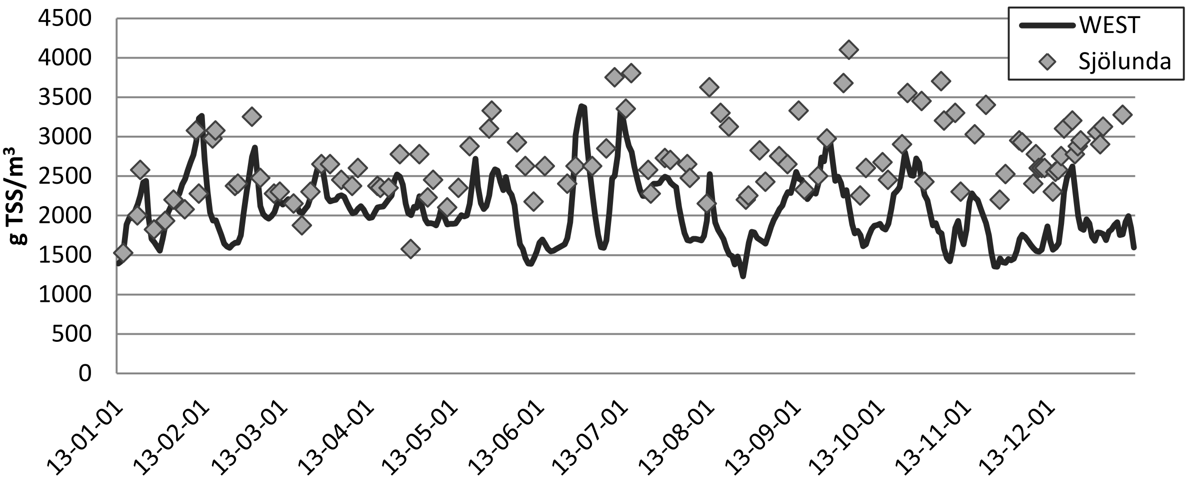
### 7.1.4 Modelling process for the activated sludge

The continuous difficulty to increase the TSS and $PO^{3-}_4$-P concentration in the activated sludge was highly prioritised while calibrating the activated sludge units. Hence, they were modelled to favour TSS and in the same time to spare some $PO^{3-}_4$-P (Table 7.3). Parameters such as hydrolysis rate constant (k_h), saturation coefficient for $COD_X$ (K_X), rate constant for lysis and decay (b_H) and yield for $X_H$ (Y_H) were calibrated to increase the TSS concentration. Saturation coefficients for $NH^+_4$-N and $PO^{3-}_4$-P (K_NH and K_P) were calibrated to keep their concentrations from becoming too low. $S_F$ was consumed fast since the activated sludge was modelled to be more active than default. The saturation coefficient for $S_F$ was therefore increased while the saturation coefficient for $S_A$ was decreased to allow some $S_F$ to be spared while more $S_A$ was used instead.

*Table 7.3. Model parameters for the activated sludge units and their default values from WEST (DHI, 2014b) together with the final calibrated values.*

| Parameter | Description | Unit | Default value | Final value |
|---|---|---|---|---|
| **k_h** | Hydrolysis rate constant | g COD/(g COD·d) | 3 | 1 |
| **K_X** | Saturation coefficient for $COD_X$ | g/m$^3$ | 0.1 | 0.39 |
| **mu_H** | Maximum growth rate on substrate | d$^{-1}$ | 6 | 6 |
| **b_H** | Rate constant for lysis and decay | d$^{-1}$ | 0.4 | 0.25 |
| **K_F** | Saturation/inhabitation coefficient for growth on $S_F$ | g/m$^3$ | 4 | 20 |
| **K_A** | Saturation coefficient for $S_A$ (acetate) | g/m$^3$ | 4 | 1 |
| **K_NH** | Saturation coefficient for $S_{NH4}$ (nutrient) | g/m$^3$ | 0.05 | 0.7 |
| **K_P** | Saturation coefficient for $S_{PO}$ (nutrient) | g/m$^3$ | 0.01 | 0.3 |
| **Y_H** | Yield for $X_H$ | g COD/g COD | 0.625 | 0.76 |

Figure 7.5 present the calibrated result for the TSS and the $PO^{3-}_4$-P concentration in the fifth zone in the activated sludge (line) together with the data from Sjölunda WWTP during 2013 (scatter).



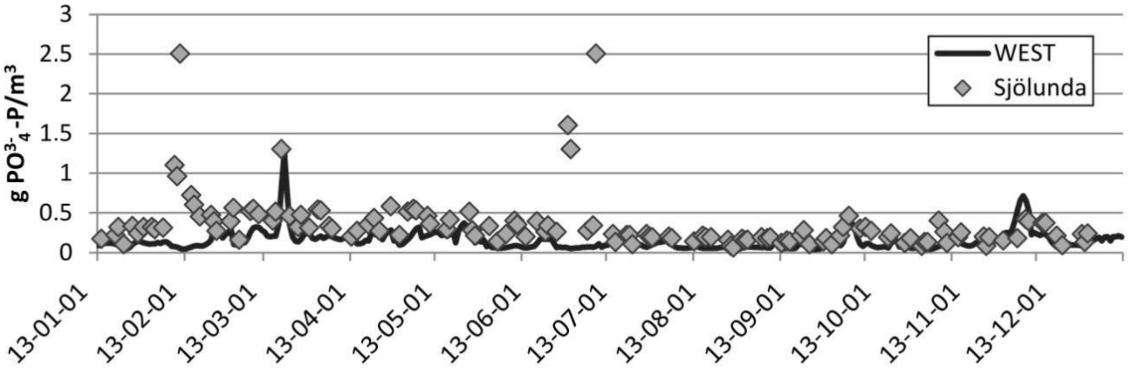


*Figure 7.5. The two graphs present the concentrations for TSS and $PO_4^{3-}$-P in the fifth zone in the activated sludge for the calibrated model (line) together with the data for Sjölunda WWTP from 2013 (scatter).*

There are around 50 parameters that may be manipulated in the activated sludge models in order to improve the calibrated result. Parameters regarding inert composition of different parameters were left with their default values since the aim of this thesis is to calibrate the model, not the inert composition of components. All parameters regarding PAO and their processes were left with default values since no bio-P activity was considered. Parameters concerning autotrophic activity were also left unchanged since the nitrogen removal section was not investigated. Around 10 parameters were then left to be manipulated and all of them were investigated during calibration. The different saturation coefficients (K_X, K_F, K_A, K_NH and K_P) were very useful since they allowed the concentration of their respective components to be kept high if their values were increased. An increased value on K_X together with a lowered value on the hydrolysis rate constant, k_h and the rate constant for lysis and decay, b_H increased the TSS concentration. A lower value on k_h yields a higher concentration of $X_S$ which favours the TSS concentration. The lower value on b_H hinders the decay of biomass, thus increasing the TSS concentration. Both K_NH and K_P were increased compared to their default values since their concentrations were desired to be kept high. The parameter concerning maximum growth rate on substrate, mu_H were manipulated several times during calibration but in the end, its default value was considered most favourable. The parameter of greatest interest was the yield for $X_H$, Y_H. Even a minor increase from the default value increased the TSS concentration in the activated sludge considerably. This value was therefore initially chosen to be relatively high, but unfortunately, this led to a considerable decrease in mainly the $PO^{3-}_4$-P concentration. Hence, the heterotrophic growth process was too active and $PO^{3-}_4$-P became the limiting component for further growth. An iterative process started where, among many changes, the Y_H was decreased and the K_P was increased. The result, presented in Figure 7.5, therefore show a TSS and $PO^{3-}_4$-P concentration somewhat lower than that of Sjölunda WWTP in 2013.

### 7.1.5 Modelling process for the secondary clarifiers

The secondary clarifiers were designed with two purposes (Table 7.4). On one hand, they were modelled to have a high settling velocity (high values on v0 and v00) in order to recirculate a higher concentration of TSS, thus increase the TSS concentration in the activated sludge. On the other hand, the secondary clarifiers were modelled to keep the TSS and TP concentrations from becoming too low in the outflow. The settling parameter, r_P was given a lower value than default and the parameter controlling the non-settleable fraction of suspended solids, f_ns received a larger value than default.

*Table 7.4. Model parameters for the primary clarifiers and their default values from ASM2dModTemp (DHI, 2014b) together with the final calibrated values.*

| Parameter | Description | Unit | Default value | Final value |
|---|---|---|---|---|
| **Q_Under*** | Secondary sludge flow (underflow) | $m^3/d$ | - | 6,548 |
| **SVI** | Sludge volume index | mL/g | 100 | 100 |
| **v0** | Maximum theoretical settling velocity | m/d | 474 | 670 |
| **v00** | Maximum practical settling velocity | m/d | 250 | 370 |
| **r_P** | Settling parameter (low concentration) | $m^3/g$ | 0.00286 | 0.0027 |
| **f_ns** | Non-settleable fraction of suspended solids | - | 0.00228 | 0.0041 |

* Q_Under is dependent on the inflow to the plant and is therefore varying.

The sludge flow from the secondary clarifiers was controlled by two on-off controllers. At Sjölunda WWTP, three pumps are active. By allowing the Large pump to overwrite the Medium Pumps u_Off value, the configuration of Sjölunda WWTP can be mimicked. It was possible to calibrate the sludge flow from the secondary clarifiers by comparing the simulated recirculated flow with available recirculated flow data from Sjölunda WWTP in 2013 (Figure 7.6). This could be done since the waste sludge flow was both low and fairly constant. The recirculated flow was shifting during the day while WEST generated daily values which made the calibration process harder. The final calibrated flows are presented in Table 7.5 and Table 7.6.

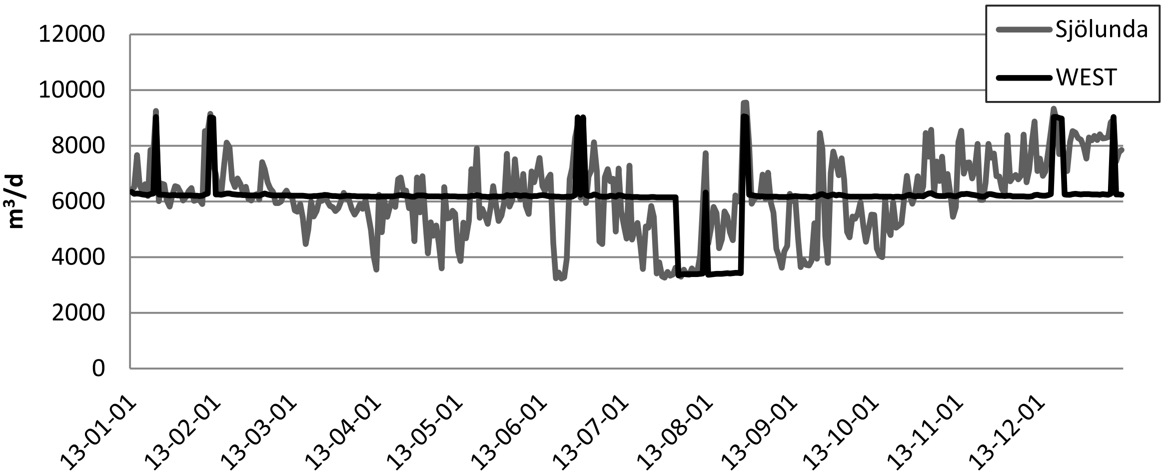


*Figure 7.6. The recirculated flow at Sjölunda WWTP in 2013 (grey line) and the recirculated flow modelled and simulated in WEST (black line).*

*Table 7.5. Parameter values for the Medium pump, both values according to Sjölunda WWTP and final calibrated values. u_On and u_Off are output signals that controls the sludge flow in the secondary clarifiers. y_Min and y_Max are threshold values for during which inflows the pump is to be active.*

| Medium pump | Sjölunda value (m$^3$/d) | Final value (m$^3$/d) |
|---|---|---|
| **u_On** | 3,283 | 3,683 |
| **u_Off*** | 6,048 | 6,548 |
| **y_Min** | 25,920 | 20,000 |
| **y_Max** | 38,880 | 34,000 |

* u_Off for the Medium pump is overwritten by the u_On of the Large pump.

*Table 7.6. Parameter values for the Large pump, both values according to Sjölunda WWTP and final calibrated values. u_On and u_Off are output signals that controls the sludge flow in the secondary clarifiers. y_Min and y_Max are threshold values for during which inflows the pump is to be active.*

| Large pump | Sjölunda value (m$^3$/d) | Final value (m$^3$/d) |
|---|---|---|
| **u_On** | 6,048 | 6,548 |
| **u_Off** | 8,467 | 9,300 |
| **y_Min** | 51,840 | 35,000 |
| **y_Max** | 64,800 | 40,000 |

Figure 7.7 present the calibrated result for the waste sludge flow. The four graphs represents the calibrated results for TKN, COD, TSS and TP (line) together with the data from Sjölunda WWTP during 2013 (scatter).

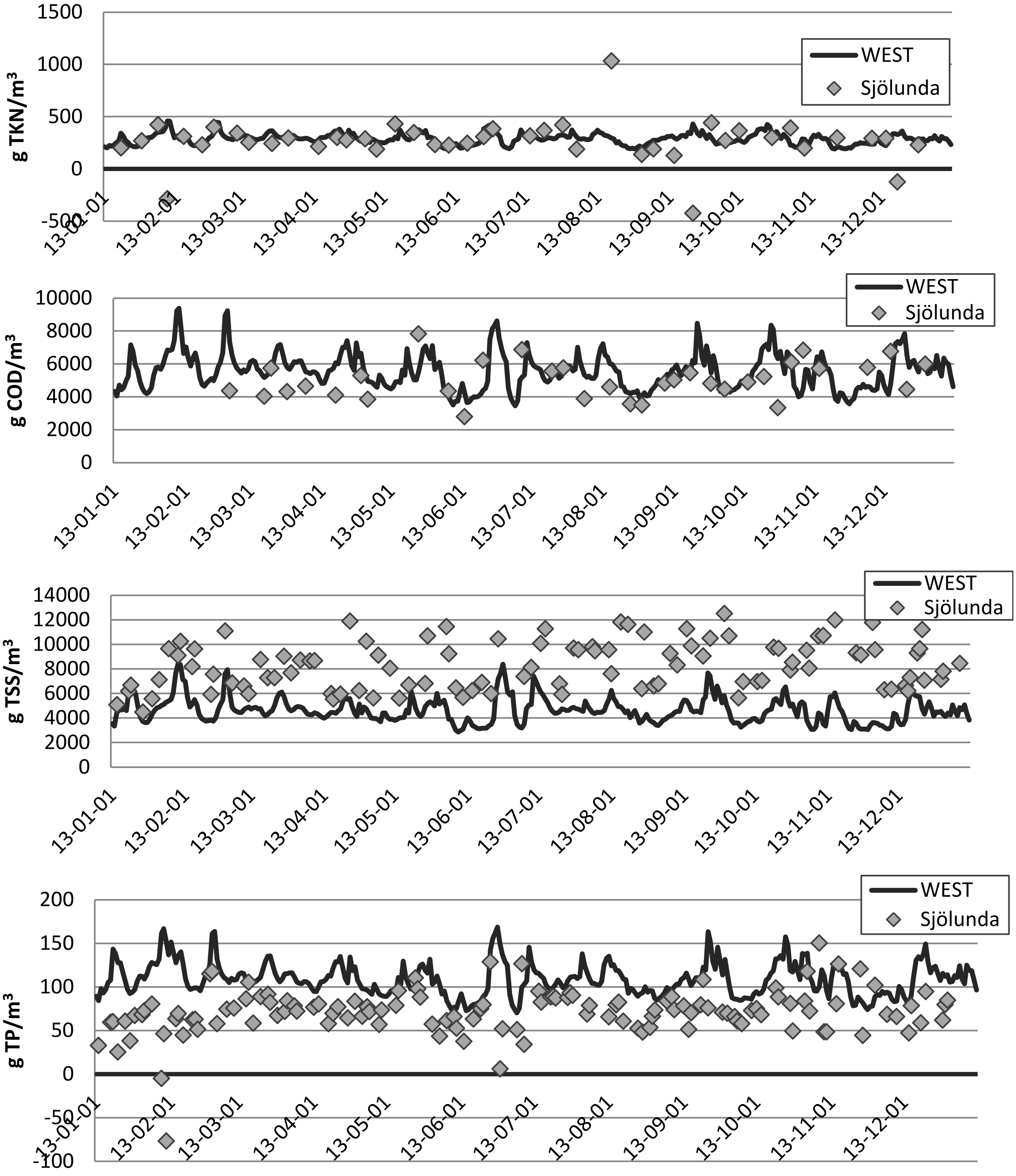


*Figure 7.7. The four graphs present the concentrations for TKN, COD, TSS and TP in the waste sludge for the calibrated model (line) together with the data for Sjölunda WWTP from 2013 (scatter).*

As discussed in section 5.7, the data available from Sjölunda WWTP concerning concentrations for TKN, COD and TP in the waste sludge showed large errors in the overall mass balances. These concentrations were therefore calculated. There are only a few negative values presented in Figure 7.7, but still the calculated values are less reliable. It was not possible to calculate the TSS concentration in the same way as for the other components since TSS is produced in the activated sludge. The TSS concentration curve from Sjölunda WWTP during 2013 (Figure 7.7) is therefore based on measured values. But since the other concentrations were incorrect, it is likely that the measured TSS concentration is incorrect as well. Improving the calibrated results for the waste sludge was therefore not prioritised since the calculated and measured data were not completely reliable.

Figure 7.8 present the calibrated result for the overflow from the secondary clarifiers. The four graphs represents the calibrated results for TKN, COD, TSS and TP (line) together with the data for Sjölunda WWTP from 2013 (scatter).

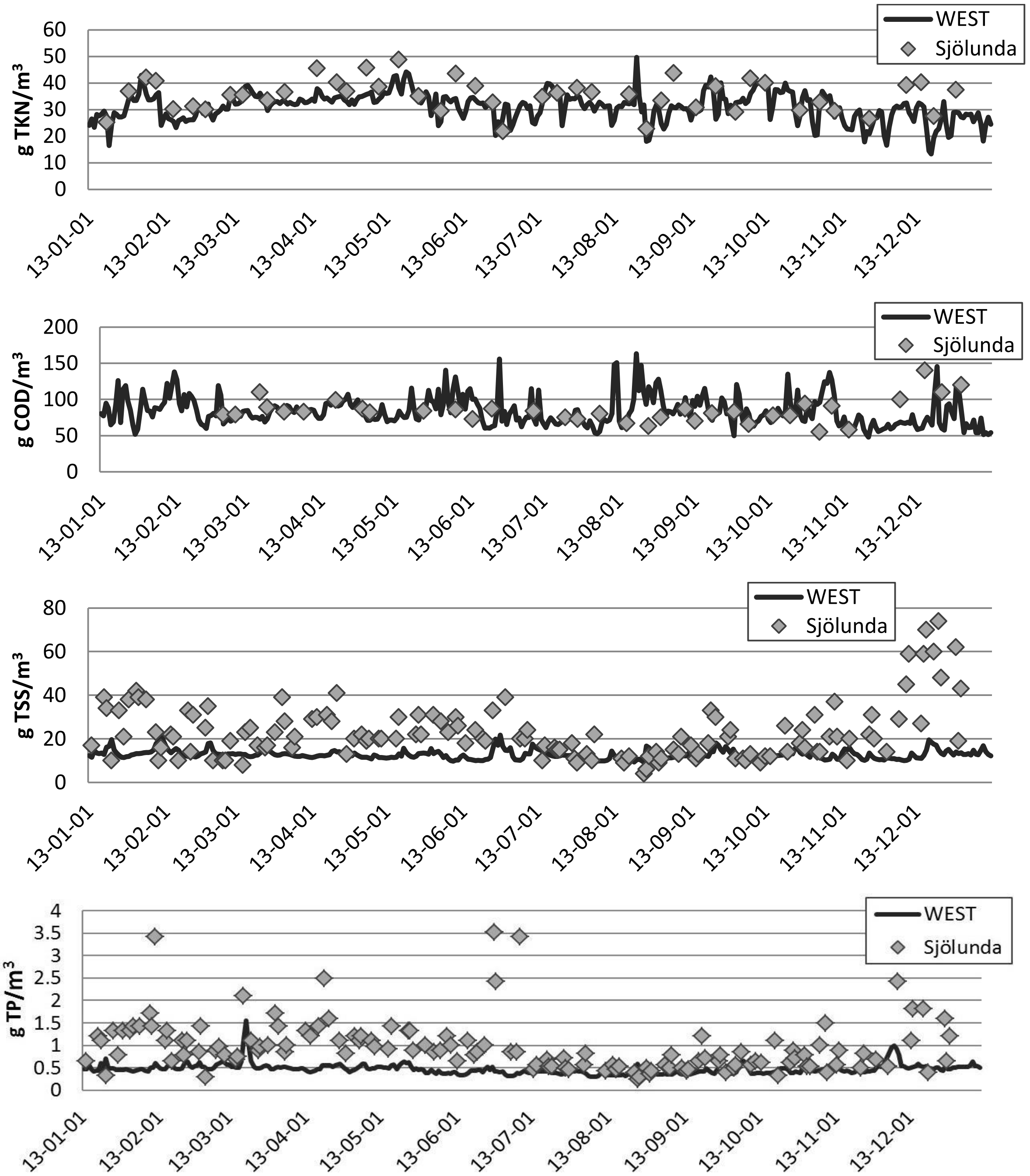


*Figure 7.8. The four graphs present the concentrations for TKN, COD, TSS and TP in the overflow from the secondary clarifiers for the calibrated model (line) together with the data for Sjölunda WWTP from 2013 (scatter).*

The overall calibration results for TKN and COD presented in Figure 7.8 are considered to be good results. The concentration curves for both TSS and TP are somewhat lower than the data from Sjölunda WWTP for 2013. Both of these curves could be increased if the secondary clarifiers were calibrated to have an impaired sedimentation capacity (lower values on v0, v00 and r_P and a higher value on f_ns). But the secondary clarifiers were also calibrated to keep a high TSS concentration in the activated sludge. An iterative process started, resulting in the graphs presented in Figure 7.8, where the TSS and TP concentrations are somewhat lower than that of Sjölunda WWTP in 2013. The parameter SVI was manipulated several times during calibration but in the end, its default value was considered most favourable.

### 7.1.6 Validation of Sjölunda WWTP

The validation result can be seen in appendix I. The validation showed similar results as for the calibrated model of Sjölunda WWTP. Particularly good results were obtained for the concentrations of components leaving the primary clarifiers, the TSS concentration in the activated sludge, and the TKN and TP concentrations in the overflow from the secondary clarifiers. Since Sjölunda WWTP data for the primary sludge was calculated, just as it was during calibration, many values are negative and others are unreasonably high which makes it hard to evaluate the results. The same dilemma exists for the waste sludge although the values were more reasonable compared to the primary sludge. The Sjölunda WWTP data for COD and TSS in the overflow from the secondary clarifiers indicate two to three times larger values during January to May compared to values during May to November. This is a behaviour the validated curves did not follow.

## 7.2 Result for the increased load simulation

It was possible to increase the load on Sjölunda WWTP for nine years without decreasing the quality of the outgoing flow on a yearly average, i.e. the flow entering the NTFs. During the 10 years simulated (during the 10th year, the quality of the outgoing flow was reduced) were the five components $H_2O$, TKN, COD, TSS and TP increased yearly according to: 26,256-32,839 $m^3/d$, 45-58 $g/m^3$, 516-623 $g/m^3$, 263-314 $g/m^3$, 6-8 $g/m^3$ (Figure 7.9). Year one, two, four, five and seven are not shown in the results since no changes were made in the model in order to keep the demands during these years.

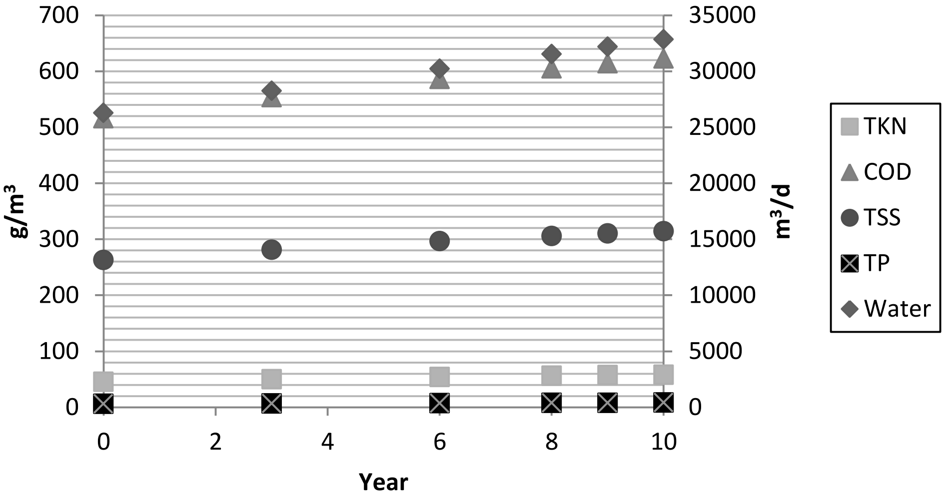


*Figure 7.9. The composition of the incoming wastewater with values on water (right vertical axis), TKN, COD, TSS and TP (left vertical axis) from year 0 to year 10.*

Four parameters were studied and changed on a yearly basis to maintain a COD concentration $\leq$ 80 g/m$^3$ and the ratio $PO^{3-}_4$-P/$NH^+_4$-N $\geq$ 0.02 (Table 7.7). The ratio $PO^{3-}_4$-P/$NH^+_4$-N was kept at 0.02 by increasing the allowed concentration of $PO^{3-}_4$-P entering the activated sludge. A concentration in the outflow of 80 g/m$^3$ for COD was harder to keep. An increase of the oxygen concentration in the activated sludge and a decrease of SRT decreased the COD concentration in the outgoing flow. An increase of the sludge outtake from the primary clarifiers also decreased the COD concentration slightly. The final year simulated, year 10, yielded a COD concentration of 82 g/m$^3$ even though all possible changes had been made.

*Table 7.7. Changes were made in the model in order to maintain the COD concentration and $PO^{3-}_4$-P/$NH^+_4$-N ratio. To facilitate the process, year one, two, four, five and seven were not simulated.*

| **Year** | **0** | **3** | **6** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|
| **$PO^{3-}_4$-P entering activated sludge (g/m$^3$)** | 1.75 | 1.91 | 2.05 | 2.19 | 2.21 | 2.25 |
| **$O_2$ concentration in zones 3 (g/m$^3$)** | 0.3 | 0.3 | 2.2 | 3.0 | 3.0 | 3.0 |
| **$O_2$ concentration in zones 4 (g/m$^3$)** | 0.8 | 0.8 | 2.2 | 3.0 | 3.0 | 3.0 |
| **$O_2$ concentration in zones 5 (g/m$^3$)** | 2.0 | 2.0 | 2.2 | 3.0 | 3.0 | 3.0 |
| **SRT (d)** | 1.64 | 1.64 | 1.24 | 0.70 | 0.60 | 0.60 |
| **Total sludge flow from primary clarifiers (m$^3$/d)** | 900 | 900 | 900 | 900 | 3000 | 3,000 |

Figure 7.10 present how the daily average concentrations for $COD_S$, $S_I$ and $COD_X$ changed over the 10 years simulated, presented as yearly averages. In Figure 7.10, it is possible to see that the $COD_X$ was lower during the ninth year than it was initially. On the other hand, $COD_S$ has been increasing steadily. The concentrations for $S_F$, $S_A$ and $S_I$ were therefore studied and the concentrations for $S_F$ and $S_A$ were found to be less than 1 g/m$^3$ each during the ninth year. Hence, $S_I$ was found to be responsible for the major parts of the outgoing COD, as can be seen in Figure 7.10. $S_I$ was assumed to leave the system with the same concentration as it had at the inlet since it is non-biodegradable and soluble, i.e. it will not settle in clarifiers. It was therefore not possible to decrease the $COD_S$ any further, hence the $COD_X$ fractions were not decreased enough.

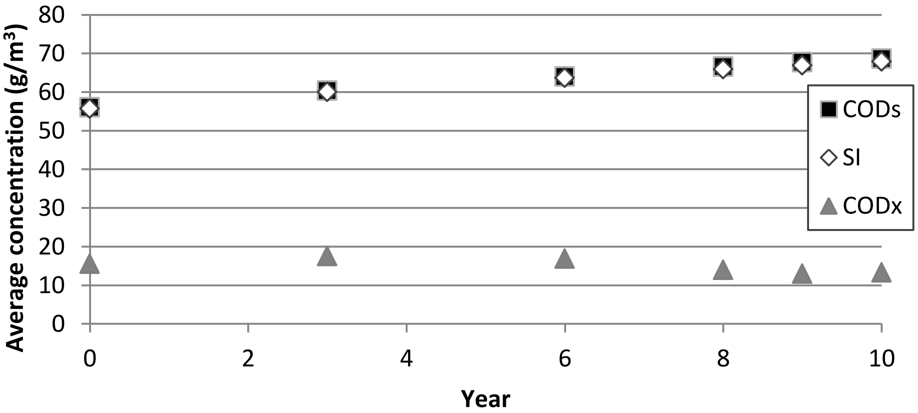


*Figure 7.10. The daily average concentrations in the outflow from the secondary clarifiers presented as yearly averages for $COD_S$, $S_I$ and $COD_X$.*

### 7.2.1 Result for the effects on biogas production

The substrates responsible for biogas production increased as the load to the plant increased. The increase in mass for $X_S$, $X_H$, $S_F$ and $S_A$ in the primary sludge can be seen in Figure 7.11 and the increase in mass for $X_S$ and $X_H$ in the waste sludge is presented in Figure 7.12.

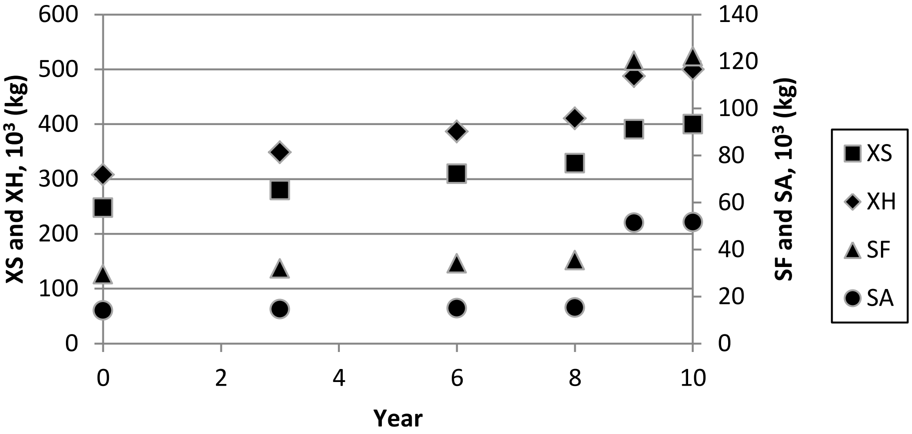


*Figure 7.11. Increase in mass (kg) for the components $X_S$ and $X_H$ (left vertical axis) and $S_F$ and $S_A$ (right vertical axis) in the primary sludge. Values presented are total mass per year.*

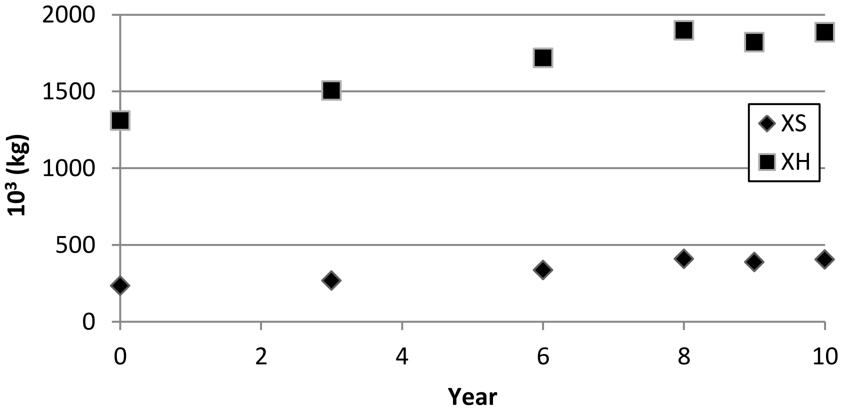


*Figure 7.12. Increase in mass (kg) for the components $X_S$ and $X_H$ in the waste sludge. Values presented are total mass per year.*

The increase in biogas producing substrates increased the potential biogas production (Figure 7.13). During year 0 (before the simulation of an increased load started), the total yearly production was calculated to 800,000 Nm$^3$. The total yearly production was on average increased by 47,000 Nm$^3$ each year (see trend line in Figure 7.13 with an $R^2$ value of 0.9913) until the ninth simulation year where the total yearly production had reached a value of 1,220,000 Nm$^3$. A correlation can be seen between the change in primary sludge outtake during the ninth simulation year and the biogas production based on primary sludge or waste sludge. During the ninth year, the primary sludge flow was increased from 900 to 3,000 m$^3$/d. This resulted in an increase of the biogas production on primary sludge and a decrease of the biogas production based on waste sludge (Figure 7.13).

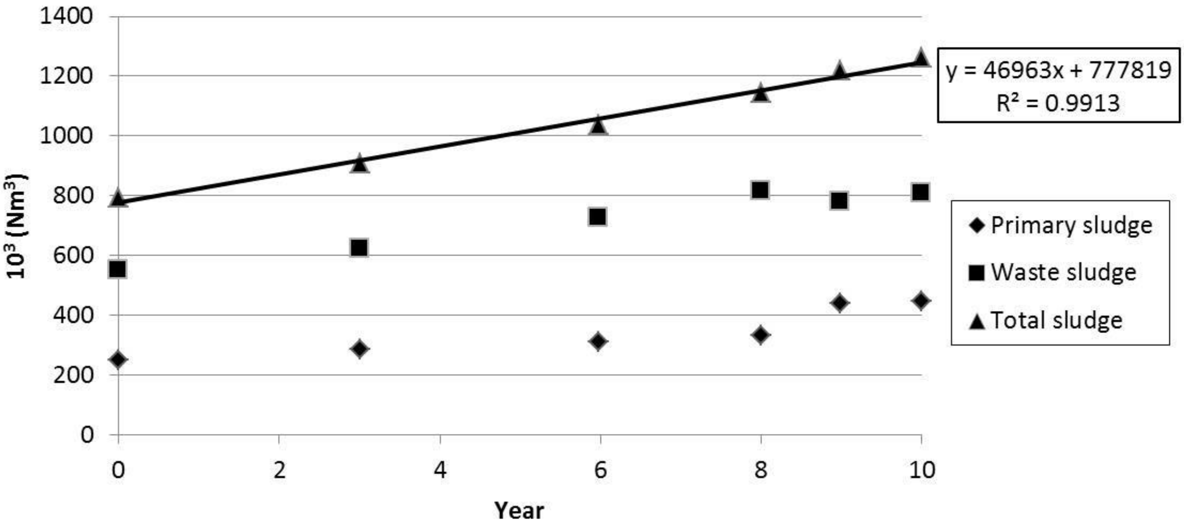


*Figure 7.13. Increase in biogas production (Nm$^3$) divided on primary sludge, waste sludge and total sludge from year 0 to year 10. Values presented are total Nm$^3$ per year.*

The total biogas production at Sjölunda WWTP during 2013 was 5,330,000 Nm$^3$. The calculated biogas production during year 0 reached 800,000 Nm$^3$, but this value is only based on half of section D1. Hence, production based on entire D1 can be calculated to 1,600,000 Nm$^3$. Since no studies or calculations have been made on the other section, D2, it is hard to evaluate how reasonable the results are. Sjölunda WWTP also receives organic material (such as grease from restaurants) delivered by tank cars that also contributes to the biogas production. But overall, the calculated biogas production is considered to be lower than expected. It is possible that the reason for the small amount of biogas produced lies with the inflow characterization. The incoming wastewater compositions presented in Figure 7.2 indicate that the non-biodegradable fractions ($S_I$ and $X_I$) represent 47 %. This means that only 53 % are biodegradable fractions and therefore available for biogas production. According to Henze *et al.* (2000), a typical wastewater composition has a total inert fraction of 21 %, 11 % for $S_I$ and 10 % for $X_I$ (Figure 5.5). But the study executed by Martinello (2013) indicated an inert fraction of 51 % (16 % $S_I$ and 35 % $X_I$) (Figure 5.6).

# 8 Conclusions

This thesis proves that it is highly possible to create a wastewater treatment model for the main COD removal parts in the water line for Sjölunda WWTP. The DHI software product WEST served as a helpful, illustrative and imaginative tool during construction, calibration and simulation of the wastewater treatment model. All processes and sections that initially were intended to be part of the model were constructed either directly using pre-programmed sub-models or by creating own sub-models (as done for the iron-based pre-precipitation and the SRT controller). Hence, WEST served its purpose as a wastewater treatment modelling tool for the modelling of Sjölunda WWTP.

The calibrated results for the primary clarifiers, the activated sludge and the secondary clarifiers showed an overall good result. The calibrated results for the primary sludge and for the waste sludge were difficult to evaluate since there were both missing data and unreasonable data presented by Sjölunda WWTP. The greatest calibration complication was to keep high concentrations of TSS and $PO^{3-}_4$-P in the activated sludge and in the overflow from the secondary clarifiers. Extensive effort was directed towards solving this complication. In the end, higher concentrations were achieved but they were still less than the data presented by Sjölunda WWTP from 2013. The calibrated results for the overflow from the primary clarifiers were considered good result as well as the concentrations for TKN and COD in the overflow from the secondary clarifiers.

The finalised model for Sjölunda WWTP was used to simulate an increased load of on average 5,000 P.E./year due to population growth in Malmö. According to the results, it is only possible to operate Sjölunda WWTP for an additional nine years without deteriorating effluent quality from the secondary clarifiers or enlarging the plant. The substrates responsible for biogas production increased as the load to the plant increased. During year 0 (before the simulation of an increased load started), the total yearly production was 800,000 $Nm^3$. The production was on average increased by 47,000 $Nm^3$ each year until the ninth simulation year where the total yearly production had reached a value of 1,220,000 $Nm^3$.

# 9 Future work

It has been proved that it is highly possible to create a wastewater treatment model for the main COD removal parts in the water line for Sjölunda WWTP. It has also been discussed that wastewater treatment modelling has become a widely accepted tool and has been found to be very useful on many levels. It is therefore proposed to continue developing the Sjölunda wastewater treatment model in order to use it as a reliable tool for optimization, upgrading and general studies of the WWTP. A well-functioning model would be very helpful for engineers and operators situated at the plant.

Initially, a well-conducted measuring campaign is proposed with the aim to get an increased knowledge of the different fractions in the wastewater. With this knowledge, it will be possible to create a more exact inflow characterisation. The measuring campaign should also include the fifth zone of the activated sludge. The activated sludge model in WEST is extremely complex and is composed of over 50 parameters open for calibration. More knowledge of Sjölunda WWTPs activated sludge would therefore facilitate the modelling process and improve the results. A biogas production study is also advised in order to investigate the yield for Sjölunda WWTP (biogas production per COD) in order to receive values that are more up to date.

It should also be studied why the concentration data for TKN, COD and TP were of such low quality in the waste sludge. It might be due to mistakes in calculations or handling of the data, but if it is not, it is extremely important to locate the error in order to be able to use the data in the future. Hence, improved mass balances are needed.

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# 11 Appendices

| | |
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| Appendix I | Validation data |
| Appendix II | Popular science article |
| Appendix III | Scientific paper |

# Appendix I

## Validation data

Validation data for outflow from the primary clarifiers (Figure A1), primary sludge (Figure A2), activated sludge (Figure A3), waste sludge (Figure A4) and overflow from the secondary clarifiers (Figure A5). The four graphs in each figure represent the validated results for TKN, COD, TSS and TP (line) together with the data for Sjölunda WWTP during 2014.01.01 to 2014.10.31 (scatter).

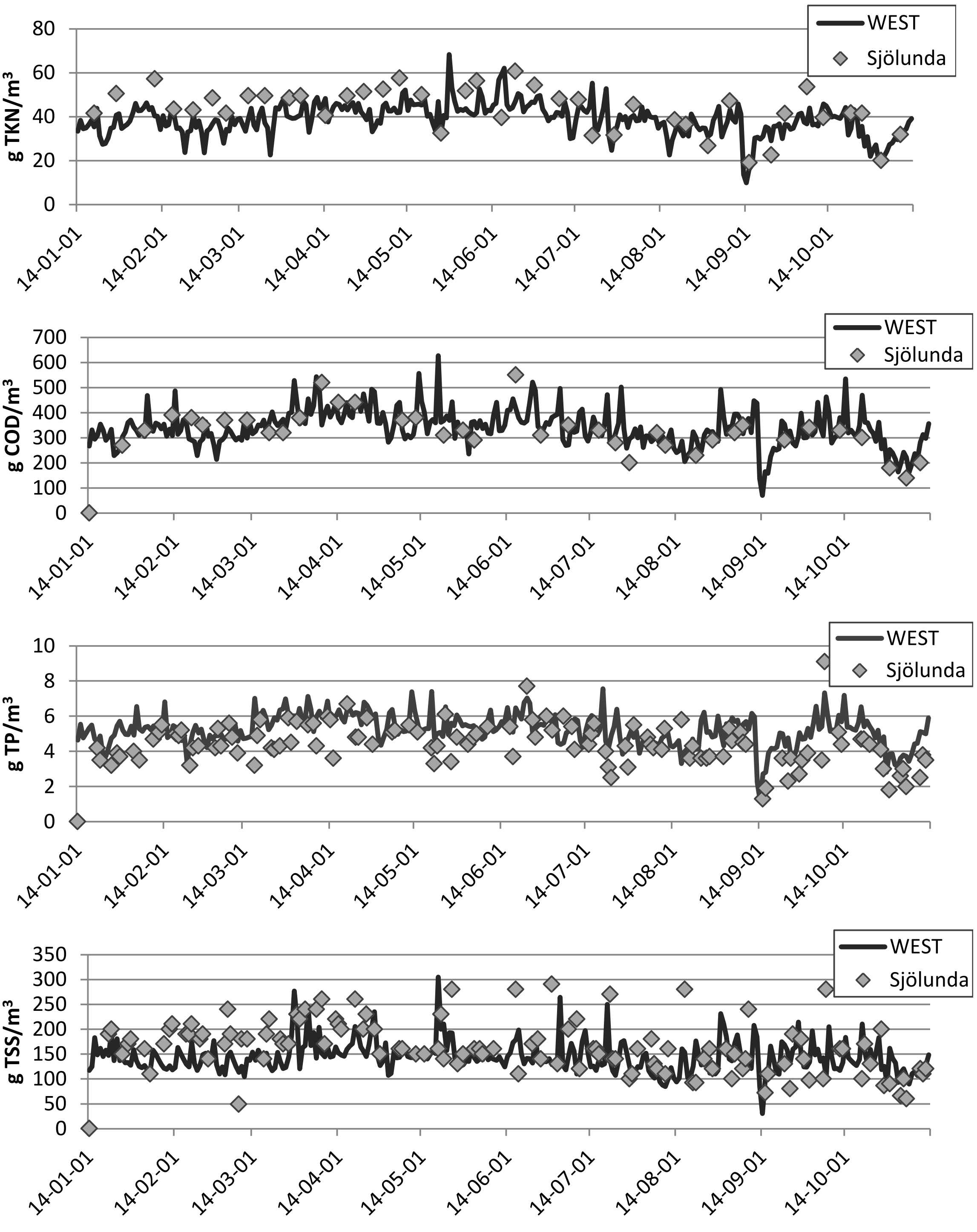


*Figure A1. The four graphs present the concentrations for TKN, COD, TSS and TP in the flow leaving the primary clarifiers for the calibrated model during the validation (line) together with the data for Sjölunda WWTP during 2014.01.01 to 2014.10.31 (scatter).*

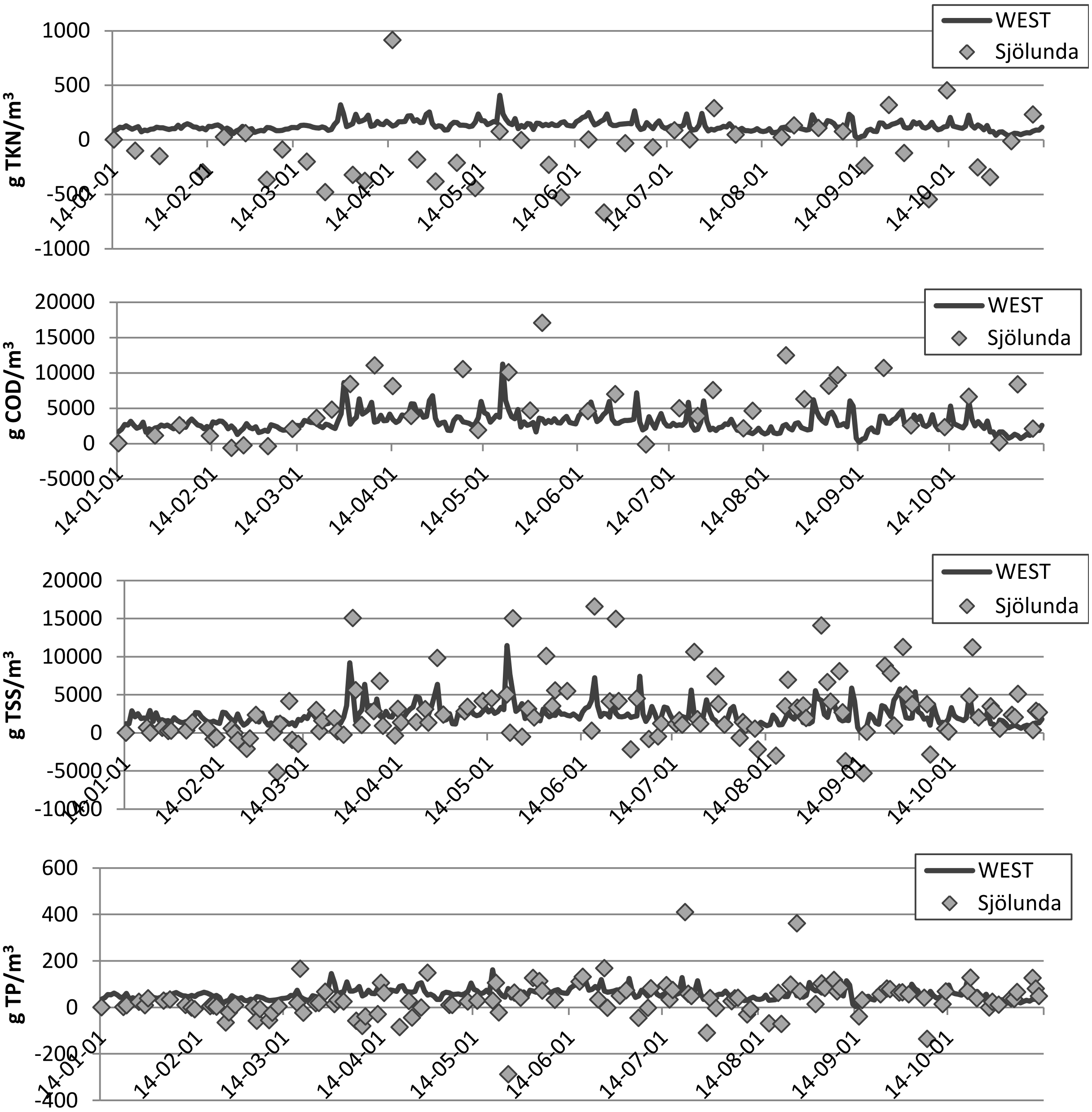


*Figure A2. The four graphs present the concentrations for TKN, COD, TSS and TP in the primary sludge for the calibrated model during the validation (line) together with the data for Sjölunda WWTP during 2014.01.01 to 2014.10.31 (scatter).*

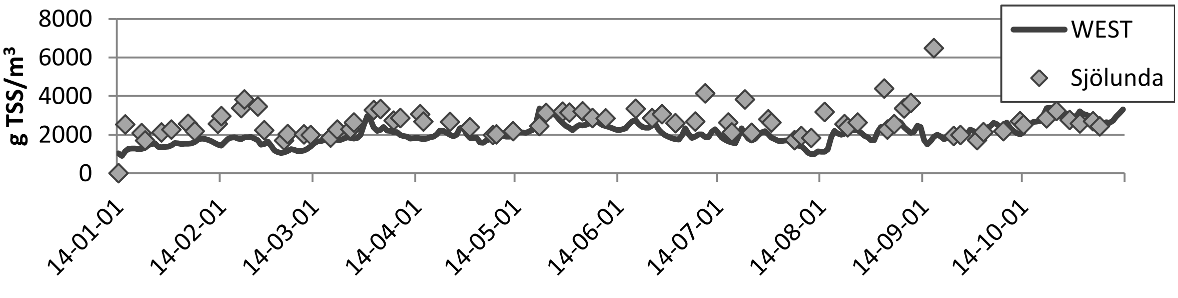


*Figure A3. The graph presents the concentrations for TSS in the fifth zone in the activated sludge for the calibrated model during validation (line) together with the data for Sjölunda WWTP during 2014.01.01 to 2014.10.31 (scatter).*

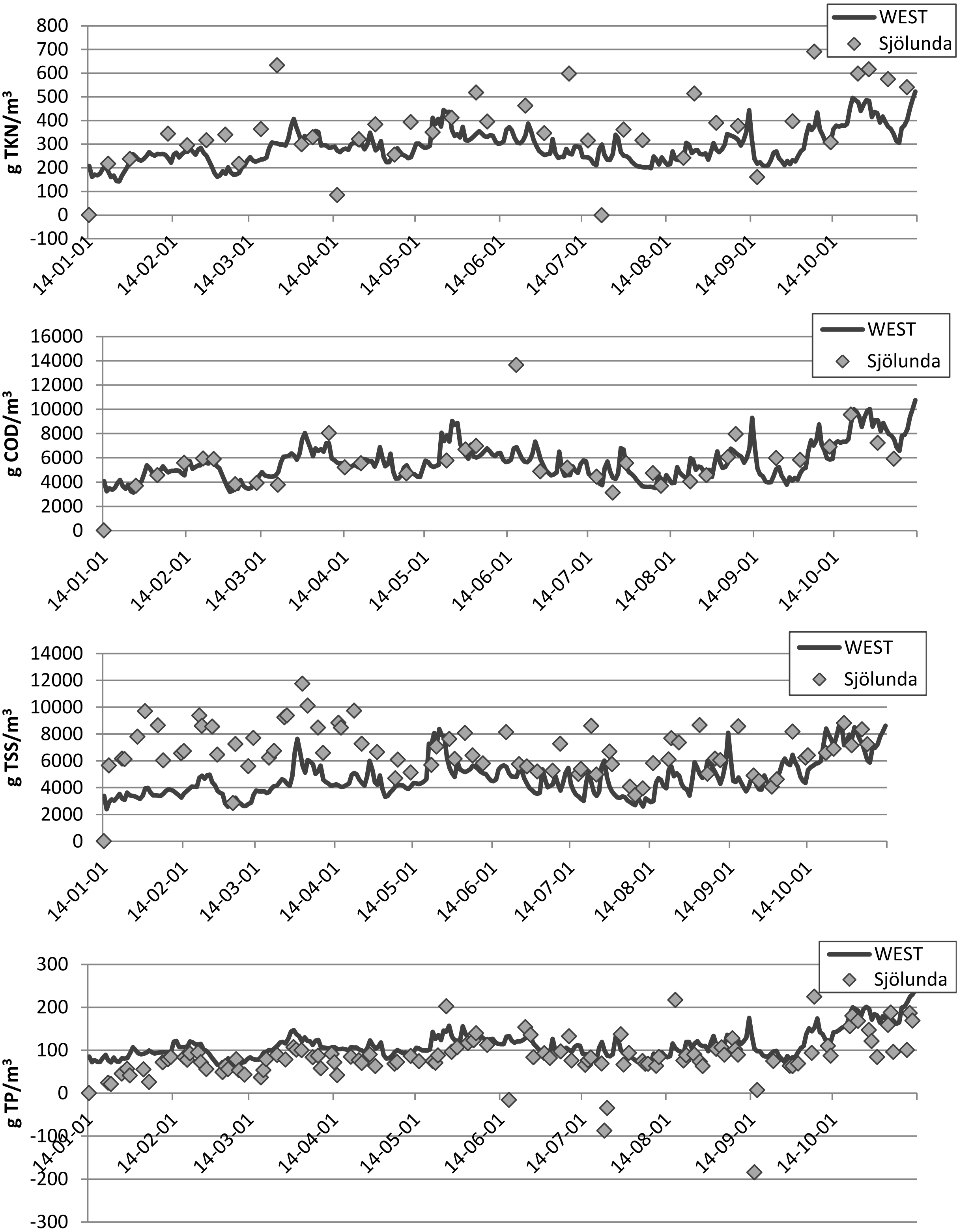


*Figure A4. The four graphs present the concentrations for TKN, COD, TSS and TP in the waste sludge for the calibrated model during the validation (line) together with the data for Sjölunda WWTP during 2014.01.01 to 2014.10.31 (scatter).*

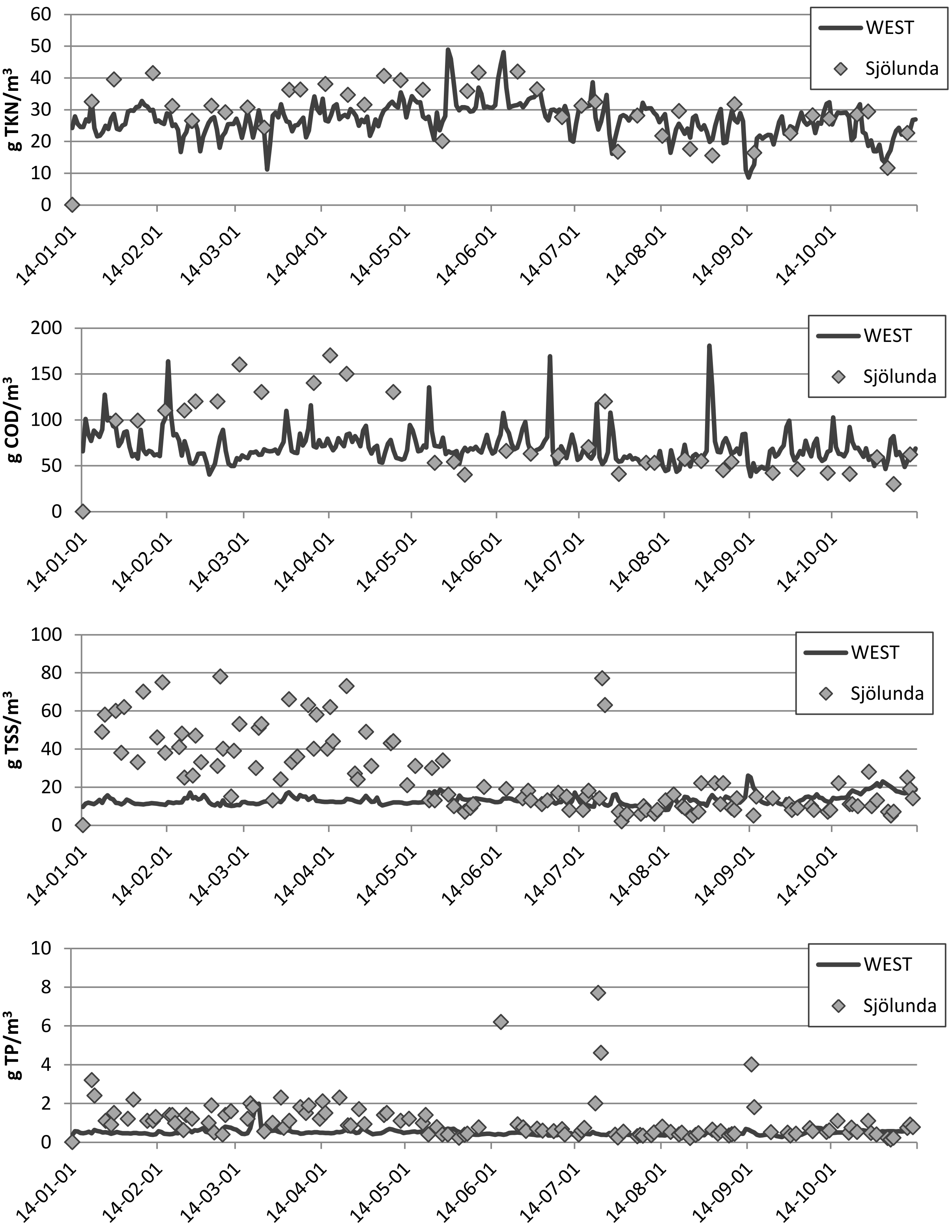


*Figure A5. The four graphs present the concentrations for TKN, COD, TSS and TP in the outflow from the secondary clarifiers for the calibrated model during the validation (line) together with the data for Sjölunda WWTP during 2014.01.01 to 2014.10.31 (scatter).*

# Appendix II

## Popular science article

# Treating wastewater in your computer

**Summer is just around the corner and soon the beaches will be swarming with people just waiting to dive into the warm clean ocean. But hang on… clean? Is it really? Are our oceans full of aquatic life thriving in the unpolluted water? Actually, as you probably already know, this is a huge problem!**

**But you can be calm, this article is not here to convince anyone that this is a problem, it is actually here to inform you of the solution! Or at least, a large step into the right direction.**

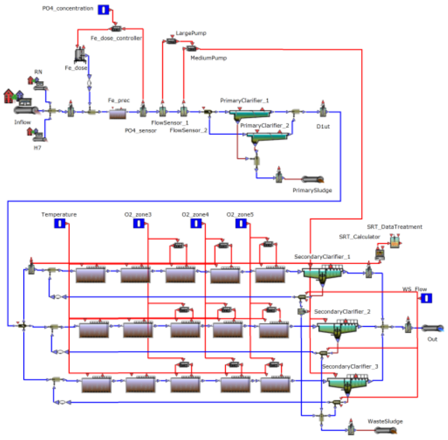
There are several wastewater treatment plants all over the world trying to clean the industries and our wastewater. The engineers and operators working at the plant are constantly monitoring and improving the plants. The better the plant works, the cleaner the water gets and the better it is for our summer swims.

But what if something happens? What if a neighboring plant shuts down and all water has to be redirected to another plant? Or perhaps there is a sudden heavy rainfall, or more long term changes such as an increased load because the city is growing? The operators and engineers have to be able to predict the effects it will have on their plant in order to assure the quality of the water leaving the plant. Imagine if they could get that knowledge by first treating the wastewater in their computers!

Fancy a well-developed model in your computer that actually mimics the plant the engineer has just outside his or her window. This would save a lot of time and money since the alternative is to do “pilot-studies” where you physically mimic the plant.

But the difficulty is to get your hands on a fine working model or to create one yourself. Let’s have a look at the procedure of creating one yourself.

The figure to the right shows the model created for parts of a plant located in Malmö (Sweden). The computer program used in this case (WEST®) allows you to graphically construct your plant. WEST then needs information such as volumes and temperatures as well as flows and concentrations of the incoming wastewater. So you can imagine the extensive amount of information needed! Once the plant is constructed with all the details available, the simulations can start. The aim is to make WEST produce flows and concentrations in different sections of the plant that mimics the same values at the real plant.



There are always difficulties to overcome and the procedure of creating a well-functioning model takes months if not years. It will be time consuming and therefore also expensive. But once the model is done, just imagine all the possible simulations you can run! Within hours you may receive the results that otherwise would have taken you years!

This tool would enhance any wastewater treatment plant by making it less costly and eventually resulting in improved operation and understanding of the plant. A plant that is easy to analyze will also be a plant that is easier to control. And a well-controlled plant will discharge high quality water next to our summer beaches!

# Appendix III

## Scientific paper

# Modelling the COD Reducing Treatment Processes at Sjölunda WWTP

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April, 2015

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## Abstract

A wastewater treatment model for the main COD removal parts in the water line of Sjölunda wastewater treatment plant was established. The DHI software product WEST® was used to create the model based on the iron-based pre-precipitation with pre-settling, the primary clarifiers, the activated sludge lines and the secondary clarifiers. The activated sludge lines were modelled using the Activated Sludge Model No. 2d (ASM2d). An increased load simulation was conducted to investigate the plants performance. The result indicates that it is possible to operate the plant for an additional nine years without deteriorating effluent quality. The increased load also increased the yearly biogas production from 800,000 Nm$^3$/y to 1,220,000 Nm$^3$/y.

*Keywords: ASM2d, biogas production, COD removal, increased load, wastewater treatment, wastewater treatment modelling, WEST*

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## Introduction

Sjölunda Wastewater Treatment Plant (WWTP) located in Malmö, in southern Sweden treats wastewater corresponding to around 300,000 population equivalents (P.E.) (considering 70 g BOD$_7$/person·d) [1]. Parts of Sjölunda WWTP are designed to handle a load corresponding to 550,000 P.E. [2]. Malmö is expected to increase by on average 5,000 inhabitants per year in the following 10 years [3] which will increase the load on Sjölunda WWTP. It is important for engineers and operators to be able to predict these kinds of future changes but also to be able to understand how it will affect their WWTP. A well-developed wastewater treatment model of the plant facilitates the understanding of how changes in inflow and composition will affect the plant and the effluent quality.

In the 80s, the International Association on Water Quality (IAWQ, formerly IAWPRC) task group on mathematical modelling for design and operation of biological wastewater treatment had an aim to create a wastewater treatment model for nitrogen-removal activated sludge processes. Their work resulted in the Activated Sludge Model No. 1 (ASM1) in 1987 [4]. Since then, simulations of wastewater processes have been more common and a widely accepted tool [5].

The main focus of this work was to create a wastewater treatment model for the main COD removal parts in the water line of Sjölunda WWTP. The model was created using the DHI software product WEST [6]. The sections modelled were the iron-based pre-precipitation with pre-settling, the primary clarifiers, the activated sludge lines and the secondary clarifiers.

The finalised model was used to simulate the increased load of on average 5,000 P.E. per year due to the population growth in Malmö. The aim was to study for how long the WWTP can handle the increased load without deteriorating the water quality or enlarging the plant. Additional biogas production due to the increased load was investigated using simple calculations.

## Materials and Methods

### *Sjölunda WWTP*

Sjölunda WWTP treats on average 1,140 L/s [2]. It is composed of iron-based pre-precipitation with pre-settling followed by the primary clarifiers. The outflow from the primary clarifiers enters a high-loaded activated sludge with focus on COD-removal. The activated sludge is connected to the secondary clarifiers with recirculation flows and sludge outtake. The following steps are focused on nitrogen removal starting with nitrifying trickling filters (NTFs) followed by moving bed biofilm reactors (MBBRs). Final particle separation is done in a dissolved air flotation plant before the treated water is discharged in the Öresund strait. The produced waste sludge is digested anaerobically creating biogas while parts of the digested sludge may be used as fertilizer.

### *Model components and processes in WEST*

The category used to model in WEST was the ASM2dModTemp and it is composed of 19 components divided into dissolved and particulate components (Table 1).

*Table 1. All components present in ASM2dModTemp [4].*

| **Short name** | **Description** | **Unit** |
|---|---|---|
| Dissolved components | | |
| **$S_O$** | Dissolved oxygen | g $O_2/m^3$ |
| **$S_F$** | Readily biodegradable substrate | g $COD/m^3$ |
| **$S_A$** | Fermentation products (acetate) | g $COD/m^3$ |
| **$S_{N2}$** | Dinitrogen | g $N/m^3$ |
| **$S_{NH}$** | Ammonium | g $N/m^3$ |
| **$S_{NO}$** | Nitrate and nitrite | g $N/m^3$ |
| **$S_{PO}$** | Phosphate | g $P/m^3$ |
| **$S_I$** | Inert, non-biodegradable organics | g $COD/m^3$ |
| **$S_{ALK}$** | Bicarbonate alkalinity | g $HCO^-_3/m^3$ |
| Particulate components | | |
| **$X_I$** | Inert, non-biodegradable organics | g $COD/m^3$ |
| **$X_S$** | Slowly biodegradable substrate | g $COD/m^3$ |
| **$X_H$** | Heterotrophic biomass | g $COD/m^3$ |
| **$X_{PAO}$** | Phosphorus accumulating organisms, PAO | g $COD/m^3$ |
| **$X_{PP}$** | Stored poly-phosphate of PAO | g $P/m^3$ |
| **$X_{PHA}$** | Organic storage products of PAO | g $COD/m^3$ |
| **$X_{AUT}$** | Autotrophic, nitrifying biomass | g $COD/m^3$ |
| **$X_{MEOH}$** | Ferric-hydroxide, $Fe(OH)_3$ | g $Fe(OH)_3/m^3$ |
| **$X_{MEP}$** | Ferric-phosphate, $FePO_4$ | g $FePO_4/m^3$ |
| **$X_{TSS}$** | Particulate material | g $TSS/m^3$ |

The main processes are: growth of biomass (heterotrophic ($X_H$), autotrophic ($X_{AUT}$) and phosphorus accumulating organisms (PAO, $X_{PAO}$)), decay of biomass, hydrolysis of particulate organics, nitrification processes and chemical precipitation of phosphorus ($S_{PO4}$). Growth of biomass is assumed to exclusively rely on readily biodegradable material ($S_F$) for substrate. Decay of biomass leads to the creation of inert particulate material ($X_I$) and slowly biodegradable material ($X_S$). $X_S$ cannot be consumed by the organisms and therefore has to undergo hydrolysis where the material is converted into $S_F$. $X_I$ is assumed not to take part in any more processes and $S_I$ is assumed to pass through the plant unchanged. The nitrifying processes are growth and decay of $X_{AUT}$. The PAO are involved in growth, storage and decay. Chemical precipitation of $S_{PO4}$ is modelled to only precipitate $PO_4^{3-}$-P [4].

### *Modelling setup of Sjölunda WWTP*

WEST is in need of an input file containing data for the components presented in Table 1 in order to do the inflow characterization. It is also possible to present data for larger components such as total Kjeldahl nitrogen (TKN), chemical oxygen demand (COD), total suspended solids (TSS) and total phosphorus (TP) and allow WEST to fractionate them into the smaller components in Table 1 and this is what was done in this work.

Two models were created, the first was calibrated based on data from Sjölunda WWTP from 2013. The second model used the first as a base but some inputs were removed in order to generalize the model to be able to use it during the increased load simulation.

The sections modelled were the iron-based pre-precipitation with pre-settling, the primary clarifiers, the activated sludge lines and the secondary clarifiers. The clarifiers were based on the models presented by Takács, Party and Nolasco [7] and the activated sludge lines were modelled using the Activated Sludge Model No. 2d (ASM2d) [4]. The model used for the primary clarifiers was Primary Takács [7]. The pre-precipitation was modelled using an iron-dosing unit connected to the mainstream before the reaction tank. A sensor post the tank informs a controller of the received $PO_4^{3-}$-P concentration that compares the values with data from Sjölunda WWTP and then informs the dosing unit if it should add more or less iron (Figure 1).

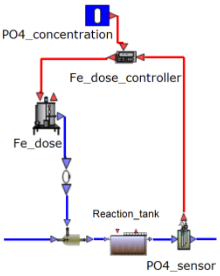

*Figure 1. The sub-model for the iron-based pre-precipitation [6].*

Three of the five zones in the activated sludge were aerated using controllers and the temperature of the wastewater was controlled by an input temperature curve. The secondary clarifiers were modelled using the Takács SVI model [7]. The sludge flow was controlled by two on-off controllers that increased the sludge flow if the incoming flow increased and vice versa (Figure 2).

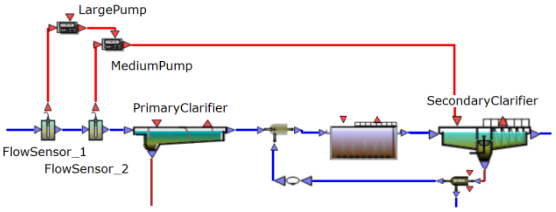

*Figure 2. The sub-model for the pump system controlling the sludge flow from the secondary clarifiers [6].*

The solids retention time (SRT) in the first model was controlled by an input from 2013. This was replaced while creating the generalized model by constructing a sub-model controlling the SRT with a fixed value (Figure 3). The SRT_Calculator calculates the SRT and sends the information to a controller via a data treatment block. The controller is governed by a fixed value and increases or decreases the waste sludge flow dependent on the calculated SRT.

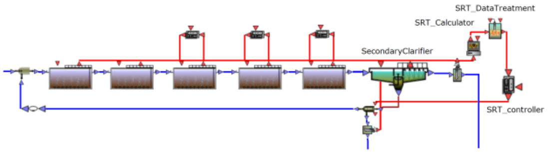

*Figure 3. The sub-model for SRT controller [7].*

### *Increased load due to population growth*

A wastewater composition study [8] was analysed in order to find how much an increase of 5,000 P.E./year will affect the different fractions in the incoming wastewater (Table 2).

*Table 2. Concentrations for $H_2O$, TKN, COD, TSS and TP in household wastewater in g/(P.E.·d) [8].*

| Parameter | Household wastewater |
|---|---|
| **$H_2O$** | 131,597.6 |
| **TKN** | 14.02 |
| **COD** | 135.0 |
| **TSS** | 66.36 |
| **TP** | 2.08 |

By using the data presented in Table 2 [8], it was possible to calculate how much 5,000 P.E. would contribute divided on the different fractions (Table 3). The mass fractions (MF) indicate how much each component is increased by in g/d and the flow factor (FF) indicates how much the flow is increased in $m^3/d$.

*Table. 3. The parameters* $H_2O$, TKN, COD, TSS and TP will be increased by their respective MF and FF *during the increased load simulation.*

| | g/(P.E.·d) | Mass factor (MF) g/(5,000 P.E.·d) | Flow factor (FF) $m^3/d$ |
|---|---|---|---|
| **$H_2O$** | 131,600 | $65.80 \cdot 10^7$ | 658 |
| **TKN** | 14 | 70,100 | |
| **COD** | 135 | 675,000 | |
| **TSS** | 66 | 331,800 | |
| **TP** | 2 | 10,400 | |

During the increased load simulation, some parameters were manipulated in order keep a sustainable quality of the overflow from the secondary clarifiers. The outgoing COD concentration had to be $\leq 80$ g/$m^3$ and the ratio of $PO^{3-}_4$-P/$NH^+_4$-N had to be $\geq 0.02$ in order to favour the nitrifying processes in the following NTFs.

### *Biogas production*

The amount of biogas produced depends on the amount of biodegradable substrate present in the sludge [9]. The components contributing to biogas production of the primary sludge are $S_F$, $S_A$, $X_S$ and $X_H$. The concentrations of $S_F$ and $S_A$ are almost zero in the secondary sludge, hence, only $X_S$ and $X_H$ are contributing to the biogas production of the waste sludge. A study [10] at Sjölunda WWTP indicates a volatile solids (VS) reduction of 44 % and 43 % for biogas production based on primary and waste sludge respectively. It is here assumed that the VS are the same as the biodegradable COD fractions. The amount of biogas produced was 0.95 $Nm^3/(kg\ VS_{red})$ and 0.82 $Nm^3/(kg\ VS_{red})$ for primary sludge respectively waste sludge [10]. The biogas production was therefore calculated according to Equation 1 and Equation 2.

*Equation 1.*

$$Biogas\ production_{primary\ sludge} = \frac{(S_F + S_A + X_S + X_H) kg\ VS}{dt} \cdot \frac{0.44\ kg\ VS_{red}}{kg\ VS} \cdot \frac{0.95\ Nm^3}{kg\ VS_{red}}$$

*Equation 2.*

$$Biogas\ production_{waste\ sludge} = \frac{(X_S + X_H) kg\ VS}{dt} \cdot \frac{0.43\ kg\ VS_{red}}{kg\ VS} \cdot \frac{0.82\ Nm^3}{kg\ VS_{red}}$$

## Results and discussion

### *Calibration results*

The calibrated result indicates that it is highly possible to create a wastewater treatment model for the main COD removal parts in the water line for Sjölunda WWTP. The calibrated result for the primary sludge and the waste sludge were difficult to evaluate due to both lack of data and data of low quality from Sjölunda WWTP. The calibrated results for the concentrations in the flow leaving the primary clarifiers were overall considered good results. The greatest calibration complication was to keep high concentrations of TSS and $PO^{3-}_4$-P in the activated sludge (Figure 4 and Figure 5), extensive effort was therefore directed towards solving this complication.

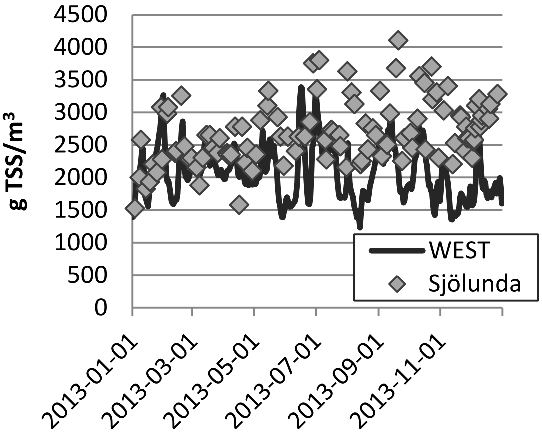

*Figure 4. Calibrated result for the TSS concentration in the fifth zone in the activated sludge.*

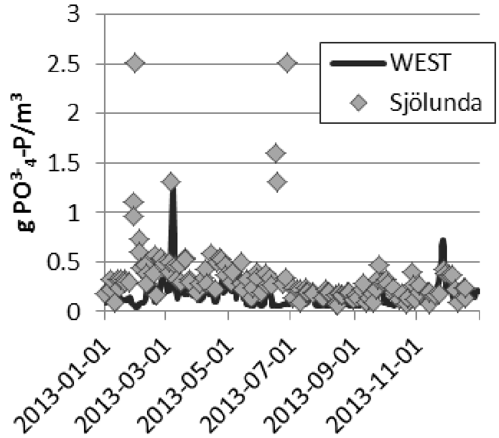

*Figure 5. Calibrated result for the $PO^{3-}_4$-P concentration in the fifth zone in the activated sludge.*

This complication affected the calibration work for both the primary and secondary clarifiers. The primary clarifiers were calibrated to sediment less than the default clarifier in order to allow more TKN, COD, TSS and TP to enter the activated sludge, thus increasing the biomass production. The calibrated result for mainly the COD and TP concentrations were therefore increased above the concentrations presented by Sjölunda WWTP. But the continuous difficulty with low TSS and $PO^{3-}_4$-P concentration in the activated sludge was of a greater priority, hence the higher concentrations for COD and TP leaving the primary clarifiers were kept.

The secondary clarifiers were on the other hand calibrated to settle as much of the sludge as possible in order to recirculate a higher concentration thus increasing the TSS concentration in the activated sludge. The concentrations for TSS and $PO^{3-}_4$-P in the outflow were therefore somewhat lower than the concentrations presented by Sjölunda WWTP. But the concentrations for TKN and COD in the overflow from the secondary clarifiers were considered good calibration results.

*Results for the increased load simulation*

The results indicated that it was only possible to operate Sjölunda WWTP for an additional nine years without deteriorating effluent quality from the secondary clarifiers or enlarging the plant. The parameters changed in order keep a COD concentration ≤ 80 g/m$^3$ and the ratio of $PO^{3-}_4$-P/$NH^{+}_4$-N ≥ 0.02 in the outflow were: the SRT, oxygen concentration in the activated sludge, allowed $PO^{3-}_4$-P concentration entering the activated sludge and the primary sludge flow (Table 4).

*Table 4. The concentration of $PO^{3-}_4$-P and $O_2$ in g/m$^3$, SRT is presented in days and the sludge flow in m$^3$/d.*

| **Year** | **0** | **3** | **6** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|
| **$PO^{3-}_4$-P** | 1.75 | 1.91 | 2.05 | 2.19 | 2.21 | 2.25 |
| **$O_2$ (Z3)** | 0.3 | 0.3 | 2.2 | 3.0 | 3.0 | 3.0 |
| **$O_2$ (Z4)** | 0.8 | 0.8 | 2.2 | 3.0 | 3.0 | 3.0 |
| **$O_2$ (Z5)** | 2.0 | 2.0 | 2.2 | 3.0 | 3.0 | 3.0 |
| **SRT** | 1.64 | 1.64 | 1.24 | 0.70 | 0.60 | 0.60 |
| **Primary sludge** | 900 | 900 | 900 | 900 | 3000 | 3,000 |

The ratio of $PO^{3-}_4$-P/$NH^{+}_4$-N was kept at 0.02 by increasing the allowed concentration of $PO^{3-}_4$-P entering the activated sludge. A COD concentration in the outflow of 80 g/m$^3$ was harder to keep. During the 10th simulation year, it was no longer possible to keep a COD concentration ≤ 80 g/m$^3$ in the outflow. The $O_2$ concentration was initially decided not to be increased more than to 3.0 $g/m^3$, hence it had been increased as much as possible. It was not possible to reach a lower SRT than 0.6 and a primary sludge flow greater than 3,000 $m^3/d$ made little difference. Figure 6 shows that the particulate COD fractions, $COD_X$ were decreased during the years but the soluble fractions, $COD_S$ and especially $S_I$ increased steadily.

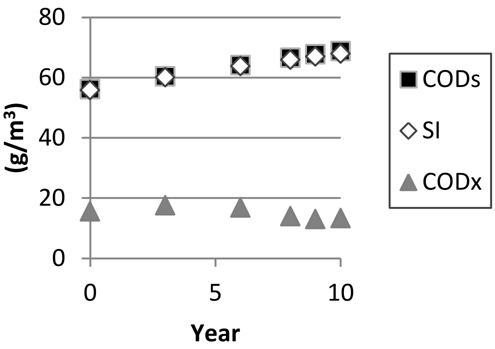

*Figure 6. The changes in daily average over the years for $COD_X$, $COD_S$ and $S_I$.*

### *Results for the effects on biogas production*

The total yearly biogas production during year 0 (before the increased load started) was 800,000 $Nm^3$. The total yearly production was on average increased by 47,000 $Nm^3$ each year until the ninth simulation year where the total yearly production had reached a value of 1,220,000 $Nm^3$ (Figure 7).

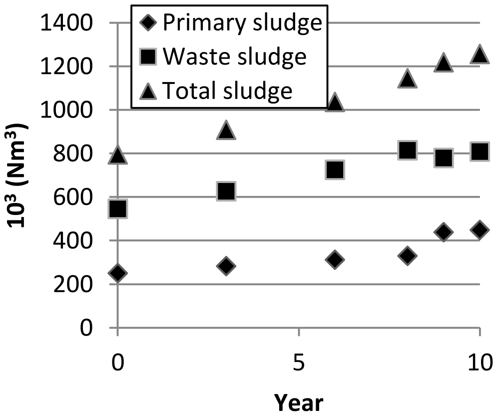

*Figure 7. Increase in biogas production ($Nm^3$) based on primary sludge, waste sludge and total sludge over the years.*

## Conclusions

It is highly possible to create a wastewater treatment model for the main COD removal parts in the water line for Sjölunda WWTP. The calibrated results for the primary clarifiers overflow and the concentrations for TKN and COD in the secondary clarifiers overflow were considered good result. The results for the primary and waste sludge were difficult to evaluate due to missing or poor quality data. The greatest calibration complication was to keep high concentrations of TSS and $PO^{3-}_4$-P in the activated sludge and in the secondary clarifiers overflow. The increased load simulation indicates that Sjölunda WWTP can be operated for an additional nine years without deteriorating effluent quality. The total yearly biogas production increased from 800,000 $Nm^3/y$ to 1,220,000 $Nm^3/y$.

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