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Performance Indicator Analysis as a Basis for Process Optimization and Energy Efficiency in Municipal Wastewater Treatment Plants

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ABSTRACT

Performance Indicator Analysis as a Basis for Process Optimization and Energy Efficiency in Municipal Wastewater Treatment Plants

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The aim of this Master Thesis was to calculate and visualize performance indicators for the secondary treatment step in municipal wastewater treatment plants. Performance indicators are a valuable tool to communicate process conditions and energy efficiency to both management teams and operators of the plant. Performance indicators should be as few as possible, clearly defined, easily measurable, verifiable and easy to understand.

Performance indicators have been calculated based on data from existing wastewater treatment plants and qualified estimates when insufficient data was available. These performance indicators were then evaluated and narrowed down to a few key indicators, related to process performance and energy usage. Performance indicators for the secondary treatment step were calculated for four municipal wastewater treatment plants operating three different process configurations of the activated-sludge technology; Sternö wastewater treatment plant (Sweden) using a conventional activated-sludge technology, Ronneby wastewater treatment plant (Sweden) using a ring-shaped activated-sludge technology called oxidation ditch, Headingley wastewater treatment plant (Canada) and Kimmswick wastewater treatment plant (USA), both of which use sequencing batch reactor (SBR) activated-sludge technology. Literature reviews, interviews and process data formed the basis of the Master Thesis. The secondary treatment was studied in all the wastewater treatment plants. Performance indicators were calculated, to the extent it was possible, for this step in the treatment process.

The results showed that all the wastewater treatments plants, studied in this master thesis, were well below regulatory requirements of effluent concentrations of organic matter and nutrients. This gap between legislated requirements and performance provides an opportunity for improving energy efficiency and maintaining discharge requirements. The removal of organic matter was consistently high at all wastewater treatment plants studied but the removal of nitrogen was slightly lower during the colder months. The results further showed that the discharge of nitrogen from wastewater treatment plants is the largest stress on the recipient.

Data regarding the energy usage was almost nonexistent and energy for aeration was therefore calculated when possible since it is aeration that accounts for the largest fraction of energy usage in a wastewater treatment plant. Sternö wastewater-treatment plant proved to be more energy efficient than Rustorp wastewater treatment plant.

Keywords: Performance indicators, wastewater treatment, process performance, energy efficiency, secondary treatment

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REFERAT

Nyckeltalsanalys som underlag för processoptimering och energieffektivisering i kommunala avloppsvattenreningsverk

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Syftet med examensarbetet har varit att beräkna och visualisera nyckeltal för det biologiska reningssteget i kommunala avloppsvattenreningsverk. Nyckeltal är ett enkelt sätt att kommunicera processförhållanden och energieffektivitet med såväl ledningsgrupper som de som är ansvariga för driften på verken. Nyckeltalen skall vara så få som möjligt, tydligt definierade, enkla att mäta, verifierbara och enkla att förstå.

De nyckeltal som varit möjliga att räkna fram genom mätningar samt kvalificerade uppskattningar har utvärderats och några få nyckeltal, relaterade till processprestanda och energianvändning, föreslås.

Fyra avloppsvattenreningsverk med tre olika processkonfigurationer av aktiv-slam teknik studerades. Sternö avloppsvattenreningsverk (Sverige) som använder konventionell aktiv-slam teknik, Ronneby avloppsvattenreningsverk (Sverige) som använder en ringformad aktiv-slam teknik kallad oxidation ditch, Headingley avloppsvattenreningsverk (Kanada) samt Kimmswick avloppsvattenreningsverk (USA) som båda använder satsvis biologisk rening (SBR). Litteraturstudier, intervjuer samt mätdata var underlag till studien. Det biologiska reningssteget studerades på samtliga avloppsreningsverk och nyckeltal räknades, i den utsträckning det var möjligt, på detta steg i reningsprocessen.

Resultaten visade att samtliga verk höll sig väl under lagkrav på utsläppta koncentrationer av organiskt material och näringsämnen. Detta ger en möjlighet för energieffektivisering och ändå hålla utsläppskrav. Reningen av organiskt material var konsistent god på samtliga verk men reningen av kväve var något sämre under de kallare månaderna. Utsläppen av kväve från verken är den största belastningen hos recipienten.

Mätningar av energianvändning var nästintill obefintliga och energianvändning för luftning räknades fram då det var möjligt, då det är luftningen som står för huvuddelen av energianvändningen på ett avloppsvattenreningsverk. Sternö avloppsvattenreningsverk visade sig vara lite energieffektivare än Rustorp avloppsvattenreningsverk.

Nyckelord: Nyckeltal, avloppsvattenrening, processprestanda, energieffektivisering, biologisk rening

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Preface

This master thesis is the last course in the Masters Programme in Environmental and Aquatic Engineering at Uppsala University. The idea for this thesis was founded by Lars Larsson at Xylem and was a collaboration project between Xylem and ÅF, and Magnus Hultell at ÅF has been my mentor. Bengt Carlsson at the IT institution at Uppsala University has been my subject examiner.

I would like to express my gratitude towards Magnus Hultell for his guidance and encouragement throughout the thesis. I would also like to thank Lars Larsson for his insight and help and also Åsa Nordenborg at Xylem for helping me understand the mechanics of pumps and diffusers.

An important help was the Forest Department at ÅF and I would especially like to thank Sara Stemme for her support in this thesis.

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This thesis was made possible by the information and interviews given to me by the process managers at the different WWTPs, I would like to pay my gratitude to them.

Last but not least I would like to thank my dear family and friends who supported and listened to me when I encountered difficulties in the process of this thesis; you were the lifeline that made me complete this thesis.

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Populärvetenskaplig sammanfattning

Nyckeltalsanalys som underlag för processoptimering och energieffektivisering i kommunala avloppsvattenreningsverk

Elin Wennerholm

Avloppsvattenreningsverk renar vatten från hushåll och industrier från organiskt material och närsalter som kväve och fosfor. Reningen är nödvändig för att inte vattendrag och hav ska övergödas av dessa näringsämnen.

Det finns olika sätt för att rena avloppsvatten och det vanligaste är att rena vattnet på biologisk väg, med så kallad aktiv slam teknik. Det innebär att mikroorganismer som finns i vattnet som ska renas använder näringsämnena när de växer. Om mikroorganismerna befinner sig i bassängen längre tid än vattnet hinner de omsätta de ämnen man vill rena vattnet från. Löst syre i vattnet är livsviktigt för dessa mikroorganismer och därmed är halten löst syre i vattnet väldigt viktigt för reningsgraden av organiskt material och kväve. Biologisk rening av näringsämnet fosfor kräver dessutom en zon utan löst syre men med syre bundet till kväve.

Olika avloppsreningsverk har olika sätt att utforma sina installationer för att få en så bra rening som möjligt. De tre varianterna som är dominerande för befintliga verk runt om i världen är konventionell aktiv slam, oxidation ditch och SBR. I konventionell aktiv slam teknik strömmar vattnet genom olika, luftade och oluftade, bassänger i en linje där vattnet renas. Oxidation ditch bygger på samma princip men vattnet cirkulerar runt i en oval eller hästskoformad bassäng istället för att strömma genom flera bassänger i linje. SBR tekniken har också luftade och oluftade zoner men vattnet befinner sig i en bassäng som vid olika tidpunkter blir luftad respektive oluftad.

Nyckeltal är ett verktyg för att kunna jämföra olika verk med varandra och även om det enskilda verket vill jämföra sina egna resultat från år till år. Kriterierna för ett bra nyckeltal är att de ska vara så få som möjligt, tydligt definierade, enkla att mäta, de ska gå att kontrollera och vara enkla att förstå.

Detta examensarbete utreder vilka nyckeltal, kopplade till reningseffektivitet och energieffektivitet, som är möjliga att räkna ut från de data som vanligtvis samlas in av verken. Examensarbetet fokuserar enbart på den biologiska reningen i verken och inte på de övriga stegen eftersom det är i den biologiska reningen den största andelen av organiskt material och näringsämnen renas och även det enskilda steg i reningsverket som använder störst andel energi.

Litteraturstudien gav underlag till en lång lista av möjliga nyckeltal och gav också insikt i vikten att veta exakt vilka antaganden och förenklingar som ligger bakom ett nyckeltal.

Data om processerna, rening samt energianvändning samlades in från fyra avloppsvattenreningsverk, två i Sverige, ett i Kanada och ett i USA. Alla de tre ovan nämnda reningsteknikerna var representerade.

Det visade sig vara mycket svårt att få tillgång till uttömmande information om reningen och speciellt svårt var det att få information om energianvändningen. Ofta mättes inte så många parametrar och mätningar på energianvändning var nästan obefintliga.

De olika avloppsvattenreningsverken hade olika lagkrav för vilka koncentrationer verket inte fick överskrida i utgående, renat vatten. Detta innebar att verken mätte olika parametrar olika noggrant. Mängd organiskt material mättes nästan alltid i de studerade verken och kväve mättes också relativt noggrant. Nyckeltal för dessa togs fram.

Utredningen visade att alla de studerade avloppsvattenreningsverken låg väl under de lagstadgade koncentrationerna i utgående vatten. Detta möjliggör satsningar på energibesparingar utan alltför stor risk att överskrida lagkraven.

Nyckeltal för energieffektivitet kunde med vissa antaganden och förenklingar räknas ut men det är viktigt att vara medveten om osäkerheten i de nyckeltalen och inte titta på de exakta siffrorna.

Abbreviations and acronyms

BOD	Biological oxygen demand
CAPEX	Capital expenditures (expenditures creating future benefits)
CBOD	Carbonaceous biological oxygen demand
COD	Chemical oxygen demand
DO	Dissolved oxygen
EMS	Environmental management system
ICEAS	Intermittent cycle extended aeration system
MLE	Modified Ludzack-Ettinger
OCP	Oxygen consumption potential
OPEX	Operating expenditures (expenditures for running a process)
Pe	Person equivalents
PI	Performance indicator
SBR	Sequencing batch reactor
SOTE	Standard oxygen transfer efficiency
SS	Suspended solids
TKN	Total Kjeldahl nitrogen
TOC	Total organic carbon
VFA	Volatile fatty acids
WWTP	Wastewater treatment plant

TABLE OF CONTENTS

1 INTRODUCTION

Society and our modern lifestyle is placing nature under enormous stress and water scarcity is forcing many regions to treat and reuse water to the greatest possible extent. When wastewater containing organic matter and nutrients reaches streams and oceans, numerous biological and chemical processes start, which leads to depletion of oxygen in the water. If too much of these substances are discharged it will eventually lead to an oxygen-free environment which is fatal for aquatic organisms. In order to prevent this scenario, there are wastewater treatment plants (WWTP) where these oxygen-consuming processes can take place instead of occurring in streams and oceans. Oxygen is added artificially in the plant and depending on process configuration and operation the water can be purified from different substances (Tchobanoglous, et al., 2003). These treatment processes are, however, expensive in terms of energy and consequently money and it is of great general interest to evaluate the efficiency of the treatment processes (Lingsten & Lundqvist, 2008). One instrument for this is performance indicators (PIs). PIs are one way to easily see dividend versus investment. PIs are a valuable tool for monitoring performance and costs for the individual WWTP. With a standardisation of PIs it is possible to perform benchmarking between WWTPs (Balmér, 2010).

Originally wastewater treatment plants were built in the 1970’s to remove sedimentable substances, organic matter and nutrients. The aim of the removal is to reduce the impact on the recipient. As a step towards environmental and economic efficiency, performance indicators are a powerful tool. The biological treatment in a WWTP uses a lot of energy, due to aeration in the tanks that account for the larger portion of the energy usage, and is therefore of great interest in this Master Thesis. Xylem, a global water technology provider, planted the seed to this thesis when wanting to expand their holistic knowledge of wastewater treatment. This Master Thesis and in extension, the performance indicator analysis, is an important stepping stone to meet their objective. ÅF and Xylem have cooperated to provide the foundation for this thesis.

1.1 OBJECTIVE

The scope of this master thesis is to calculate and visualize performance indicators (PIs) for better communication and understanding of process conditions. The aim is to concentrate information to a few, easily understandable, performance indicators that are easy to link to optimization and energy efficiency goals. Four WWTPs with three different process configurations of the activated-sludge technology; conventional activated-sludge, oxidation ditch and SBR, that together cover most of the installed facilities, will be studied. PIs will be suggested for each WWTP that will be used to evaluate the secondary treatment step for each plant and for comparison between WWTPs. If possible, this thesis will lead to a categorization of PIs that can be applied for any WWTP. A secondary objective for this study is to provide an evaluation of the performance and efficiency of the four different WWTPs covered in this thesis.

1.2 METHODS

A comprehensive literature study including the fundamentals of wastewater treatment (biological treatment in particular) and performance indicators was first conducted to provide a broad basis of information. The processes of wastewater treatment and what affects these processes were investigated. The literature study also covered the available information on existing studies and pilot projects regarding performance indicators in context to wastewater treatment. Information and data was scarce and pilot projects were often not detailed enough. It is also difficult to come by sufficient amounts of process data from many WWTPs. For these reasons the natural approach was by quantitative case studies. Four cases were studied in this Master Thesis. The data from the different WWTPs is only, at most, for two years due to lack of homogeneity (e.g. changes to the process were made or data samplings were absent).

Four wastewater treatment plants with different process configurations were selected; two in Sweden, one in the U.S. and one in Canada. The WWTPs in Sweden operated with conventional activated-sludge process and oxidation ditch process, which corresponds to 40 percent of all global installations (pers. comm. Larsson, 2012). The two WWTPs in the U.S. and Canada operate with a batch-technology called SBR. SBR technology corresponds to about 10 percent of all global installations. Together these process configurations cover the most common activated-sludge processes globally.

Several interviews were conducted with people in charge of the processes at the different WWTPs. The interviews led to a better understanding of each specific process, the different steps in the process, how they were operated and where measurements were performed. Measurement data was collected and processed. Where data was inadequate, qualified assumptions and approximations were made. Calculations were made through the chemical and mathematical formulas presented in this thesis. The PIs that were possible to calculate were presented graphically as charts and numbers followed by explanatory comments. In the discussion of the results the credibility of conclusions made are discussed, as well as the validity of the results outside of this master thesis.

1.3 DELIMITATIONS

This Master Thesis focuses on the secondary treatment in WWTPs. The critical substances that are treated in WWTPs are organic matter, nitrogen and phosphorus. Organic matter is removed in the secondary treatment step and often this step also includes nitrogen removal. The secondary treatment is the most energy demanding step in a WWTP which makes it an excellent point to start when energy efficiency measures are to be taken. Hence, the secondary treatment step is a good starting point for process optimization. The report covers different process solutions for secondary treatment to make evaluation possible for most WWTPs worldwide. To cover all treatment steps is beyond the scope of this master thesis.

1.4 OVERVIEW OF THE REPORT

Chapter 2 offers a background on wastewater treatment, with special focus on the secondary treatment step. The different biological processes and what is removed in this step are covered. Further, the mechanical processes needed in this step are explained as well as the different configurations of activated sludge processes that this thesis deals with.

Chapter 3 gives an introduction to performance indicators and summarizes what previously has been done regarding PIs and wastewater treatment. The chapter explains what should be considered when using performance indicators as a tool for understanding a WWTP.

Chapter 4 gives an overview to the four different WWTPs that are studied in this master thesis, how the plants are operated, what is measured and legislated requirements from authorities. Chapter 4 also includes an explanation of which PIs were chosen and why.

Chapter 5 presents calculated PIs for the different plants and also the analysis of the results are presented in this chapter. It also includes sensitivity analysis and the Excel modeling that has been performed.

Chapter 6 discusses the possibility of choosing other PIs for future studies and what errors are embedded in the resulting PIs, as well as which variables have affected the result and, if possible, to what extent.

Chapter 7 states what conclusions and experiences to be drawn in this thesis work, i.e. a summary of the analysis in chapter 5.

2 WASTEWATER TREATMENT

This chapter aims to explain the process of wastewater treatment. First, the general outline of wastewater treatment is explained and then what steps are included in the biological wastewater treatment, which is of interest in this master thesis. To understand the biological treatment, it is important to understand the microorganisms that ‘biologically’ purify the wastewater. The chapter continues with what the wastewater contains and what pollutants are removed in the biological treatment. The most common process solutions for the biological wastewater treatment are covered, which are also the same process configurations that are covered in the case study. Since the biological wastewater treatment uses lot of energy there is a section explaining the mechanical operation of this treatment step and what affects energy efficiency. Lastly, the different operational parameters of a WWTP are explained, since these are parameters that the process operators are able to alter.

2.1 GENERAL INTRODUCTION

Wastewater reaching the treatment plant generally consists of domestic wastewater, industrial wastewater, infiltration/inflow and stormwater. Domestic wastewater is discharged from residences and commercial, institutional or similar facilities and is often rich in nutrients. Wastewater from industries is, on the contrary, often not rich in nutrients. Infiltration is water entering the collection system through leaking joints, cracks or porous walls and inflow is stormwater that enters the collection system from storm drain connections (e.g. roof leaders and basement drains). Stormwater is runoff resulting from rainfall and snowmelt.

2.2 WASTEWATER TREATMENT PLANTS IN GENERAL

The objective of a WWTP is to produce a disposable effluent that will not harm the environment and thus, prevent pollution. The process consists of several steps, called preliminary, primary, secondary and tertiary treatment, see Figure 1.

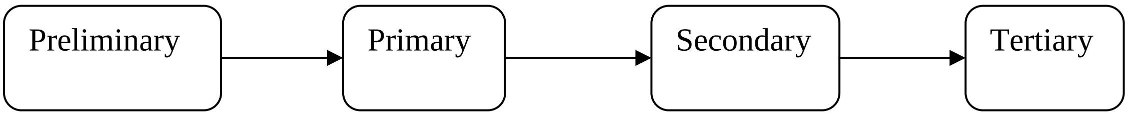

Figure 1. *Conceptual scheme of the different steps in wastewater treatment.*

The preliminary treatment removes wastewater constituents like rags, sticks and grease that will cause operational or maintenance problems. The influent water passes through a bar screen that removes all large objects. These objects are either disposed in a landfill or incinerated. The preliminary treatment often includes a sand or grit chamber. Adjustments are made so that the velocity of the water allows for grit and stones etc. to settle. There are sometimes basins for flow equalisation for flow peaks. In larger plants fat and grease are removed by skimmers in a small tank.

In the primary step, suspended solids (floating and settleable materials) are removed by sedimentation. Sewage flows through basins, called primary clarifiers, where sludge settles and grease and oil rise to the surface and are skimmed off.

The secondary treatment, which is of interest in this master thesis, is the biological treatment. This step removes biodegradable organic matter and suspended solids from the wastewater. Removal of nutrients like nitrogen and phosphorus may be (often but not always) included in this step. Some nutrients are always removed even if the plant does not actively try to remove them.

In the tertiary treatment, residual suspended solids are removed. Normally, disinfection is included in this step, and nutrient removal is often included. The purpose of tertiary treatment is to raise effluent quality before it is discharged to the recipient. Sand filters remove much of the residual suspended solids. Activated carbon may be used to remove toxins. Nutrients, like phosphorus, may be treated in this step by precipitation.

2.3 BIOLOGICAL WASTEWATER TREATMENT IN PARTICULAR

Removal of organic matter and nutrients in the secondary step is a consequence of respiration and growth of various microorganisms, held in suspension in a basin. It is therefore interesting to know more about these organisms and what affects their efficiency to understand the processes in the secondary treatment step.

2.3.1 Microorganisms in WWTP

The secondary treatment in WWTP is biological treatment. This is carried out using sludge of active microorganisms (bacteria, fungi, protozoa and algae) that transform different compounds found in wastewater. The process configuration for treating wastewater where microorganisms are used for removal of pollutants is called activated-sludge. Normally, bacteria are the dominant type of microorganism in secondary treatment. Bacteria are single-celled prokaryotic organisms with a typical cell composition of 50 percent carbon, 20 percent oxygen, 14 percent nitrogen, 8 percent hydrogen and 3 percent phosphorus (Tchobangoglous & Burton, 1991). Municipal wastewater normally contains enough of these substances to be a good substrate. Wastewater from industries are generally more unbalanced and the amount of nitrate and phosphorus relative to organic matter are often small (Balmér & Hellström, 2011).

Most bacteria are heterotrophic, which means that they need an organic substance for the formation of cell tissue. They extract energy by an aerobic process where the organic matter is oxidized to carbon dioxide, water and oxygen is reduced. In the absence of oxygen there are autotrophic bacteria that can perform an anaerobic process where part of the organic matter is oxidized to carbon dioxide and water, while something other than oxygen, normally ammonia or sulphides, is reduced. Some bacteria are facultative, which means that they are able to survive in both aerobic and anaerobic environments.

2.3.2 Factors that affects the efficiency of microorganisms

There are several factors that affect the growth of microorganisms. Most bacteria prefer a pH value around 7 and a small deviation slows the growth process and a large deviation could kill the population. Municipal wastewater has in general a pH value near 7 and a high buffer capacity. The pH value can differ in systems with nitrogen removal.

The biochemical reactions of cell growth increase with temperature. At high temperatures cell growth decreases due to the destruction of important enzymes in the cell, thus there is a curve for growth rate. Different microorganisms have different curves and therefore different temperature optimum. Microorganisms with an optimum around 15-20°C are called cryophilic, those with an optimum around 30-35°C mesophilic and those with an optimum around 50-55°C are called thermophilic (Balmér, et al., 2010). Under normal conditions in an activated-sludge process temperature is not a limiting factor but biological nitrate removal processes needs special consideration because the temperature affects the growth rate of nitrifying bacteria. Low temperatures slow down the growth rate and therefore the activated-sludge process takes longer to nitrify incoming nitrogen.

The concentration of substrate is also of importance; at high concentrations of substrate microorganisms have a high growth rate, and thus a high decomposition rate of substrate.

2.3.3 Treatment of organic matter

The removal of organic matter is important, because of the oxygen consuming reactions that pollute the recipient (Tchobangoglous & Burton, 1991). Removal of organic matter is the primary target for wastewater treatment. Equation (1) shows oxidation of organic matter and synthesis of cell tissue and equation (2) shows the endogenous respiration.

$$COHNS + O_2 + nutrients \xrightarrow{bacteria} CO_2 + NH_3 + C_5H_7NO_2 + other\ end\ products \quad (1)$$

$$C_5H_7NO_2 + 5O_2 \xrightarrow{bacteria} 5CO_2 + 2H_2O + NH_3 + energy \quad (2)$$

where,

COHNS = organic matter in wastewater (carbon, oxygen, hydrogen, nitrogen and sulphur)

$C_5H_7NO_2$ = cell tissue

At high pH values, over 8.0, nitrogen is mostly in the ammonia form (NH_3) but when the wastewater is acidic or neutral (municipal wastewater is neutral), the majority of nitrogen is in the ammonium form (NH_4^+), further explained in section 2.3.4.

The removal of organic matter is usually measured as BOD (Biological Oxygen Demand), TOC (Total Organic Carbon) or COD (Chemical Oxygen Demand).

The most widely used is BOD and it is linked to the measurement of dissolved oxygen used by microorganisms in the biochemical oxidation of organic matter. BOD is calculated from measuring the dissolved oxygen in samples before and after incubation.

The dissolved oxygen is lower after incubation due to oxidation of organic matter in the sample. The difference in the amount of dissolved oxygen is then divided with the volumetric fraction of sample used. The time of incubation is either a 5-day period (BOD_5) or a 7-day period (BOD_7) at 20 °C. For municipal wastewater the relationship between the two is according to Gillberg, et al. (2003);

$$BOD_7 = 1.15 \cdot BOD_5 \qquad (3)$$

A hazard with the BOD test is nitrification. Nitrifying bacteria grow slowly but they reach significant numbers to exert a measurable oxygen demand, due to oxidation of carbonaceous material, within 6 to 10 days. Since nitrification is not included in biochemical oxygen demand the BOD test will show a lesser value than if nitrification did not occur, hence indicating that the treatment process is not performing well when in fact it is. To overcome the effects of nitrification, chemicals can be used to suppress the nitrification reaction. The resulting BOD is known as carbonaceous biochemical oxygen demand, CBOD, and is sometimes the measurement required for regulatory permits. CBOD should only be measured on treated effluent, which contains small amounts of organic carbon, because large errors will occur when CBOD is measured on wastewater containing significant amounts of organic matter like untreated influent wastewater.

TOC is also a measurement of organic matter and is very applicable when concentrations of organic matter are small. The unit for BOD and COD is mg O_2/l whereas for TOC it is mg C/l. The organic carbon is oxidized to carbon dioxide in the presence of a catalyst and then measured by infrared analyser. An advantage is that the test can be performed very rapidly, in only 5 to 10 minutes (Tchobanoglous, et al., 2003). A disadvantage is that there are certain resistant organic compounds that may not be oxidized, thus causing the test to show less than the amount in the sample.

COD test includes using a strong chemical oxidizing agent in an acidic medium and measuring the oxygen equivalent of the organic matter that can be oxidized. The COD can be determined in just two hours (Tchobangoglous & Burton, 1991). An advantage is that the test can be used to measure the organic matter in both industrial and municipal wastes that contain compounds that are toxic to biological life. In general, the COD test is higher than the BOD because more compounds can be oxidised chemically than biologically. Thus, the ratio between COD/BOD indicates the degree of biodegradability of wastewater. Matter that biodegrades relatively easily has low values, i.e. COD/BOD < 2 (Gillberg, et al., 2003) and a high value indicates that the organic matter will biodegrade slowly.

2.3.4 Treatment of nitrogen

Nitrogen is undesirable in wastewater effluent because of the environmental hazards. Free ammonia is toxic to fish and other aquatic organisms. It is also oxygen-consuming and depletes the dissolved oxygen in the receiving water. Nitrogen in all forms is a nutrient and therefore contributes to eutrophication.

The biological removal of nitrogen is a three-step process (US. EPA, 2008). First, organic carbon is converted to ammonium through hydrolysis and microbial activities according to equation (4), which is called ammonification. Then ammonia converts to nitrate, equation (5) and (6), under aerobic conditions with oxygen, the process is called nitrification. In equation (7) the nitrate then reacts with organic carbon to form nitrogen gas. This process is called denitrification and occurs under anoxic conditions, which means that there is no soluble oxygen present.

$$Organic\ nitrogen \xrightarrow{hydrolysis,bacteria} NH_4^+ \tag{4}$$

$$NH_4^+ + \frac{3}{2}O_2 + 2HCO_3^- \xrightarrow{bacteria} NO_2^- + 2H_2CO_3 + H_2O \tag{5}$$

$$NO_2^- + \frac{1}{2}O_2 \xrightarrow{bacteria} NO_3^- \tag{6}$$

$$NO_3^- + organic\ carbon \xrightarrow{bacteria} N_2(g) + CO_2(g) + H_2O + OH^- \tag{7}$$

where,

NH_4^+	= ammonium
HCO_3^-	= bicarbonate
H_2CO_3	= carbonic acid
NO_2^-	= nitrite
NO_3^-	= nitrate

Equation (4) – (7) gives following theoretical oxygen demand for oxidation of ammonium:

$$\frac{kg\ O_2}{kgNH_4 - N} = \frac{M(2O_2)}{M(N)} = \frac{4 \times M(O)}{M(N)} = \frac{4 \times 16.00}{14.01} = 4.57 \tag{8}$$

Thus, 4.57 kg O_2/ kg N is required to oxidize ammonium.

When wastewater enters the WWTP, about 60 percent of the nitrogen is in organic form and 40 percent is in the ammonium form (Sedlak, 1991), i.e. equation (4) has already occurred. A build-up of nitrite is seldom seen, thus it is the ammonia to nitrate conversion rate that controls the rate of the overall reaction (Sedlak, 1991). The carbonic acid derived from equation (5) lowers pH and if pH goes below 7 (municipal wastewater often have a pH value of 7) the activity of nitrifying bacteria decrease but the presence of denitrification, see equation (7), counteracts this reduction of pH. Optimal nitrification rates occur at pH values between 7.5 and 8.0 (Tchobanoglous, et al., 2003). The effect on pH depends on the alkalinity of the wastewater.

There is equilibrium, see equation (9), between the species of ammonia depending on pH value in the water. At pH below 9, a larger percentage is in NH_4^+ form.

$$NH_4^+ \leftrightarrow NH_3 + H^+ \tag{9}$$

Total nitrogen (Tot-N or TN) is the sum of organic nitrogen, ammonia ($NH4^+/NH_3$) nitrogen, nitrite and nitrate. Another parameter is total Kjeldahl nitrogen (TKN), which is the total of organic nitrogen and ammonia nitrogen. Organic nitrogen is determined by the Kjeldahl method. The outline of the method is boiling of an aqueous solution to drive off ammonia and then digestion, converting the organic nitrogen to ammonia. Total Kjeldahl nitrogen is determined in the same manner but with the exception of driving off ammonia before digestion (Tchobangoglous & Burton, 1991). The average nitrogen concentration reaching the WWTP is 16 g/ (pe day) (Sedlak, 1991). Nitrifying bacteria fixate carbon dioxide which is highly energy demanding, this means they grow slowly. The generation time of nitrifying bacteria varies from eight hours to several days (Carlsson & Hallin, 2010), this limits the process and requires quite long solids retention time (SRT) (explained in section 1.4) to maintain nitrification.

About 10-30 percent of influent nitrogen accumulates in sludge due to the formation of cell tissue but the largest fraction will leave the system as harmless nitrogen gas (N_2) (Carlsson & Hallin, 2010)(nitrogen gas is a common substance in the atmosphere).

To reach high efficiency of *nitrification,* the following are hence required (Balmér, et al., 2010);

- sufficiently long SRT in the basin for bacteria growth
- sufficiently high rate DO (preferably around 2 mg O_2/L)
- sufficiently high temperature

SRT and temperature is inversely proportional to each other, i.e. low temperatures require higher SRTs to maintain the same efficiency.

To reach high efficiency of *denitrification,* the following are hence required (Balmér, et al., 2010);

- high concentrations of nitrate
- absence of oxygen, thus anoxic environment
- good quality and amount of carbon source
- sufficiently high temperature

The organic carbon source, see equation (7), can either be the wastewater or an external carbon source like methanol. Methanol is a more accessible carbon source than the organic matter in wastewater and consequently gives a higher rate of denitrification.

2.3.5 Treatment of phosphorus

Phosphorus is a nutrient and contributes to eutrophication, which makes it harmful for the recipient. The major sources of phosphorus are detergents and human waste (Gillberg, et al., 2003). It is also a finite resource and so it is desirable to remove and return to agriculture.

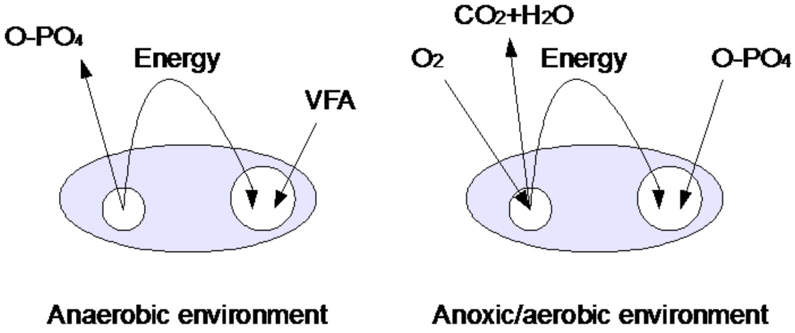

Figure 2. *The process in which bacteria releases orthophosphate to get energy to bind VFA anaerobically and during metabolism in an anoxic/aerobic environment bind orthophosphate (modified from Carlsson & Hallin, 2010).*

Phosphorus is normally removed through precipitation but in order to reduce the use of chemicals, which is costly, and reduce sludge production, biological removal in the secondary treatment is an alternative. Special bacteria, called phosphate-accumulating organisms (PAO) (US. EPA, 2008), assimilates short volatile fatty acids (VFA) and stores them in the cell. To release energy needed for the uptake, orthophosphate (O-PO_4) is cleaved, thus increasing the phosphorus concentration in the water. This occurs in an anaerobic environment. When the organisms reach an aerobic or anoxic environment, metabolism i.e. oxidation of organic matter releases energy and enables binding of phosphate to the bacteria cells, as can be seen in Figure 2. Due to disposal of stored phosphorus with the waste sludge the net effect will be a reduction of dissolved phosphorus in the water. To have high removal rate of phosphorus a high concentration of VFA is required and an anaerobic environment, without oxygen or nitrate. Incoming wastewater contains some VFA and more septic wastewaters, e.g. from collection systems with minimal slopes in warm climates, will contain higher concentrations of VFA. The process favours a short solids retention time, which could be contradictory to the longer solids retention time required to perform nitrogen removal.

2.3.6 Process summary

A compilation of essential flows are shown in Figure 3, the dashed line surrounds the different processes possible in the secondary treatment. The arrows into the secondary treatment represent the compounds that are needed for that process to function and the arrows going out from the secondary treatment represent possible result products from each process.

The anaerobic zone releases O-PO_4 through the assimilation of VFA into the water. NO_3 and organic carbon (Org-C) reacts through denitrification to form N_2 gas as emissions to the atmosphere. In the aerobic zone, O-PO_4 enters in soluble form and binds to bacteria cells, hence phosphorus exits the system through the waste sludge. To accomplish nitrification, NH_4^+ is necessary and NO_3^- is the end product but at incomplete nitrification, NO_2^- may also exist in the effluent. Organic carbon (Org-C) oxidizes in the aerobic zone to inter alia form NH_3. NH_3 then reacts further, due to a pH value near neutral, to form NH_4^+. The result is an increase of NH_4^+ comparing with the influent concentration. The formed NH_4^+ is then converted in the nitrification process.

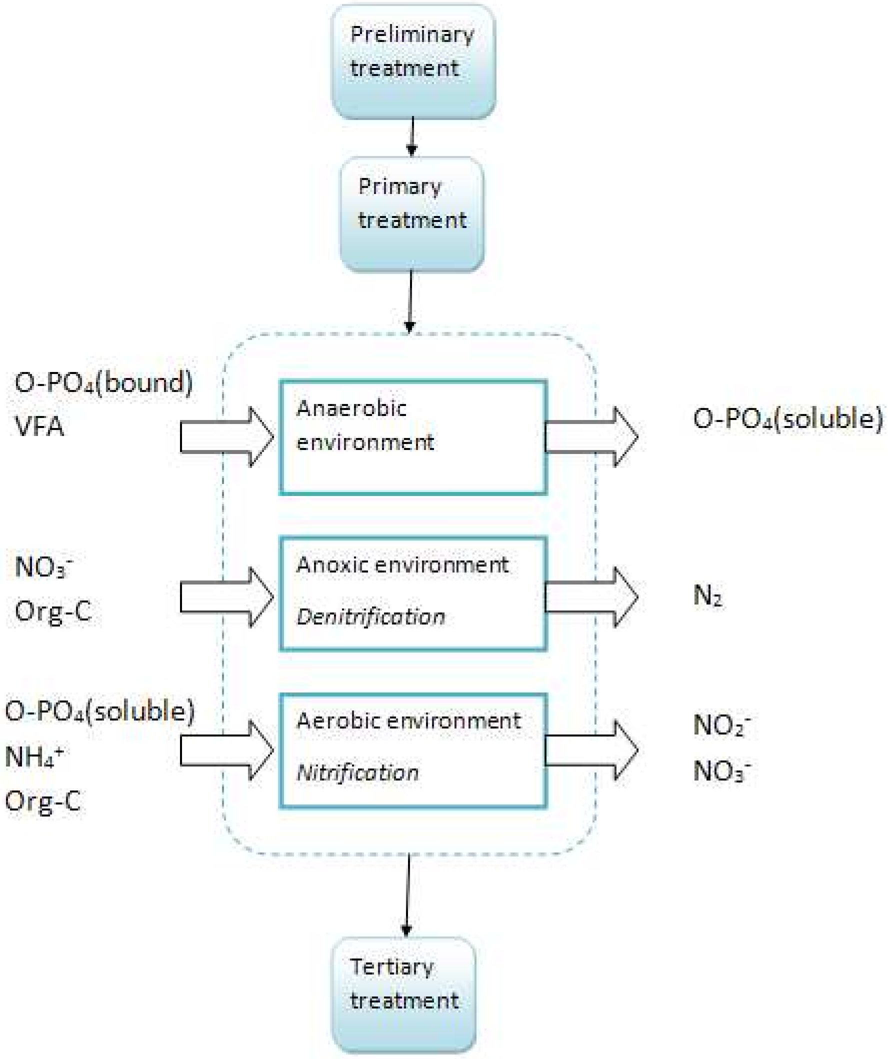

Figure 3. *Flowchart of influent and effluent parameters in different zones in the secondary treatment step.*

2.3.6 Solids retention time

The most critical parameter for the activated-sludge design is solids retention time (SRT) since it affects the treatment process performance, aeration tank volume, sludge production and oxygen requirements.

There are several definitions of SRT or sludge age as it also is called. SRT is measured as total or aerated. Total SRT is the average time (in days) a sludge particle is in the activated-sludge basins (both aerated and non-aerated) before it is removed as excess sludge. Aerated SRT is the time the particle remains in the aerated compartment. The definition of SRT shows in equation (10) (Balmér, et al., 2010).

$$SRT(d) = \frac{V \cdot SS}{Q_w \cdot SS_w + Q_e \cdot SS_e} \qquad (10)$$

where,

V = total or aerated volume [m^3]
SS = mean suspended solids (total or aerated) [kg m^{-3}]
Q_w = flow rate of waste sludge [m^3 d^{-1}]
SS_w = suspended solids in excess sludge [kg m^{-3}]
Q_e = flow rate of effluent from sedimentation [m^3 d^{-1}]
SS_e = suspended solids in treated effluent [kg m^{-3}]

Suspended solids (SS) is a measure including organic matter, non-degradable matter (e.g. fine sand) and chemical flocks.

In an activated-sludge process, the SRT must be long enough to maintain nitrification for nitrogen removal but not too long to inhibit biological phosphorus removal if such strategies are used. The optimum SRT depends on several factors, like wastewater temperature, dissolved oxygen concentration, pH, alkalinity, organic load, variations in hydraulic flow and inhibition of chemicals (US. EPA, 2008). For example, the growth of the bacteria is temperature-dependent and hence low water temperature requires longer SRT to maintain the same efficiency. Typical minimum SRT ranges for BOD removal is 1-2 days, for complete nitrification 3-18 days and for biological phosphorus removal 2-4 days (Tchobanoglous, et al., 2003).

2.4 THE ACTIVATED-SLUDGE PROCESS

The activated-sludge process is the most common way to remove organic matter and nutrients from wastewater and it is the three main configurations of this process (that together cover most of the installed base of wastewater treatment), which is reviewed in this master thesis. The case studies are based on these three main configurations.

The principle of the activated-sludge process is that microorganisms (activated-sludge), particularly bacteria, use organic matter for the formation of cell tissue thus removing organic matter from the wastewater. The microorganisms originate from the sewer mains (Carlsson & Hallin, 2010). A prerequisite for microorganisms to do this is soluble oxygen. The key is to keep the retention time for the sludge longer than the retention time of the water in the WWTP. This is achieved through recycling a part of the sludge (microorganisms) from the system, see Figure 4. Aeration is needed to add soluble oxygen to the process but it also serves as a mixer to keep the sludge in suspension. The sludge also adsorbs suspended colloidal particles that otherwise are unable to settle. In an activated-sludge process for treatment of organic matter, about 30-50 percent is oxidised, 40-45 percent is used for formation of cell tissue and discarded with excess sludge and 10-25 percent is discharged with the effluent (Balmér, et al., 2010).

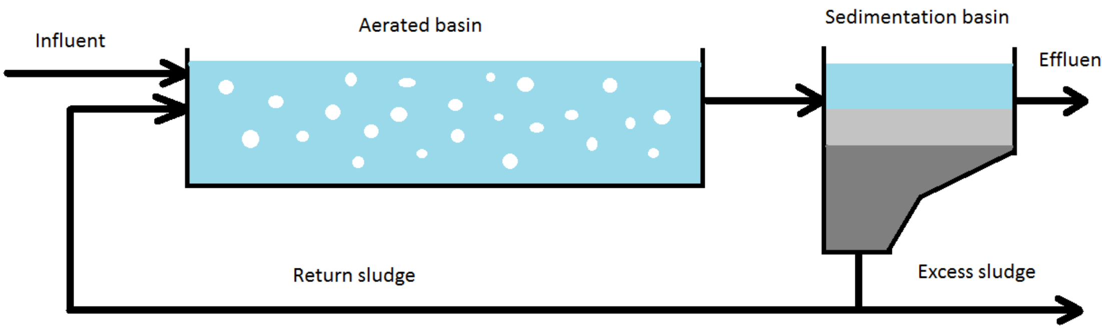

***Figure 4**. Basic activated-sludge system (modified from Carlsson & Hallin, 2010).*

The sludge consists of different types of microorganisms that coalesce, a process called flocculation. It is important that the sludge has the right mixture of microorganisms to settle properly (Carlsson & Hallin, 2010). A good sedimentation is critical for a functioning activated-sludge process. The transfer efficiency of oxygen from gas to liquid is relatively low, which means that only a small amount of the oxygen may dissolve in the tank to be used by microorganisms to oxidize organic matter. If dissolved oxygen (DO) is too low it limits the growth of microorganisms and filamentous organisms may predominate, which leads to poorer sedimentation properties. In general, DO concentrations should be maintained at 1.5-2 mg/l (Tchobanoglous, et al., 2003) and concentrations above 4 mg/l does not improve operations significantly but increase costs.

2.4.1 Biological nitrogen removal in the activated-sludge process

The activated-sludge process may be modified to also include treatment of nitrogen. There are two main process solutions; pre denitrification process and post denitrification process.

In *post denitrification processes* an anoxic compartment is placed after the aerobic compartment. In the aerobic compartment ammonium oxidises to nitrate and thereafter converted to nitrogen gas in the anoxic compartment. This solution requires an external carbon source, usually methanol, added to the anoxic compartments. This solution is preferable if the influent contains low concentrations of COD relative nitrogen and it is possible to achieve 100 percent nitrogen removal (Carlsson & Hallin, 2010).

A *pre denitrification process*, see Figure 5, has the anoxic compartment before the aerobic compartment. This solution often includes recirculation of water with high concentrations of nitrate from the aerated compartment to the anoxic compartment. The advantage of this solution is that it does not require an external carbon source. A high concentration of organic matter is required for effective denitrification. The degree of nitrogen removal is usually between 50-80 percentages.

The activated-sludge process may be further altered, in some cases as to include biological phosphorus removal. The addition of an anaerobic compartment, preferably first in line, enables removal of phosphorus. To prevent nitrate to enter the anaerobic compartment, the return sludge may be led to the anoxic compartment and recirculation of water from the aerobic to the anoxic compartment.

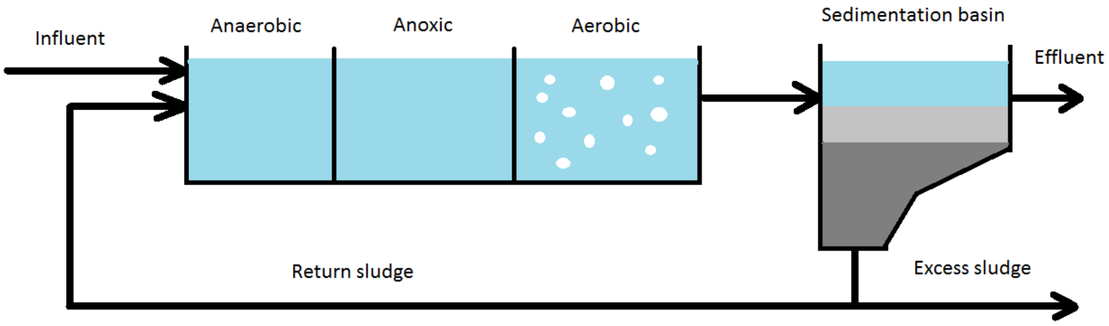

Figure 5. *Pre denitrification process, which is recognized by the anoxic compartment preceding the aerobic compartment, this solution often has recirculation from the aerobic to the anoxic zone. Biological phosphorus removal is enabled by an anaerobic compartment (modified from Carlsson & Hallin, 2010).*

2.4.2 Oxidation ditch

An oxidation ditch is a modified activated-sludge biological treatment process that has complete mix systems. A typical configuration of the process consists of a single- or multichannel in the shape of a ring, oval (Figure 6) or horseshoe-shaped basin. Oxidation ditches are often called "racetrack type" reactors. Preliminary treatment, such as grit removal, normally exists but primary treatment is not typical in this design (EPA, 2000). Aerators mounted horizontally or vertically are needed for aeration in the ditch and also provide circulation in the reactor. Modern design of oxidation ditch separates the aeration and the mixing by using fine bubble diffused aeration and submersible mixers in combination for better oxygen transfer. The velocity of the mixed liquor must be at least 0.3 m/s to prevent settling (Balmér, et al., 2010).

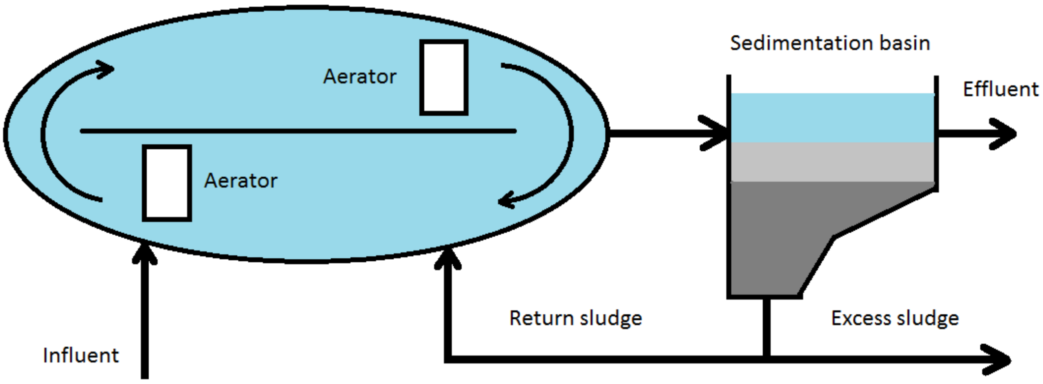

Figure 6. *Oxidation ditch, an alternative configuration of the activated-sludge process (modified from EPA, 2000).*

This process solution utilizes long SRT to remove biodegradable organics and if design SRT is selected for nitrification, a high degree of nitrification will occur. Modification to the process enables partial denitrification, one of the most common called Modified Ludzack-Ettinger (MLE) (EPA, 2000). High levels of denitrification are achieved with an anoxic tank added upstream of the ditch along with mixed liquor recirculation from the aerobic zone to the tank. Operation may differ but normally the process is reversed. When mixed liquor flows into the second reactor (which operates under aerobic conditions), the process reverse and the second reactor begins to operate under anoxic conditions.

Another process configuration for achieving denitrification in oxidation ditches is to implement on-off operation of the aeration system (Moore, 2006). This means that the aerators are turned off and the mixers are turned on to maintain the channel flow and prevent biomass from settling. The reactor operates under anoxic conditions during the off period and a probe is used to determine when to start aeration.

2.4.3 SBR

Another form of activated-sludge treatment is a fill-and-draw system, called sequencing batch reactor (SBR). The unit processes in SBR is the same as in conventional activated-sludge systems except for one important difference. As can be seen in Figure 7, in the SBR system, the operation processes are carried out sequentially in the same tank. SBR systems are uniquely suited for low or intermittent flow conditions (EPA, 1999). Improvements in aeration devices and control systems enable SBRs to successfully compete with conventional activated-sludge systems. SBRs have an advantage in terms of footprint (i.e. the area required for the plant) and capital investment cost over a conventional activated-sludge process.

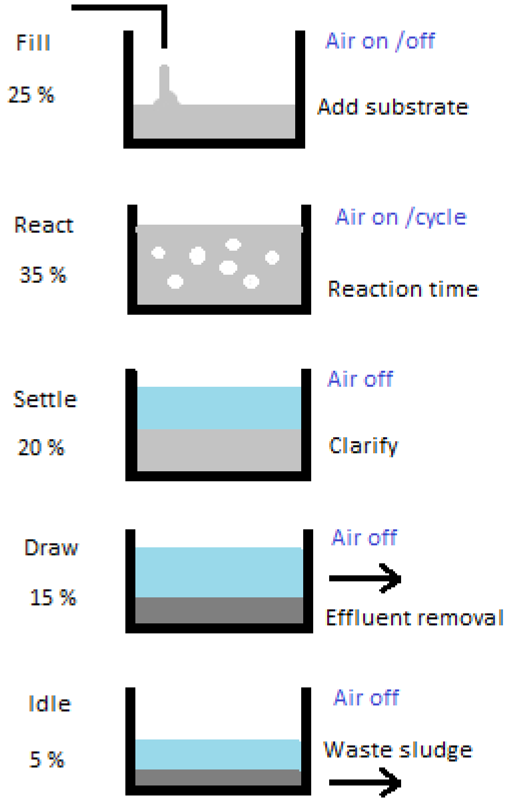

Figure 7. *The different stages in a SBR process, showing the same basin at different times. The left hand side shows how large percentage of the total cycle the different stages occupy (modified from Tchobangoglous & Burton, 1991).*

There are five steps in an SBR process, first the fill (1) where the tank is filled with influent. In reaction (2) the tank is aerated and this is the step that requires most percentage of the time in the cycle. For the process to include nitrogen removal, the conditions include both aerobic and anoxic time (US. EPA, 2008). In the settle phase (3) biomass settles to the bottom and in the draw phase (4), effluent is removed. The last step is idle (5), where waste sludge is removed, thus there is no need for a return activated-sludge system. In SBR systems time is the parameter that changes, rather than space in the conventional process design. A unique feature of SBR is that there is no need for a return activated-sludge system since both aeration and settling occur in the same tank. A modified version of the SBR called the Intermittent Cycle Extended Aeration System (ICEAS) that allows influent wastewater to flow into the reactor tank on a continuous basis. Since it allows for a continuous flow it has only three stages; (1) react, (2) settle and (3) decant (draw). Design configurations are very similar to conventional SBR but in ICEAS a baffle wall may be used to buffer the continuous inflow.

2.5 ENERGY USAGE IN WWTP

Since the secondary treatment uses a lot of energy it is of great importance to map. There are mainly two aspects that affect the energy usage in WWTPs, namely which control strategy is in use and what equipment is used.

2.5.1 Different control strategies that affects the secondary treatment

To be able to adapt the usage of blowers in the WWTP, which generate the air pumped into the secondary treatment, control strategies are often in place. The control strategy of a WWTP can be at different ambition levels. It can be summarized into three levels (Olsson, 2008);

1. keeping the processes and the machinery going
2. ensure that effluent water is of sufficient quality
3. maximize efficiency in operation and minimize the costs

The simplest form of control is called open loop (Olsson, 2008), which means that timers are used for switching the blowers in on/off mode. There is no measurement of DO concentration in the reactor thus the process uses more energy than is needed. The lack of measurement entails a risk for deficient aeration at certain times of the day.

For better control, oxygen measurement devices are used for so called on/off control. Suppose you want to keep the DO concentration in the reactor at 3 mg/l. If the oxygen sensor measure a too low DO concentration blowers will be activated and if the concentration is too high the blower will be turned off. This method causes wear on the blowers but can be avoided with speed control on the machinery, the aeration is constant but with different airflow. A more advanced form of control strategy is achieved with several oxygen sensors and pressure control through different degree of valve openings. The control strategies can be further elaborated with ammonium sensors and different controlling each section of the reactor differently thus creating a more ambitious control system.

A common way of control is by the PID controller (proportional-integral-derivative controller), which is a control loop feedback controller (Carlsson & Hallin, 2010). The proportional part of the controller is an enhancer by having a setpoint that is proportional against the error. The integral part is used to minimize the remaining error and the derivative part is used to achieve the desired speed of the controller without having an unstable control strategy. These three part can be used separately or in combination. Just using the proportional and integral part (PI controller) is common when the control requirements are moderate.

2.5.2 Aeration

Measurements of energy need in the secondary treatment step are unusual but an estimate of the energy need for aeration is possible to calculate with some information about the plant and some approximations. A review of equations used in this thesis for calculating energy demand for aeration is found in Appendix A.

3 PERFORMANCE INDICATORS

This chapter gives a general introduction to performance indicators and also a summary of other PIs and benchmark studies globally. This chapter also addresses which PIs could be in question for this master thesis and why.

3.1 PERFORMANCE INDICATORS IN GENERAL

To easily evaluate, control and perform follow-ups in organizations there is a need to condensate information about the performance of the organization. For organizations to be able to meet their management goals they need to strive for high degrees of efficiency and effectiveness. PIs are an easily understandable and effective tool to summarise the performance of an organization. For PIs to be useful they should be (Stahre, et al., 2000)

- Clearly defined
- Easy measurable
- Verifiable
- Easy to understand, even by non-specialists
- As few as possible

PIs can be used to evaluate an organization historically over previous time periods or to evaluate comparable organizations. Historical trends may show improvement or deterioration in performance so that remedial measures can be taken before service is affected. When new systems or equipment are being implemented, PIs enables follow-ups for efficiency and effectiveness.

PIs are used for benchmarking of organizations and are included in what is usually referred to as metric benchmarking. Metric benchmarking is used for monitoring of the organization itself and also for comparison between organizations. PIs for monitoring are usually shown graphically as line charts, which show changes over time, and for comparison in column charts (Balmér, 2010).

3.2 PERFORMANCE INDICATORS FOR WWTP'S

A PI is a ratio between a quantitative description of an organization (usually some kind of consumption or a cost) and a performance factor of the organization. For a WWTP, this is often a number related to the load on the plant (Balmér & Hellström, 2012). Examples of performance factors can be the mass of COD or OCP (explained in section 3.4) removed and examples of expressions for the load are population equivalents (pe), volume of wastewater treated and volume of wastewater billed to the customers (Balmér & Hellström, 2012). The latter often equals the consumption of drinking water.

It is preferable to compare WWTPs with each other, rather than a comparison between municipalities because that eliminates statistical misguidance due to scale differences (Lingsten & Lundqvist, 2008).

BOD removal is a process that needs aeration and thus electricity. The removal of nitrogen is also an energy consuming process. In a Swedish energy report, the connection between nitrogen removal and use of electricity was investigated but no real correlation was found (Lingsten, et al., 2011). According to the same report specific electricity use is sometimes calculated relative to influent water. This is fallacious because the specific energy use seems to decrease at increasing amount of water added. Stormwater and additive water also dilute the concentration in influent and thus may obstruct an energy efficient process. It is better to use organics and nutrient load instead and relate specific energy data to the reduction of OCP (see section 3.4 for explanation of OCP).

3.3 THE TERM PE

Population equivalents (pe) is a commonly used denominator for PIs. It refers to the average amount of substance, for example nitrogen, a person emits in urine and faeces. These numbers differ between countries, due to different diets etc. In this study, using data from Jönsson et. al. (2005), values of 70 g BOD_7/p,d and 14 g N/p,d are used in this thesis.

3.4 PERFORMANCE INDICATORS IN WWTP’S GLOBALLY

There have been initiatives from different organizations to develop PIs for benchmarking between WWTPs but they are often of a general sort and often not specific enough to be used for altering and improving the processes in the WWTPs. Since WWTPs rarely publishes their measurements (or calculated PIs) it is difficult to find concrete examples.

3.4.1 Summary of other performance indicator studies

In a case study in Portugal (Marques & Monterio, 2001) regarding implementing performance indicators, the PI’s were grouped into three levels. The first group provides general information of the water utilities. These are generic and not meant for benchmarking with other water utilities. A development level which contains indicators that enables clarification in operation and maintenance and lastly a strategic level to evaluate the performance of operational management, the quality of service delivered and the economic and financial health of the utilities. The strategic level is used for benchmarking between utilities.

A performance assessment system has been developed for urban WWTPs world-wide, with special regards to plant efficiency and reliability, personnel, finances and safety (Perotto, et al., 2008) which have not been the case earlier. It is a combination of environmental management system (EMS) and PIs. The PI group of plant efficiency and reliability evaluates the overall performance for quantifying plant volumetric efficiency and mass removal efficiency. Examples of this are average and peak flow rates of COD, BOD_5, nutrient mass loadings and aeration (Quadros, et al., 2010).

In Austria there is a benchmarking system well adapted for operation of WWTPs but it is limited to cost and energy use and in Germany there are many benchmarking projects but not much published on a detailed level (Balmér & Hellström, 2012). In Italy software has been developed to compute performance indicators used for analysis and management of urban drainage systems (Balmér & Hellström, 2012). Following indicators are evaluated; technical, managerial, environmental and database reliability (Artina, et al., 2005). The indicators are dimensionless and range from 0 to 1. The meanings of the values are different for each indicator, and the indicators are combined to an indicator of global efficiency.

The International Water Association (IWA) has developed a manual of best practice called *Performance Indicators for Wastewater Services* to enable evaluation of the wastewater services as a whole, including personnel, financial, physical, operational, environmental and quality of service aspects (Matos, et al., 2003). It is stated, among other things, that PIs should each be mutually exclusive without overlap and have a concise meaning and a unique interpretation. The outline of the manual is six categories of performance indicators with complementing context information. This context information includes undertaking profile, where the business context of the undertaking is outlined, system profile focuses on the physical assets and the technological means and also the demographic aspects of the customers and region profile provides information to understand the demographic, economic, geographical and environmental context. The manual deals with uncertainty of data with confidence grades. These confidence grades ensure the undertakings quality and reliability of information provided for the PIs. There are reliability bands going from highly reliable to highly unreliable. There are accuracy bands, which are defined as the approximation between the result of a given measurement and the correct value for the variable to be measured. The accuracy bands range from “better than or equal to ± 1%” to “better than or equal to ± 100%”. Every PI is assigned with a letter, indicating the reliability band, and a number, indicating the accuracy band, thus telling how uncertain the PI is. PI systems have been developed in different contexts and according to (Balmér & Hellström, 2012) the IWA Manual of Best Practice was not detailed enough for the operator level.

The Swedish Water Association represents the water service companies in Sweden and they have developed a database for reporting statistics, called VASS. The database, introduced in 2003, contains data for water services both at municipality level and facility level. More than 70 % (Bergman, 2012-09-28) of the municipalities report their data to VASS. Different reports and specific data can be accessed from VASS. The reports account for the operation of water services in the form of performance indicators. However, these performance indicators are at a “high” level, i.e. they do not show how well specific treatment steps perform at facility level.

In a report issued by Svenskt Vatten concerning energy efficiency, one conclusion was the importance of performance indicators to evaluate how energy is used and the development progress at the plant (Olsson, 2008).

3.4.2 Lessons from other performance indicator studies

Quality of data is an important factor; if PIs are based on inadequate data their value for the organization is limited. It is therefore important to review data by defining limits of reasonable accuracy and calculate mass balances. For example with phosphorus balances it is reasonable to expect accuracy within ± 15 percent (Balmér & Hellström, 2012). It is also important not to make PIs too few, which always leads to losses of knowledge (Marques & Monterio, 2001). In order to make PIs comparable they should be quantitatively adjusted for local differences when possible (Balmér & Hellström, 2012). Example of such a difference is energy consumption; some plants have nitrogen treatment which increases the need for aeration as compared to plants which only have treatment of organic matter.

In a report considering environmental performance and indicators in a case study it was concluded that results can be highly affected by uncertainty when based on BOD measurements (Perotto, et al., 2008). BOD is often falsely considered a value unaffected by uncertainty. It was also concluded that the uncertainty of raw data for environmental PIs could lead to meaningless or even misleading results. Data should therefore be selected with regards to the following; the lowest possible number of indicators that can describe the situation should be chosen and redundant information should be avoided. For metrological traceability reference conditions; analytical methods and calibration of instruments should be clearly specified and there should be an assessment of the uncertainties of the measurements.

3.5 OCP AS A WEIGHTED VALUE OF OXYGEN CONSUMPTION

OCP (Oxygen Consumption Potential) is a way to analyse the plant developed by Professor H. Ødegaard (Swedish Environmental Protection Agency, 2003). Oxygen consumption in a receiving water body can be divided into primary oxygen consumption (i.e. bacterial consumption of organic matter and ammonia) and secondary oxygen consumption (i.e. bacterial degradation of algae, growth promoted by phosphorus and nitrogen). OCP makes it possible to express BOD, nitrogen and phosphorus in a common unit. The calculation of OCP is based on the following data (Swedish Environmental Protection Agency, 2003);

- 1 kg BOD results in maximum 1 kg primary oxygen consumption
- 1 kg Tot-N results in maximum 4 kg primary oxygen consumption
- 1 kg Tot-P results in maximum 100 kg secondary oxygen consumption
- 1 kg Tot-N results in maximum 14 kg secondary oxygen consumption

This deduces following relationship (Danielsson, 2010);

$$OCP = BOD + 4\ Tot\text{-}N + 14\ Tot\text{-}N + 100\ Tot\text{-}P \qquad (11)$$

Equation (11) thus allows calculation of a weighted value of the oxygen consumption used in a WWTP during removal of BOD, nitrogen and phosphorus.

3.6 POSSIBLE PERFORMANCE INDICATORS FOR THIS STUDY

This master thesis limits the study of PIs to the secondary treatment step, which is why the PIs stated in Table 1 only concern this treatment step. To cover all possible PIs for benchmarking in WWTP would require many more PIs and is beyond the scope of this thesis.

Since the primary objective of WWTPs is to reduce the content of organic matter in wastewater, the percentage of removal is of great interest since it gives information about how well the process of removal is functioning. A secondary objective is to remove nutrients like nitrogen and phosphorus which makes them important as well. When biological phosphorus removal is in place, this process is also considered for making PIs. Since the secondary step uses a lot of energy, it is important to relate energy usage to reduction quotas. This gives an insight of the plant's efficiency (for the secondary treatment).

Reduction quota is often related to total reduction at the plant, including every treatment step in the system boundaries. However, this thesis aims to analyze only the secondary treatment. This means that the system boundaries in this thesis are set at the inlet to the biological treatment and outlet of secondary sedimentation. Measurements at those two points are uncommon, which makes it necessary to calculate these values based on literature and qualified approximations and estimates.

The unit kg/pe, year is a unit commonly used, which is good when reviewing the plant at the end of a year. It is a unit that often corresponds to legislation requirements but to the operators it is also important to know how the plant performs during the year. Performance is seldom equally high during a year since different seasonal variations affect water temperature and hence affects the performance of the bacteria in the secondary treatment. It is therefore of value to consider the unit kg/pe, month to see monthly fluctuations of process performance.

It is important for most WWTPs to be aware of their energy usage since it often is a large expenditure. To evaluate performance it is therefore important to link removal efficiency to energy usage. In a WWTP there are many processes that use energy but to be able to focus on the ones that use the most energy, an approximation is needed.

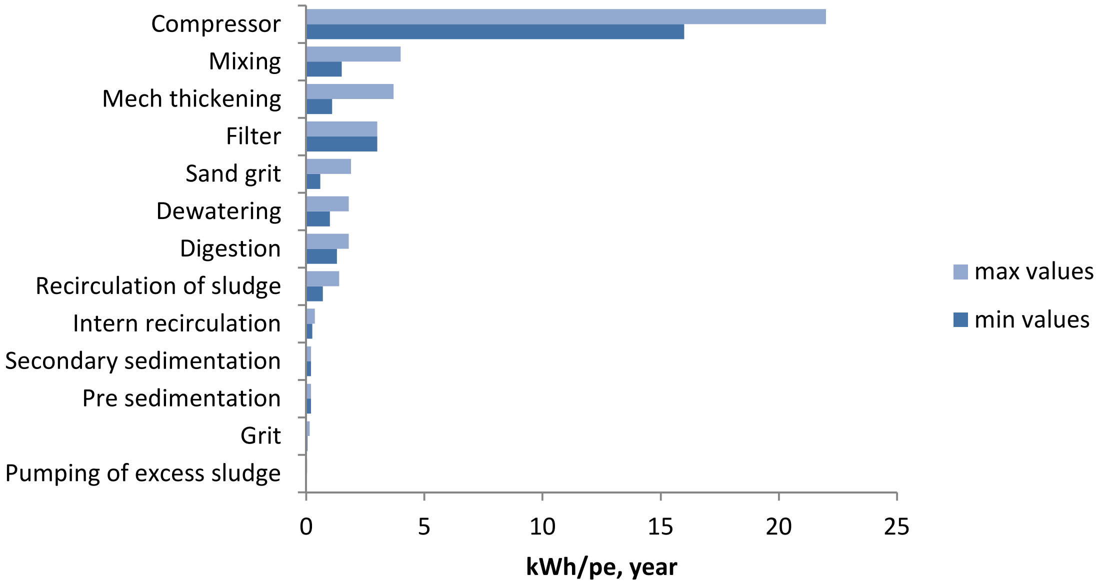

Figure 8. *Conceptual chart of which processes need the most energy (pers. comm. Balmér, 2012). The values are approximations and given in a range, the top range represented by the maximum values and the bottom represented by the minimum values.*

From Figure 8 and Table 1 it is seen that the aeration (which is done by compressors) is the process that is by far the most energy demanding with about 55-60 percent of total energy need. The mixing of the water and biomass in the reactors, which takes place in the secondary treatment, is also energy demanding with about 6-10 percent of total energy need. Filtration is also an energy demanding process, about 7-12 percent of total energy need. However, filtration is a part of the tertiary treatment and thus outside the scope of this study and will therefore not be investigated further.

Table 1. *Energy usage for the different steps in wastewater treatment (pers. comm. Balmér, 2012).*

	kWh/pe,år		**%**	
	min	**max**	**min**	**max**
Pumping of excess sludge	0.02	0.04	0.1	0.1
Grit	0.05	0.15	0.2	0.4
Pre sedimentation	0.2	0.2	0.8	0.5
Secondary sedimentation	0.2	0.2	0.8	0.5
Intern recirculation	0.26	0.36	1.0	0.9
Recirculation of sludge	0.7	1.4	2.7	3.5
Digestion	1.3	1.8	5.0	4.4
Dewatering	1	1.8	3.9	4.4
Sand grit	0.6	1.9	2.3	4.7
Filter	3	3	11.6	7.4
Mech thickening	1.1	3.7	4.2	9.1
Mixing	1.5	4	5.8	9.9
Compressor	16	22	61.7	54.3

Total	25.93	40.55	100	100

Since energy is seldom measured separately for the secondary treatment it is necessary to calculate these values from other measurements and approximations. Section 2.3 gives an introduction to the energy consuming processes in the secondary treatment used for calculation of certain values.

With the literature study of PIs as a basis, the following PIs will be investigated in this study. Note that this is merely a list of possible PIs to evaluate all configurations of WWTP on the market. All PIs in Table 2 might not be applicable due to different process configurations in the WWTPs covered in this thesis.

***Table 2.** Listing of possible PIs for performance and efficiency in the secondary treatment step. The last seven PIs correspond to effluent values for easy comparison with legislation requirements.*

PI	**Unit**
BOD_{red}	%; kg/pe,time-interval
COD_{red}	%; kg/pe,time-interval
TOC_{red}	%; kg/pe,time-interval
$Ntot_{red}$	%; kg/pe,time-interval
$Ptot_{red}$	%; kg/pe,time-interval
$NH_4/NH_3\text{-}N_{red}$	%; kg/pe,time-interval
OCP_{red}	%; kg/pe,time-interval
$energy_{aeration}$	kWh/pe,time-interval; kWh/kg oxygen need; % of total energy need
$energy_{mixing}$	kWh/pe,time-interval; % of total energy need
energy/reduced parameter	kWh/kg reduced parameter
precipitation	mole metal/pe,time-interval; mole metal/mole P
external carbon source	kg COD/pe, time-interval; kg COD/kg $N_{denitrified}$
BOD_{eff}	%; kg/pe,time-interval
COD_{eff}	%; kg/pe,time-interval
TOC_{eff}	%; kg/pe,time-interval
$Ntot_{eff}$	%; kg/pe,time-interval
$Ptot_{eff}$	%; kg/pe,time-interval
$NH_4/NH_3\text{-}N_{eff}$	%; kg/pe,time-interval
OCP_{eff}	%; kg/pe,time-interval

The first seven PIs in Table 2 with the index red (reduced) refer to the wastewater treatment in the WWTP and are commonly used for investigating the removal of organic matter and nutrients in the plant. The difference between influent and effluent values of a substance gives the reduction. The time-interval may vary depending on what the purpose of the PI is. A benchmark between WWTPs may benefit yearly time-intervals, which is also a commonly used interval (Balmér & Hellström, 2011). The ammonia nitrogen is a PI that probably is more suitable for monitoring the processes within a plant. OCP is, as mentioned earlier, a weighted value of both organic matter and nutrients and is therefore a suitable PI for benchmarking between plants. However, it should be noted that using OCP in plants that do not have limits on discharged nutrients (thus having higher effluent values of nutrients) will have higher OCP values than other plants. Since energy for aeration and mixing are the most energy consuming processes in the secondary treatment, the PIs related to this will be investigated in this Master Thesis. The PI energy/ reduced parameter is a way to try and link the need of energy used for a specific process to the removal of the parameter in the process, e.g. kWh for aeration per kg BOD removed. The last seven PIs refer to discharge to the recipient and are easy to use for investigating which time-interval is most likely to breach the legislated effluent limits.

3.7 BALANCE CALCULATIONS

Balance calculations are a way to assess if data is reliable. Nitrogen is removed from the process through nitrification and denitrification and also by assimilating into the sludge. The following connections can be drawn;

$$\text{denitrified N} = \text{removed N} - \text{N in sludge} \quad (12)$$

$$\text{nitrified N} = \text{denitrified N} + NO_2\text{-}NO_3\text{-N in effluent water} \quad (13)$$

N in equations (12) and (13) refers to the element of nitrogen. Removed N is referring to the nitrogen removed from the plant in the form of nitrogen gas and sludge, see Figure 9.

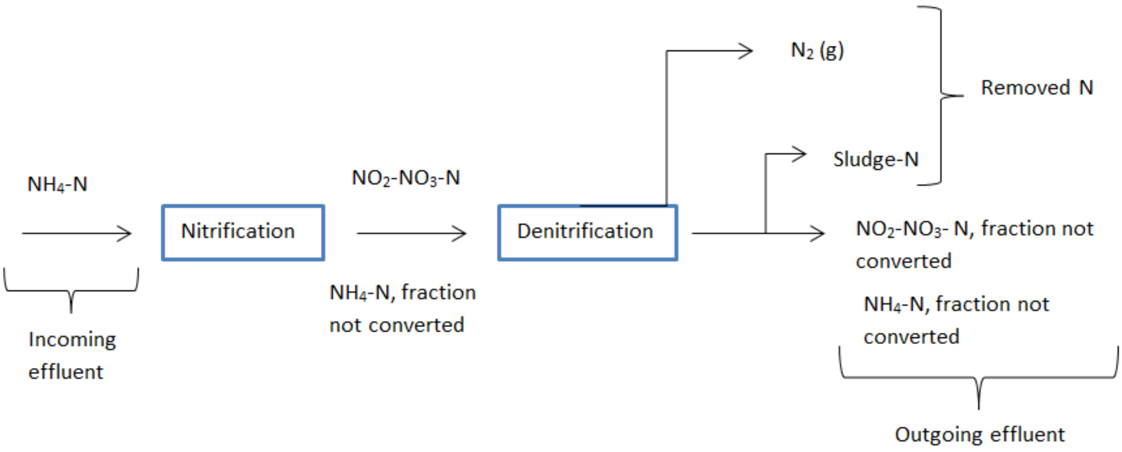

***Figure 9.** Flowchart of the conversion of nitrogen in the secondary treatment step.*

If external sludge is received from septic tanks or other WWTP a general approximation must be done concerning the extra nitrogen added to the process by these sources.

COD is removed in the process as carbon dioxide and in sludge. A COD balance is a more uncertain method due to lots of approximations of COD in external sludge; external added organic material and gas-meters are often not calibrated. The following connection can be drawn, equation (14);

$$\text{COD oxidized} = \text{COD in influent water} - \text{COD in biogas} - \text{COD in digestate} - \text{COD in effluent water} \quad (14)$$

COD in influent water must be corrected if the plant receives sludge from septic tanks or other WWTPs. Some plants measure TOC instead of COD but if the plant-unique relation between TOC and COD is known it may be possible to calculate the COD balance.

Another balance that is more reliable is phosphorus balance. Since phosphorus doesn’t react to form any gaseous phase, incoming and outgoing values should be the same;

$$\text{influent } P = \text{effluent } P + P \text{ in sludge} \quad (15)$$

P in equation (15) refers to the element of phosphorus.

Corrections must be made if the plant receives external sludge from septic tanks or other WWTPs.

4 SITE DESCRIPTION

This master thesis covers three different process configurations, which together represents the largest part of the WWTP market. Four different WWTPs of medium size were chosen to be analysed, two in Sweden, one in the U.S. and one in Canada.

- Sternö WWTP, Sweden – Conventional activated sludge
- Rustorp WWTP, Sweden – Oxidation ditch
- Headingley WWTP, Canada – SBR
- Kimmswick WWTP, U.S. – SBR

4.1 STERNÖ WWTP

Sternö WWTP is located in Karlshamn, in the south of Sweden, and collects wastewater from surrounding areas and sludge from individual plants. The plant is a conventional activated sludge treatment plant and is dimensioned for 26 000 pe (Karlshamns kommun, n.d.) calculated on a specific BOD_7 load of 70 g/ (pe, day) but have a permit for a pollution load corresponding to 41 000 pe at highest. The recipient for effluent is Karlshamn fjord. Sternö WWTP had an actual load of 17 814 pe in 2010. There have not been any significant changes in number of subscribers or industries since 2010 and therefore the loading of 17 814 pe is adopted for 2011 and 2012, which is the time period for the collected data. There are some data of parameters in the secondary treatment step available for 2011 and 2012.

4.1.1 Process configuration

The process includes screening, grit chambers, primary sedimentation, secondary biological treatment and tertiary treatment, which include filtration, see Figure 7. The WWTP can operate with biological phosphorus removal. The secondary treatment removes organic matter, nitrogen and phosphorus biologically. The influent is separated at the entry of the biological treatment by a metallic disc. This separates the flow to 52/48 % to line 1 and 2 respectively (Larsson, 2011). The aerated SRT is about 12 days but it is not a parameter that is used to control the processes at the WWTP. The control logic is controlling the process by a DO setpoint. Hydraulic bypass, due to overflows, is maneuvered on the pumping stations and not at the plant. The filter at the end of the process removes remaining suspended solids and nutrients.

Sternö receives sludge from external plants and facilities (e.g. septic tanks). This external sludge goes through a separate grit screening and is stored in a separate basin to later be pumped to the primary sedimentation, see Figure 10.

During 2011 the plant did some equipment upgrades to one of the two lines (Line 1), the other line (Line2) was left untouched as a reference to the upgrades. The following upgrades were done to Line 1; in April a new blower with a motor power of 45 kW were installed and in May and June new air diffusers were installed.

Aeration control was also upgraded in line 1. In April a new control logic (DO cascade control) was implemented together with a MOV-logic (most open valve) and were fine tuned in September when the MOV-logic were activated so that the valves were open between 75 and 95 % of their controllable range. In October another control logic (ammonium feedback) was implemented to one of the aerated zones in the reference line (whereas the other aerated zone operated with DO cascade control).

4.1.2 Measurements

At Sternö, an accredited lab analysed the influent between the screening and the sand/grit removal and analyses the effluent after the filtration step. The parameters measured at the influent measure point were as follows; flow, BOD_7, TOC, total phosphorus (Tot-P) and total nitrogen (Tot-N). All were day samples, but Tot-P which were weekly samples and TOC were both in day and weekly samples. The same parameters were measured at the effluent measure point, after the filtration, with the addition of ammonia nitrogen (NH_4-N) (also day samples). Energy data for the whole plant is also available. The above mentioned parameters are normally measured at Sternö WWTP but further data were available for 2011 and 2012 because of additional measurements due to the upgrading of the system.

Because of the upgrade-project and another master thesis, conducted by Larsson in 2011, weekly flow-proportional laboratory data are available of influent BOD_7 and NH_4-N (measured at inlet of the biological treatment) and effluent BOD_7 and NH_4-N (measured at the outlet from secondary sedimentation) from the biological treatment. The different measurement points are shown in Figure 10. Additional measurement data from the biological treatment includes on-line measurements of power consumption, airflow and DO. Separate measurements on external sludge do not currently exist but the approximate received volume is 400 m^3/ monthly.

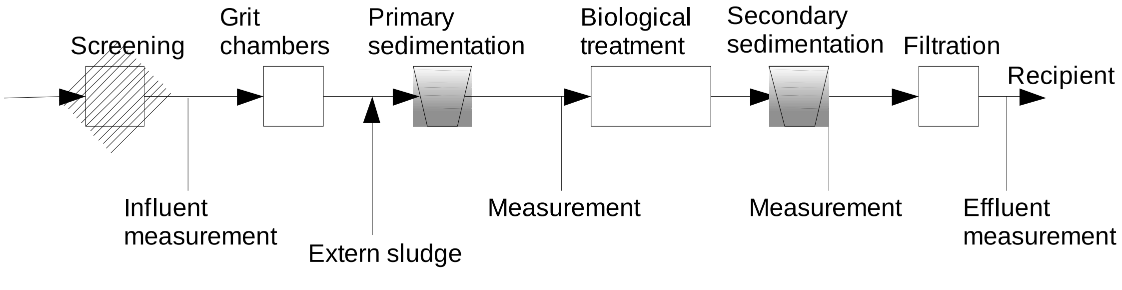

Figure 10. *Flow chart of the different treatment steps in Sternö WWTP. Flows are represented by arrows and measurement points by lines.*

4.1.3 Legislation

The European Union has issued directives concerning discharge requirements for WWTPs, which is incorporated into Swedish legislation by the SNFS regulation. SNFS 1994:7 contain effluent water restrictions for Swedish WWTPs (Naturvårdsverket, n.d.).

Discharge requirements for Sternö WWTP issued by Swedish authorities are presented in Table 3 below.

Table 3. *Effluent restrictions for Sternö WWTP, discharges from the plant were well under restricted values during 2011 (Karlshamns kommun, n.d.).*

Parameter	**Unit**	**Effluent restriction (annual mean)**	**2011**
BOD_7	mg/l	10	3
Nitrogen	mg/l	12	6.3
Phosphorus	mg/l	0.3	0.07

From Table 3 it can be seen that emitted concentrations of organic materials and nutrients for year 2011 were well below restriction values. There are also monthly mean effluent restriction values of 0.5 mg/l phosphorus to recipient, which have been held (Karlshamns kommun, n.d.).

4.2 RUSTORP WWTP

Rustorp WWTP is located in the southeast of Sweden in Ronneby and is designed for 25 000 pe and in 2010 and 2011 respectively, the load was 11 594 pe and 9 503 pe (Ronneby Miljö & Teknik AB, 2011, 2010) .The plant is an oxidation ditch, or racetrack as the configuration is also called. Rustorp has biological nitrogen and phosphorus removal but uses chemicals for removal of residual soluble phosphorus and suspended solids. Normal flows are 5 000 – 25 000 m^3/d but average is about 10 000 m^3/d.

4.2.1 Process configuration

The biological treatment has partitions to separate the inflow. Aerated SRT is on average 8.2 days. After the biological treatment about 90 – 110 g/m^3 $FeCl_3$ is added for flocculation and flotation is used to separate any residual suspended solids or soluble phosphorus, a larger amount is added during winter due to higher flow. The control logic is operating the process by a DO setpoint, which is about 3.5 – 4 mg/l.

Thickened external sludge, around 10 000 m^3/year, from septic tanks is added at night to the biological treatment after the influent measurement point, see Figure 11. The influent measurement point is located between the screening and the grit/sand removal and the effluent measurement point is located prior to discharge to the recipient. Bypass of water due to overflows occurs at the plant and is caused by large flows due to leakage into the sewer piping system. Industrial discharge consists of leachate from a waste facility.

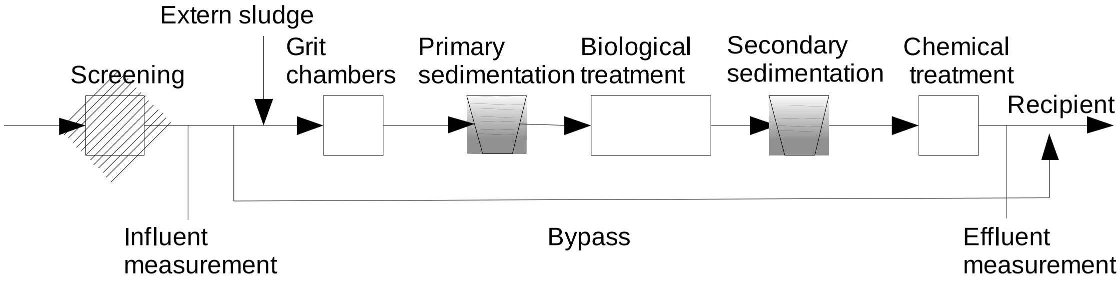

Figure 11. *Flow chart of the different treatment steps in Rustorp WWTP. Flows are represented by arrows and measurement points by lines. There is a bypass of water when flows are exceptionally high.*

4.2.2 Measurements

Regular measurements at Rustorp include; day samples of flow, BOD_7, Tot-N, ammonium nitrogen (NH_4-N), nitrite-nitrate nitrogen (NO_2-NO_3-N), suspended solids (SS), COD and TOC. There are also weekly measurements of flow and Tot-P. All the above mentioned parameters are measured both at the influent measurement point and at the effluent measure point. Data of energy is for the whole plant and at a yearly basis.

Pumps and mixers for circulation of water are in on-mode continuously, also the aeration makes the water circulate in the reactor. The aeration system was upgraded during winter 2011 and spring 2012 and included new blowers and diffusers. Two out of eleven pumps are operated with variable frequency drives (VFDs).

4.2.3 Legislation

Discharge requirements from the Swedish authorities are presented in Table 4.

Table 4. *Effluent restrictions for Rustorp WWTP. The values for 2011 are under restriction values (Ronneby Miljö & Teknik AB, 2011).*

Parameter		Unit	Effluent restriction	2011
BOD_7	monthly average & benchmark	mg/l	10	<5.0
	quaterly average & limit	mg/l	15	<4.5
Nitrogen	annual mean & benchmark	mg/l	10	8.2
Phosphorus	monthly average & benchmark	mg/l	0.5	≤0.3
	quaterly average & limit	mg/l	0.5	≤0.25

4.3 HEADINGLEY WWTP

Headingley WWTP is located in east Canada in the Manitoba region. The plant has a version of SBR configuration called ICEAS. Organic matter and nitrogen are removed biologically and phosphorus is removed through chemical precipitation. Normal flows are about 500-600 m^3/day. The plant is a size that corresponds between 2 584 pe, calculated with a specific load of 14.0 g N/p,d (Balmér, 2010) and 3 043 pe, calculated with a specific load of 110 g COD/p,d.

4.3.1 Process configuration

The process is adapted for removal of organic matter and nitrogen but biological phosphorus removal is also present to some extent despite that the plant was not originally configured for this. Alum is used as precipitant for chemical removal of phosphorus but during the year that the plant has been in use operators have noticed a decrease in amount of alum needed, thus supporting this assumption. There is no industrial influence in the wastewater. Due to slow movement of wastewater in the collection system the wastewater gets anaerobic and thus the influent has high sulfide levels, which is toxic for the bacteria in the secondary treatment. Therefore they add $FeCl_3$ to remove excess sulfide from the water before it enters the secondary treatment. The addition of $FeCl_3$ also results in a loss of alkalinity, which is counteracted with NaOH added to the wastewater. The current inflow to the plant is relatively low so only one of two reactors is in use during the time of collected data. Due to this low flow bypass of wastewater has never to this point been necessary.

The control logic is a DO setpoint of 2 mg/l, aeration stops when the setpoint is reached and there are three aerobic cycles and three anoxic cycles before the draw phase. Due to extreme seasonal variations (e.g. + 30°C in summertime and -30°C in winter), SRT is altered (longer SRT during winter) to compensate for this. There have not been any large changes or improvements since the startup of the plant, just some smaller alterations in the amount of chemicals added.

4.3.2 Measurements

Measurements are performed by operators at the plant and by an accredited laboratory. Measurements in influent wastewater were COD, NH3-N, temperature and pH. There were also a few measurements of Ptot, Ntot and orthophosphate. Data of influent and effluent wastewater flow is also available. There are some data collected in the basin of temperature, pH and SRT. Measurements in effluent wastewater include; pH, temperature, Ptot, orthophosphate, Ntot, NH_3-N, NO_3-N, NOx-N, CBOD and TSS. Diffusers are located 30 cm above the basin floor and the top water level is about 4.5 m.

4.3.3 Legislation

The following requirements for effluent quality are stated by authorities to be held by Headingley WWTP.

Table 5. *Legislated effluent quality of wastewater at Headingley WWTP.*

Parameter		**Unit**	**Effluent restriction**	**Dec 2011-Aug 2012**
cBOD	monthly average	mg/l	25	>6.5
TSS	monthly average	mg/l	25	4.4-20.6
Phosphorus	monthly average	mg/l	1	0.2-0.9
Nitrogen	monthly average	mg/l	15	6.2-32.1
NH_3	Oct-Apr	kg/d	15.1	0.4-10.3
NH_3	May-Sep	kg/d	7.6	0.2-3.4

As seen in Table 5, effluent restrictions are met for all parameters but nitrogen. It is the months December (2011) – April (2012) that are above legislated values for nitrogen.

4.4 KIMMSWICK WWTP

In Rock Creek, Missouri, US, lies Kimmswick WWTP. The weather at the plant is seasonal with warm summers and cold winters. It is a four basin SBR facility, which is designed for 48 000 pe. The treated wastewater is discharged in Mississippi River. There is no industrial influence in influent wastewater, only residential waste. The plant is designed for an average daily flow of 18 200 m^3/d (Department of Natural Resources, 2012) and a peak hourly flow of 60 000 m^3 but normal flows varies between 5 700-9 500 m^3/d (pers. comm. Seger, 2012). Kimmswick WWTP do not conduct any measurements on energy and electricity but uses on average 400 000 kWh/month.

4.4.1 Process configuration

Kimmswick WWTP has four identical basins for the secondary treatment but due to current flows only three basins are in operation. The incoming flow is equally distributed to the three basins. No chemicals are used for precipitation of phosphorus. Kimmswick WWTP controls their process mainly by SRT and MLSS and has average STR of 21 days. The plant produces on average about 151 000 liters of 3 percent sludge. There is no bypass of water at the plant. There have not been any changes in the process at the time of collected data. DO in the basins vary between 1-3 mg/l. Kimmswick WWTP has two blowers in use and one blower for back-up. The plant has four mixers to mix the wastewater when aeration is in off mode. pH is always between 6.9 and 7.2 (neutral).

4.4.2 Measurements

Measurements of MLSS and SVI are done at the plant (in each basin) and once a month external lab tests are done on effluent wastewater of TKN, NH_3-N, org-N, NO_2NO_3-N, TN and TP. Influent wastewater samples include BOD_5, TSS and pH. Influent samples are collected at the grit basin and effluent samples are collected out of the flume, before the effluent pump station.

4.4.3 Legislation

Kimmswick WWTP has limitations of BOD_5 and TSS, see Table 6. The monitoring requirement for phosphorus, organic nitrogen and total nitrogen was removed from their permit in 2011 since no specific criteria limit is established for the Mississippi River (Department of Natural Resources, 2012).

Table 6. *Legislated effluent wastewater values for Kimmswick WWTP.*

Parameter		**Unit**	**Effluent restriction**	**Nov 2011 - Oct 2012**
BOD_5	weekly average	mg/l	45	<<45
	monthly average	mg/l	30	4,2
TSS	weekly average	mg/l	45	<<45
	monthly average	mg/l	30	2,5

As Table 6 shows, effluent wastewater contains levels of BOD_5 and TSS that are well below limits.

5 RESULT AND ANALYSIS

The results are presented separately for each WWTP to easily give an overview of the performance in the secondary step. The PIs possible to calculate from the data are presented together with an analysis. This approach makes it easy to draw conclusions of which PIs convey the most condensed and relevant information. Due to differences in amount and type of data results may be presented in an inconsistent way. To plot all measurement points separately was proved to be unusable because isolated measurement points may vary significantly due to the circumstances at the time of measurement, also different parameters were sometimes measured sporadically during the time of data collection. Data from the different WWTPs has, in this master thesis, been presented in monthly and yearly time-intervals. Data has been aggregated so that each monthly or yearly value represents an average of the collected data from that time-interval (with sometimes different number of measurement points due to scarcity of data).

5.1 STERNÖ

A summary of the different parameters with respective temperature curve is visualized in Figure 12. The original data were aggregated into monthly data to get a more comprehensive picture of trends and to be able to compare different parameters to each other.

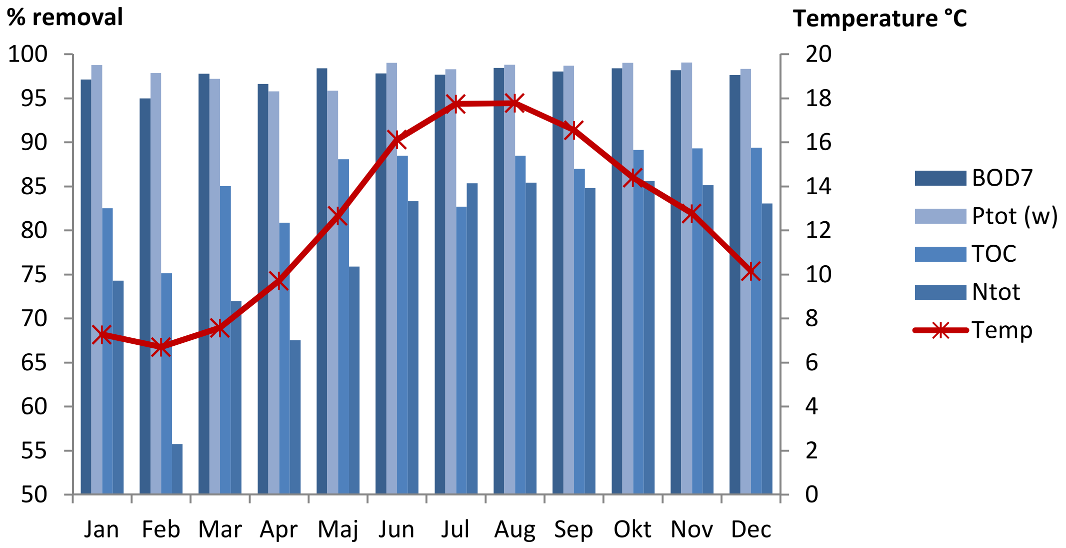

Figure 12. *Removal for each month in 2011 of different parameters (for the whole plant) and water temperature. The column furthest to the right is N-tot and is the parameter that varies the most. The scale to the left starts from 50 %.*

The removal of BOD_7 is almost constant during the year, only in February the removal is at a minimum of 95 % removal. The weekly samples of P-tot also have a removal consistency throughout the year, only varying by a few percent. TOC removal varies between 75 – 89 %, with the lowest values in the beginning of the year. N-tot is the parameter with the greatest variation of the removal; between 56 – 86 %. The nitrogen removal is considerably lower in the beginning of the year. The temperature curve shows the lowest value (between 7 – 10°C) in early spring and the highest temperature is in summertime, when it rises to 18°C.

From Figure 12, it is N-tot that seems to be the most affected by temperature variations, which is supported by section 2.2.2 and 2.2.4.

A correlation analysis between N-tot and temperature versus TOC and temperature can be found in Appendix B. Like BOD_7, TOC is a measurement of organic matter but TOC also includes organic matter that does not give rise to oxygen consumption in the recipient, see section 2.3.3. While BOD_7 removal is consistently at 95 % and above, TOC removal varies below that. This indicates that other particles (which do not give rise to oxygen consumption in the recipient) are discharged to the recipient. However, as stated in 2.3.3, TOC is an unreliable parameter so the values cannot be trusted.

Since there are measurements from another master thesis (Larsson, 2011) connected to the upgrades of one of the treatment lines in Sternö, there are measurements available from the period 2011-04-09 to 2011-11-13 for the secondary treatment step.

Table 7. *Removal of BOD_7 and NH4-N in the secondary treatment in Sternö in percent and corresponding unit, kg/pe, year. The removal of both parameters are near 100 percent in this step, which means that very small amounts of these parameters flow to the next step in the WWTP.*

Secondary treatment	BOD_7	NH4-N
%	96.7	97.1
kg/pe, year	18.8	2.3

As Table 7 shows, the removal is above 95 percent for both parameters in the secondary treatment. Almost all ammonia nitrogen (NH4-N) is removed in the secondary treatment, which corresponds to 2.3 kg/pe, year. Comparing to Table 8, ammonia nitrogen is thus almost 40 percent of total removed ammonia (N-tot) at Sternö.

Table 8. *Removal of different parameters when the wastewater has gone through all treatment steps in Sternö WWTP. The bottom row is amount in effluent. The two parameters to the right are weekly samples.*

Whole plant	BOD_7	N-tot	TOC	P-tot (w)	TOC (w)
%	97.4	78.6	85.5	98.0	86.9
kg/pe, year	25.5	5.8	15.7	0.7	
kg/pe, year	0.64	1.34		0.01	2.22

Almost all ammonia nitrogen (97.1 percent) is removed in the secondary treatment step and 78.6 percent, see Table 8, of total nitrogen is removed, which means that of the nitrogen discharged to the recipient, most is in other forms. These forms are organic bound nitrogen not removed in earlier steps or assimilated to the sludge and/or nitrite and nitrate not converted through denitrification to nitrogen gas. TOC values in Table 8 are lower than BOD_7 values. Since TOC is a measure of total organic carbon it includes forms of carbon that do not give rise to biological oxygen consuming processes in the recipient.

Table 9. *BOD_7 in kg/day into the plant, into secondary treatment, out from secondary treatment and out from plant to recipient for the period 2011-07-09 to 2011-11-13. The approximate removal in percent between these steps that follows from this is also presented.*

	Influent WWTP	**Influent sec.treatment**	**Effluent sec.treatment**	**Effluent WWTP**
kg/d	1360.3	923.9	29.8	28.5
	Step 1	**Step 2**	**Step 3**	
%	32.1	65.7	2.2	

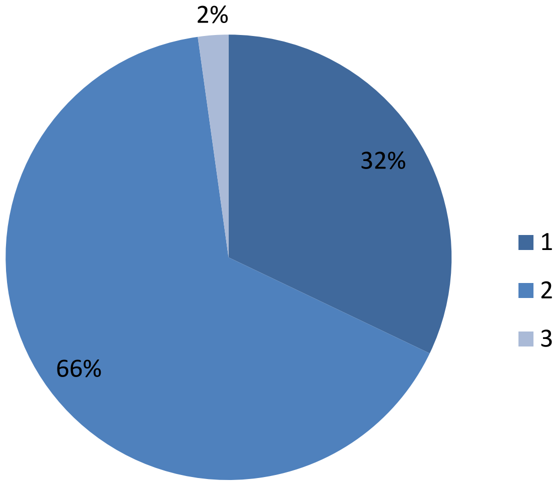

Figure 13. *Percentage distribution of removal of BOD7. 1 refers to the step between influent to the WWTP and influent to secondary treatment. 2 refers to the step between influent to secondary treatment and effluent of secondary treatment. 3 refers to the step between the eluent in secondary treatment and effluent of the WWTP.*

It can be seen from Table 9, and more clearly in Figure 13, that about 32 percent of BOD_7 is removed between the inlet to the WWTP and the inlet to the secondary treatment. The largest fraction, about 66 percent, is removed in the secondary treatment and almost nothing is removed in the following steps.

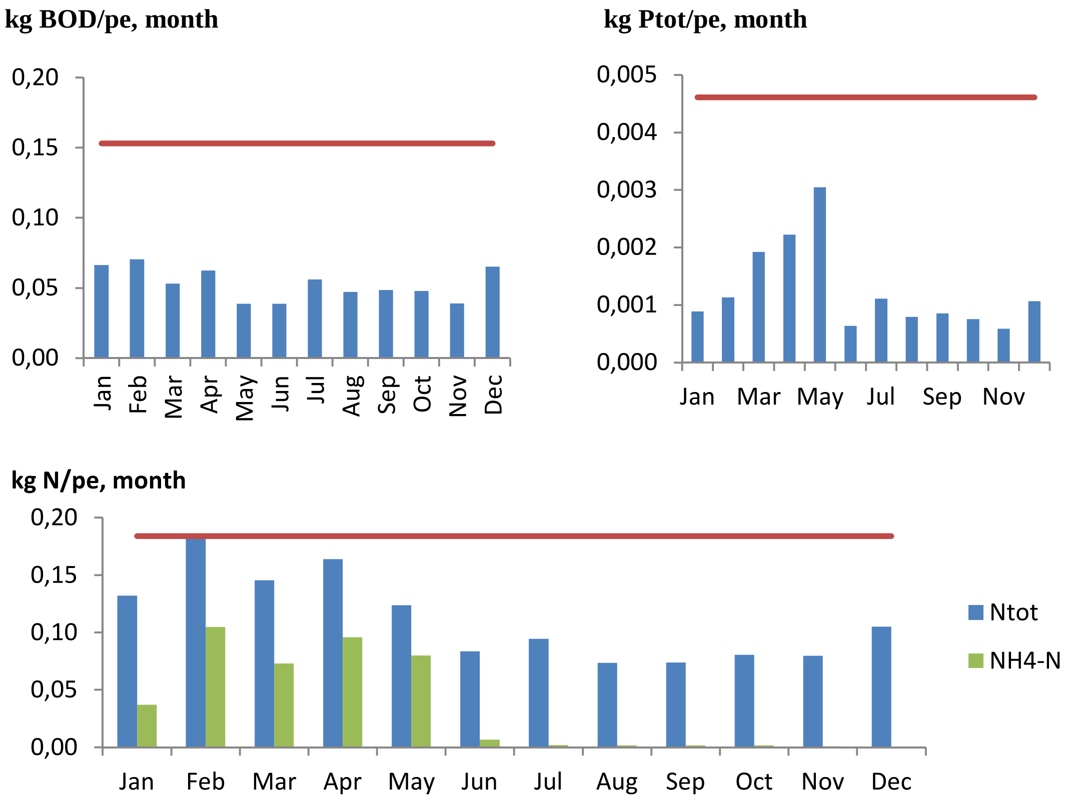

Figure 14. *Effluent with unit kg/pe, month on all y-axes, upper left chart shows* BOD$_7$*in effluent with the restriction limit (0.153 kg/pe, month) as a line. Upper right chart shows Ptot in effluent with the restriction limit (4.61E-3 kg/pe, month) as a line. Bottom chart shows Ntot and* NH$_4$*-N in effluent with the restriction limit (0.184 kg/pe, month for Ntot) as a line (*NH$_4$*-N values are too low in August and forth to be visible in the figure).*

BOD$_7$ in effluent is consistent well below the restriction limit with little variation as seen from the upper left chart of Figure 14. Ptot is also well below the restriction limit but increases from February to May. There is an improvement seen from June and forth. One reason for that could be the upgrade of the treatment system, see section 4.1.1 hence improving removal. Ntot tangents the restriction limit in February, which should be a month that requires special attention with the possibility of more stringent restrictions. NH$_4$-N, and subsequently Ntot, is lower from June to November thus indicating that nitrification is functioning well during these months. NH$_4$-N is at the highest about 65 % of Ntot in the effluent. Since all parameters are well under legislated values from June and forth, this time period could be of interest for testing energy saving measures such as less aeration whilst still keeping the legislated limits.

Table 10. *Total electricity use for 2011 (Sternö Avloppsreningsverk, 2011) and electricity need for aeration in Line 1 and Line 2 in Sternö (from July 2011 to June 2012).*

	kWh	%
Total	1311945	100
L1	119792	9
L2	350938	27
L1+L2	470730	36

The energy needed for aeration is 36 percent of total electricity need at Sternö, see Table 10. The energy for aeration in line 1 and line 2 is 9 respectively 27 percent of total electricity need at Sternö (Line 1 has the new aeration equipment).

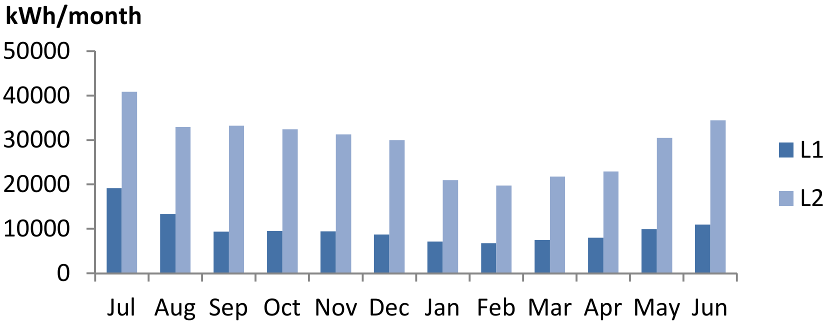

Figure 15. *Energy for aeration in kWh/month for line 1 and 2 respectively.*

The energy usage in kWh is lower for line 2 from January to April, Figure 15. Line 1 shows a similar, but not as distinct, pattern with lower values during springtime.

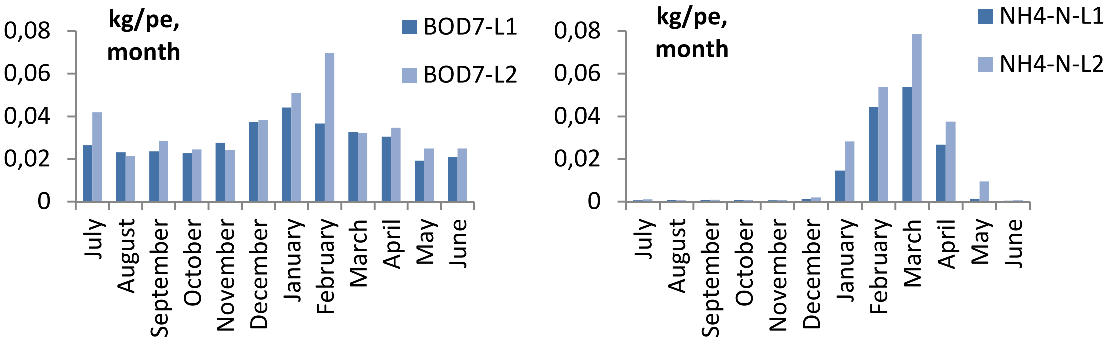

Figure 16. *Outgoing BOD_7 and NH_4-N in kg/pe, month after the secondary sedimentation. Line 2 (with the old equipment) often has higher values than line 1.*

The removal of BOD_7 is lower from December to February, hence the higher values in the left chart, Figure 16. The value for line 2 in July has no obvious explanation. NH_4-N in effluent from secondary sedimentation is near zero for both line 1 respectively 2 throughout the year except for January to April (line 2 has a non-zero value in May).

NH4-N discharge to the recipient increases dramatically in these months, with a peak value in March. It is therefore clear that the efficiency of the nitrifying bacteria is affected during January to April. Line 2 has consistently higher values than line 1, indicating a higher efficiency of nitrification in line 1.

5.2 RUSTORP

The following four charts show percent removal of different parameters divided by month for 2010 and 2011. Since data was available for two years both values for 2010 and 2011 is presented in the same graphs to easily detect any recurring trends.

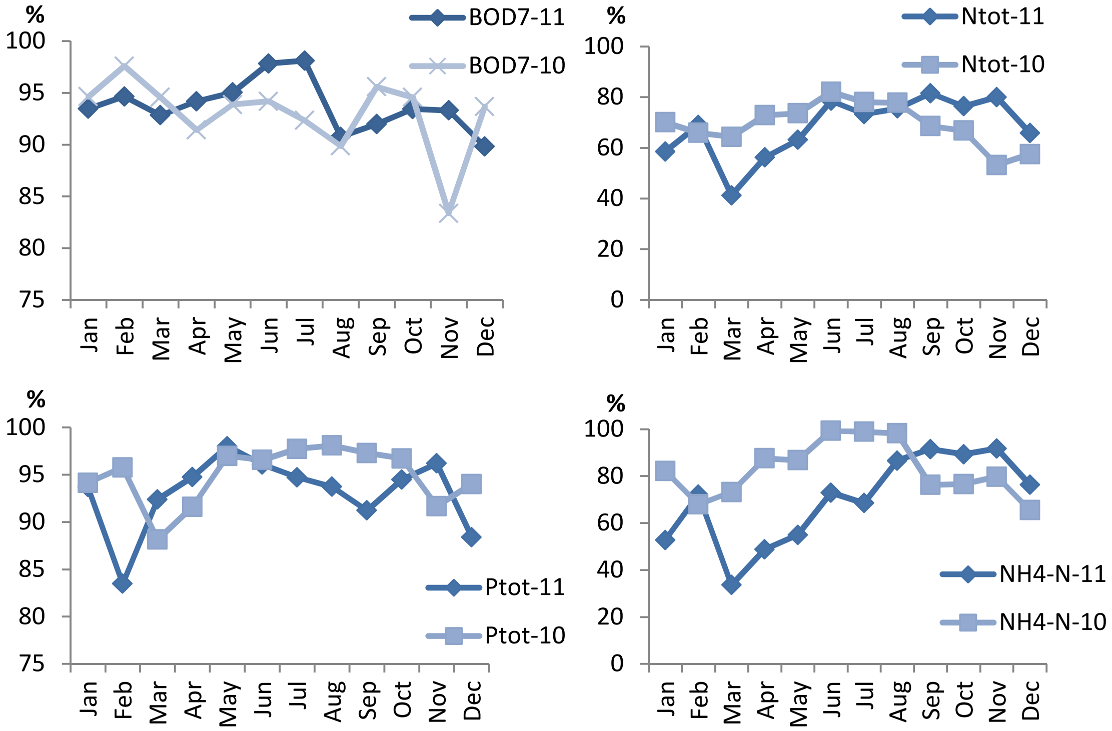

***Figure 17**. Removal in percent of the parameters BOD$_7$, Ntot, Ptot and NH$_4$-N divided by month. The dark columns represent values from 2011 and the lighter columns represent values from 2010.*

Measurements of outgoing BOD$_7$ reach down to 3.0 mg/l due to limitations in the equipment. The slightly lower removal for BOD$_7$ (2010) in November is caused by low ingoing measurements, hence giving a lower reduction rate. The removal of Ntot is lower for both 2010 and 2011 than the other parameters. Removal of Ntot from March to May is significantly lower in 2011 but no such trend can be seen for 2010. The upper right chart and the lower right chart, Figure 17, show the same trend, when removal of NH$_4$-N is poor so is the removal of Ntot, which is natural since NH$_4$-N is included in Ntot. The large difference in removal of Ptot in February has no obvious reason. Removal of Ptot is nearly always above 90 percent.

Table 11. *Values for 2011 at Rustorp WWTP. The bottom row shows how large percentage the bypass of each parameter is in effluent water to the recipient.*

	BOD7	Ntot	Ptot	NH4-N	NO2NO3-N	COD
Influent (kg/pe,year)	25.6	10.1	1.2	6.1	0.5	95.9
Bypass (kg/pe,year)	0.4	0.2	0.01	0.1	-	1.7
Effluent (kg/pe,year)	1.1	2.9	0.05	1.7	1.0	13.9
Bypass+Eff (kg/pe,year)	1.5	3.1	0.06	1.8	-	15.6
Bypass % of Effluent	28	6	17	5	-	11

Ammonia nitrogen is 1.7 kg/pe, year and nitrite-nitrate nitrogen is 1.0 kg/pe, year, Table 11, which means 59 and 35 percent respectively of effluent Ntot. Thus, remaining 6 percent is organic nitrogen. This indicates that neither nitrification nor denitrification is fully completed but nitrification is the process that may need the most improvement. However, with the process configuration being an oxidation ditch, a process alteration with higher aeration may also affect the anoxic zone hence lowering efficiency of denitrification. 28 percent of BOD_7 and 18 percent of phosphorus to receiving recipient originates from bypass water. Nitrite-nitrate nitrogen is 0.5 kg/pe, year in influent water and 1.0 kg/pe, year in effluent water, thus has not all the nitrite-nitrate nitrogen, converted through nitrification, been converted to nitrogen gas through denitrification. The bypass of water was in 2011 about 3 percent of total inflow to the WWTP (and about 2.7 percent for 2010).

Table 12. *Values for 2010 at Rustorp WWTP. The bottom row shows how large percentage the bypass of each parameter is in effluent water to the recipient.*

	BOD7	Ntot	Ptot	NH4-N
Influent (kg/pe,year)	25.6	7.7	0.9	4.9
Bypass (kg/pe,year)	0.2	0.1	0.02	0.1
Effluent (kg/pe,year)	1.0	2.3	0.03	0.9
Bypass+Eff (kg/pe,year)	1.1	2.4	0.05	1.0
Bypass % of Effluent	17	5	38	5

Influent Ntot and Ptot are lower 2010 than for 2011, see Table 12. Note that the bypass of wastewater is responsible for almost 40 percent of the phosphorus discharged to the recipient; otherwise values are similar to those of 2011. A more efficient way to lower discharge of different parameter to the recipient, with a possible future of more stringent limits, could be to add a treatment to the bypass wastewater, which is responsible for a significant portion of effluent levels of BOD_7 and phosphorus.

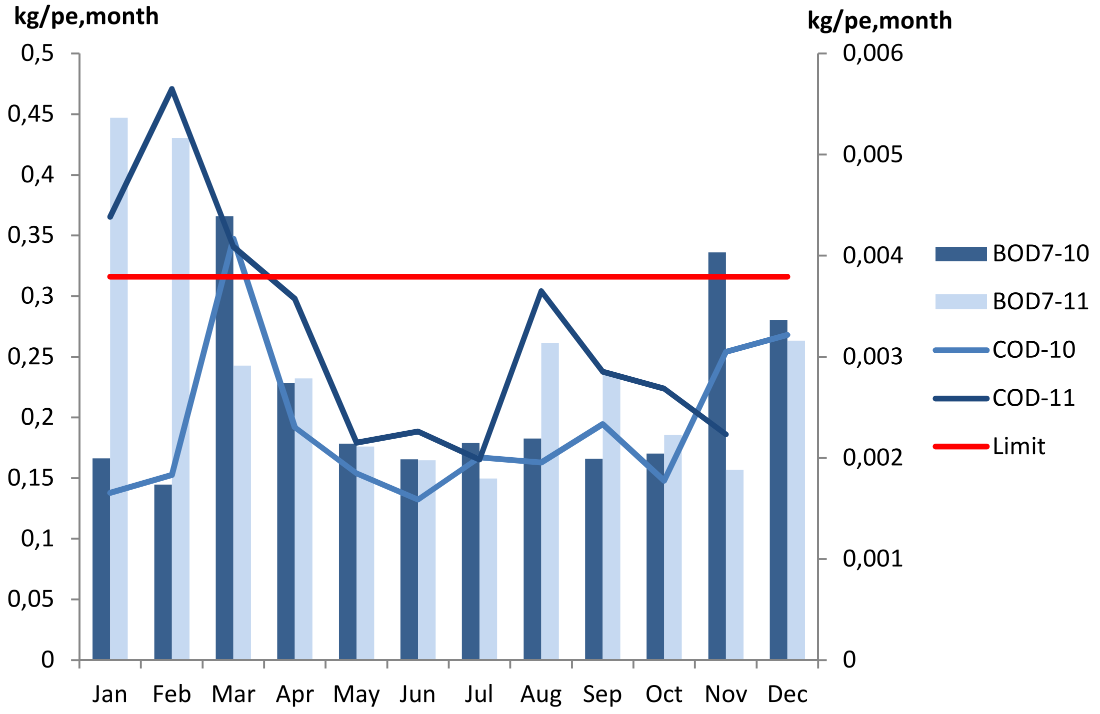

Figure 18. *Columns show effluent* BOD_7 *(kg/pe, month) for 2010 and 2011 respectively. Lines represent effluent COD (kg/pe, month) for the same time period. The left y-axis is for COD and the right y-axis is for* BOD_7*.The bright line is legislated limit (0.32 kg/pe, month).*

Figure 18 shows the same pattern for COD and BOD_7 for the same years. There is a large difference in effluent values between 2010 and 2011 in January and February, which has no obvious explanation. For 2010, the peak value is in March and for 2011, the peak value is in January and February.

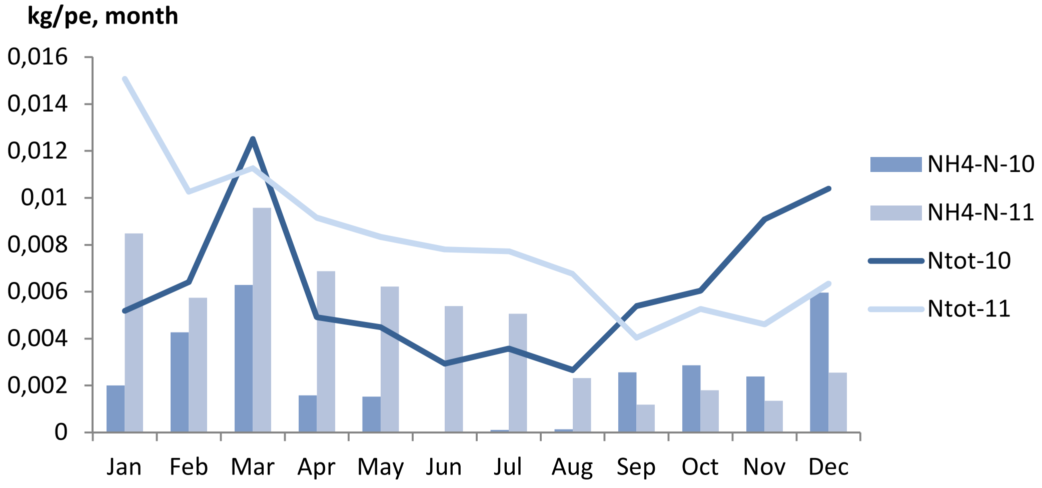

Figure 19. *Effluent values of Ntot and* NH_4*-N for 2010 and 2011.*

Ntot for 2011 is higher than for 2010 due to higher NH_4-N values during this time period, Figure 19. Ntot is lower in the summer months in 2010 and in 2011 the effluent Ntot is continuously lower with every month during the year.

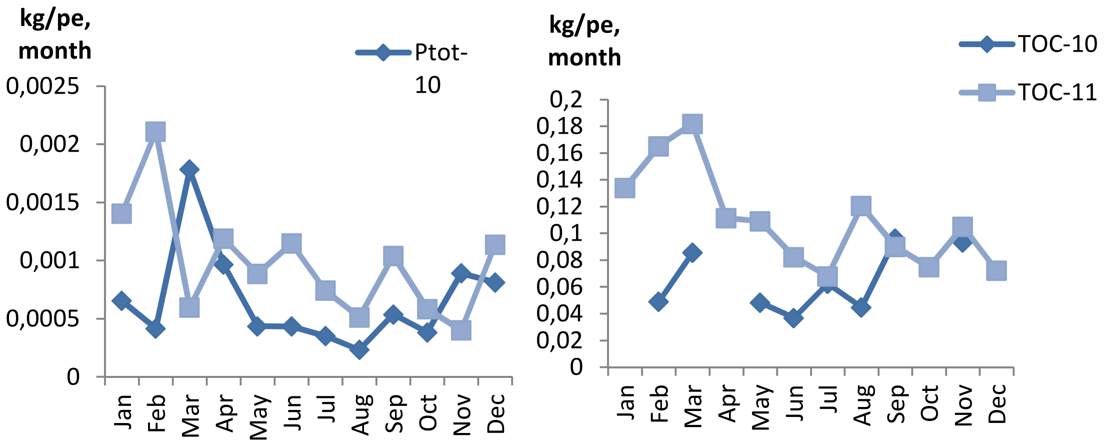

***Figure 14**. Effluent values of Ptot and TOC for 2010 and 2011.*

The effluent values for both Ptot and TOC are generally higher for 2011 than for 2010, Figure 14. The discharge to the recipient is nevertheless lower in the summer months for both years. The legislated limit for phosphorus is 0.02 kg/pe, month, which is a lot more than current effluent values.

***Table 13.** Calculated energy for aeration at Rustorp WWTP. First with three different temperatures and constant SOTE and DO and then with constant temperature and another SOTE value (explained in Appendix A) and DO value.*

		2010	**2011**	**2010**	**2011**
SOTE: 20 %	**temp °C**	**kWh/pe.year**		**% of tot electricity**	
DO: 4 mg/l	**7**	38	51	25	28
	13	35	47	23	25
	17	33	44	22	24
temp: 13°C	**DO mg/l**				
SOTE: 20 %	**3.5**	33	44	22	24
temp: 13°C	**SOTE %**				
DO: 4 mg/l	**18**	39	52	26	28

There is no data logged for temperature at Rustorp WWTP but Rustorp and Sternö are geographically relatively close to each other in Sweden so, in this thesis, the temperature data from Sternö is assumed to be a good approximation of the temperature in Rustorp. A sensitivity analysis was conducted to see how the energy need varies with the parameters that are uncertain. The temperature of the wastewater in Sternö was aggregated to four average temperatures, representing the four calendar quarters in a year. The average temperature for January to March was 7°C, average temperature for April to June was 13°C, average temperature for July to September was 17°C and average temperature for October to December was 13°C. Thus these are the temperatures used in Table 13. DO measurements were also non-existent but approximated to 3.5 - 4 mg/l (pers. comm. Andersson, 2012). SOTE is collected from the manufacturer, in this case from a diagram; therefore it could be between 18 – 20 percent. With the different temperatures, the energy needed for aeration is between 22 – 25 percent for 2010 respectively 24 – 28 percent for 2011 of total electricity at the plant. A lower DO (3.5 mg/l) decreases the energy need with 1 percent. A lower SOTE (18 percent) increases the energy need with 3 percent, see Table 13.

5.3 HEADINGLEY

Headingley WWTP is smaller than the others but has quite a lot of data available. Data is for almost one year (Dec 2011 – Aug 2012) with more frequent measurement for each month. COD is measured only in influent wastewater and CBOD is measured only in effluent wastewater, therefore some of the PIs calculated in other plants are not possible to calculate for Headingley WWTP. Also, Headingley had no exact number for pe so three different ways to calculate pe have been conducted, resulting in three different pe values; pe based on 14 g N/p,d, pe based on 110 g COD/p,d (a value adopted for Austria) and pe based on 120 g COD/p,d (a value adopted for Germany and Switzerland) (Balmér, 2010). Since nitrogen in wastewater is directly linked to human excretion and no specific official value of COD for Canada is known (in this Master Thesis) the pe based on nitrogen is hereafter used. (The calculated pe was as follows; 2584 for 14 g N/p,d; 3043 for 110 g COD/p,d; 2789 for 120 g COD/p,d.)

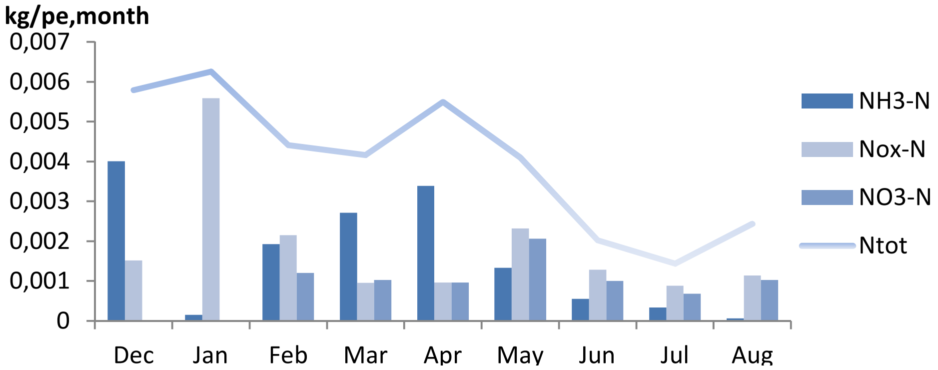

Figure 21. *Effluent values of different fractions of nitrogen.*

Figure 21 visualizes measurement values from effluent wastewater. NOx-N and NO_3-N have almost the same values, which indicates that almost no NO_2-N is discharged to the recipient (NOx-N consists of NO_2-N and NO_3-N). That NO2-N rarely accumulates is supported by the literature study. The high value for Ntot in January is caused by poor denitrification rate although nitrification is well-functioning. Ntot has another peak in April, where denitrification is relatively good, the reason for high values are high NH3-N, indicating low nitrification rates. A possible reason for this could be snowmelt that causes a decrease in temperature of the wastewater thus decreasing the growth and efficiency of nitrifying bacteria, see section 2.3.2 and 2.3.4.

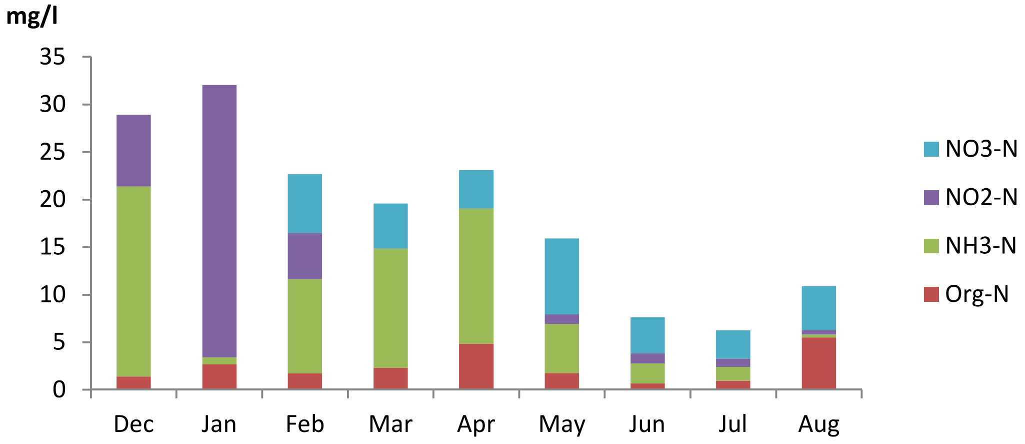

Figure 22. *Fractions of nitrogen in effluent wastewater, the total height of the columns equals total nitrogen.* NO_3*-N is not measured for December and January and is therefore included in* NO_2*-N values for those months.*

Organic nitrogen is generally a small portion of total nitrogen except in August, see Figure 22. This indicates that ammonification is well-functioning. Nitrite is generally low (apart from December and January where nothing can be said). The efficiency of denitrification varies somewhat during the year but the efficiency of nitrification is significantly better from May and forth.

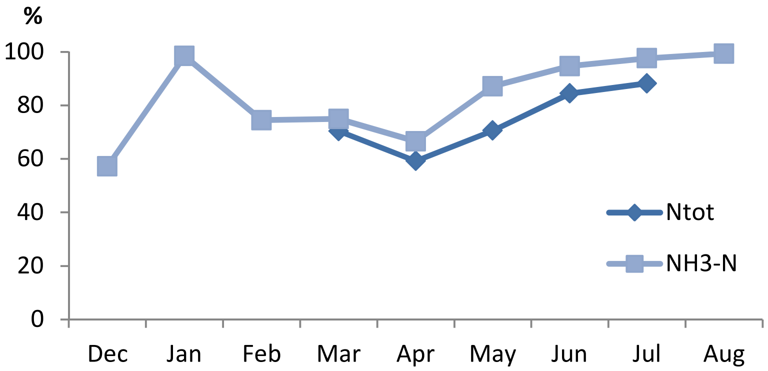

Figure 23. *Removal of Ntot and* NH_3*-N at Headingley WWTP.*

The removal of ammonia nitrogen is near 100 percent, Figure 23, in January to decrease until May where the removal steadily increases. Ammonia and total nitrogen follow the same pattern.

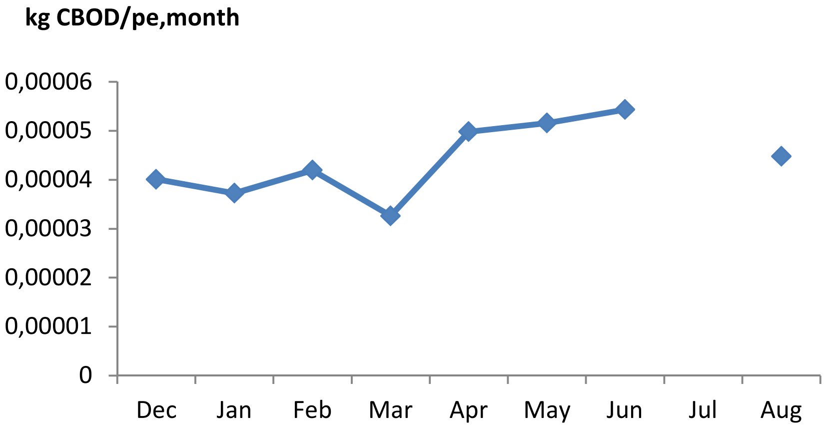

Figure 24. *Effluent CBOD in kg/pe, month. Note that values are well under BOD values for Rustorp and Sternö.*

Headingley has no measurement of BOD in influent wastewater but measures CBOD in effluent wastewater. As Figure 24 shows, effluent CBOD is well below restriction values.

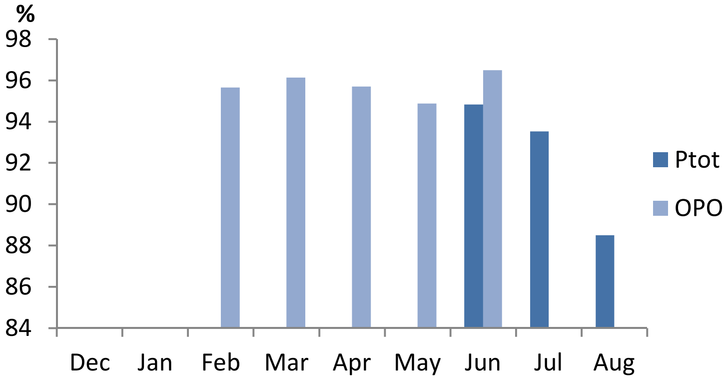

Figure 25. *Removal of total phosphorus and orthophosphate, they-axis begins at 84 percent. There are no data available for December and January.*

The removal of orthophosphate is above 94 percent, Figure 25, and is relatively constant during the months of collected data. This indicates that Headingley is successfully operating an anaerobic cycle. The values for June indicate that not all phosphorus is transformed to soluble form. It is only two months that have measurements of both P_{tot} and OPO.

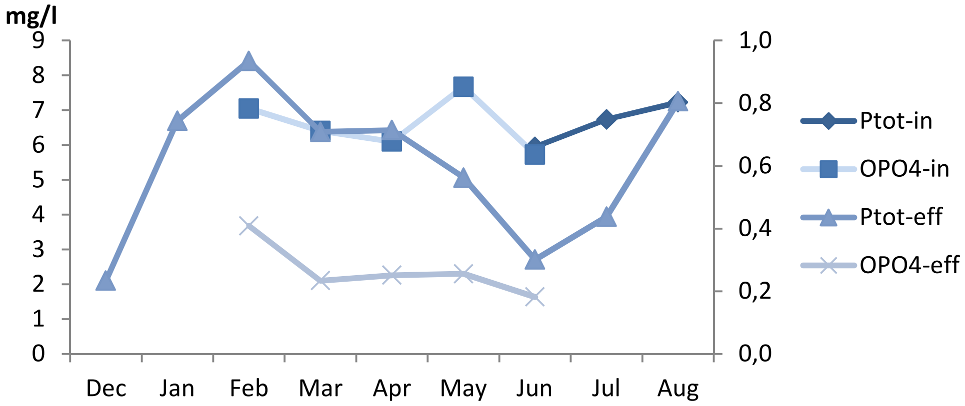

Figure 26. *Influent and effluent values of total phosphorus and orthophosphate. The left y-axis represent the influent scale (mg/l) and the right y-axis represent the effluent scale (mg/l).*

Ptot varies during the year though OPO4 is relatively constant, which indicates that it is the amount of bound phosphorus that is responsible for the variation, see Figure 26. It is not possible to correlate influent values with effluent values due to scarcity of data.

5.4 KIMMSWICK

Kimmswick WWTP installed new software in November 2011, the old software is on a format that is very time consuming to process, which is why data only is for one year (November 2011 to October 2012).

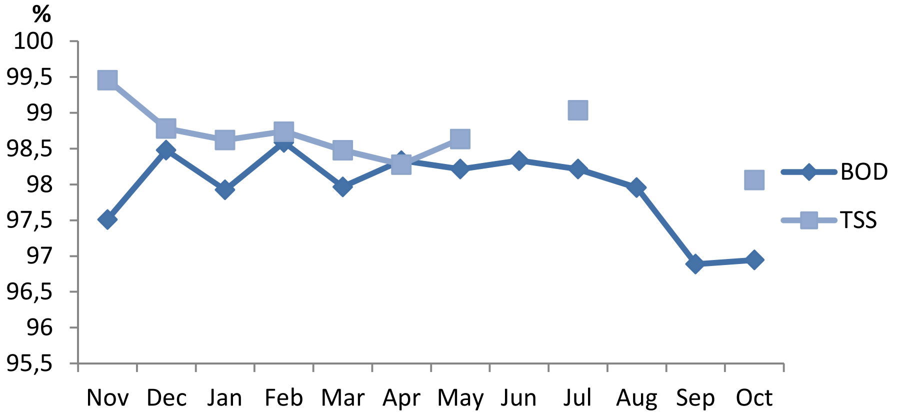

Figure 27. *Removal of BOD and TSS at Kimmswick WWTP during November 2011 to October 2012.*

Removal of BOD is always above 96 percent, Figure 27, and rather constant, the removal is somewhat less from September to November. Removal of total suspended solids is slightly higher that the removal of BOD and also rather constant.

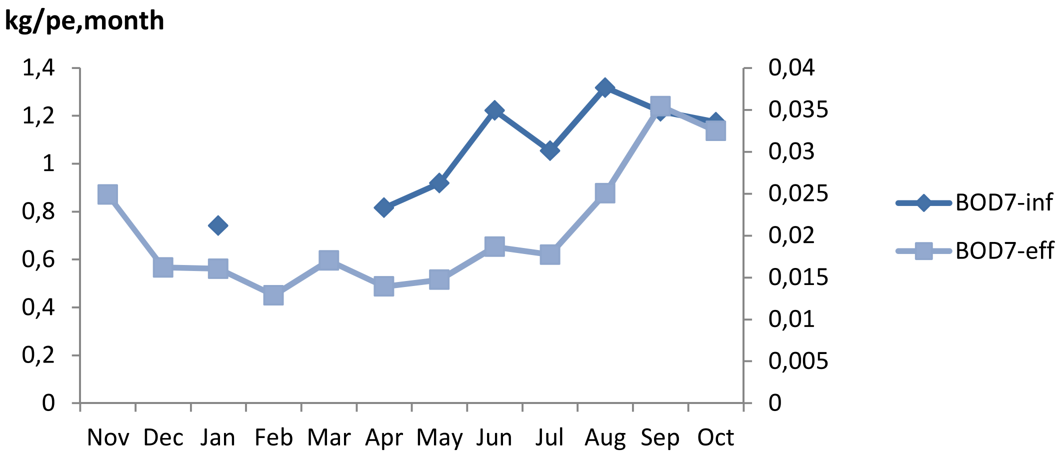

Figure 28. *Influent and effluent BOD7 values (calculated with equation 3). Left y-axis represent influent scale and right y-axis represent effluent scale.*

Since Kimmswick measures BOD5 and comparison between plants is one objective with this thesis, equation 3 has been used to convert values to BOD7. There are no real similarities between influent and effluent values in Figure 28. Effluent values are slightly higher from August to November.

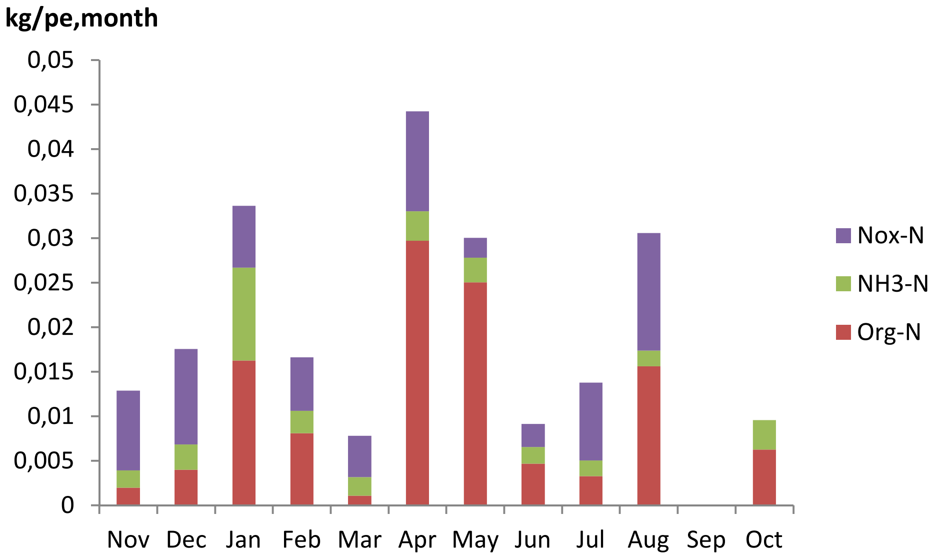

Figure 29. *Effluent divided in fractions of nitrogen, the height of the column is equal to total nitrogen.*

Peak value of total nitrogen (and organic nitrogen) is in April, Figure 29. The months with the highest values of total nitrogen have also by far, the highest values of organic nitrogen, indicating poor ammonification. The fraction of NOx-N is often larger than the fraction of NH_3-N, which indicates that nitrification is more efficient than denitrification.

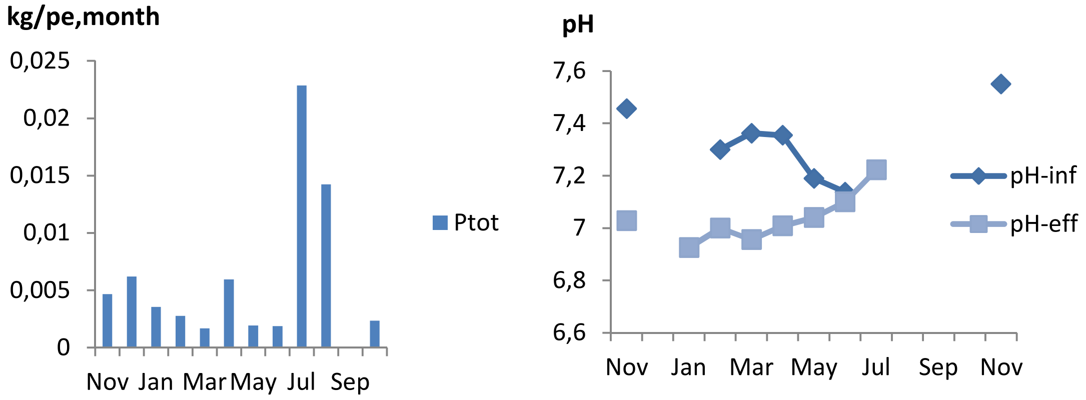

Figure 30. *Left chart shows effluent phosphorus and right chart shows pH in influent and effluent respectively.*

Effluent values of total phosphorus are low and relatively constant except for July and August, which show considerably larger values. There is no obvious reason for the high values. From the right chart in Figure 30 it can be seen that pH decreases during the process.

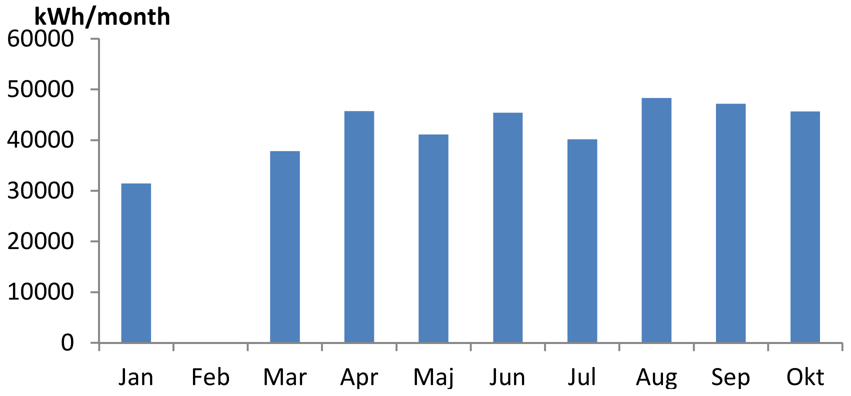

Figure 31. *Calculated energy need for Kimmswick WWTP, 2012.*

Because there were samplings of DO in the basins at Kimmswick, it was possible to calculate energy need for aeration at a monthly basis, Figure 31, but no significant trend is seen (the calculation includes rough estimates and the deviation between months are too small). Based on the rough estimates, the aeration at Kimmswick is about 17 percent of total energy need. This number seems low, comparing to literature (chapter 3).

5.5 STATISTICS FOR REMOVAL IN WWTS'S IN SWEDEN

Statistics for Sweden (Naturvårdsverket & SCB, 2012) show that removal of phosphorus is independent of the size of WWTP as well as which treatment is in use (i.e. biological, chemical, or mixed biological and chemical), with values between 91 to 96 percent. The reduction rate of nitrogen is highly dependent on plant size and the reduction rate of BOD_7 shows a similar trend but to a lesser extent. A plant with a size of 2 000 - 10 000 pe has a nitrogen and BOD_7 reduction rate of 41 and 93 percent respectively and a plant with a size of 10 001 – 20 000 pe has a nitrogen and BOD_7 reduction rate of 51 and 96 percent respectively (Naturvårdsverket & SCB, 2012).

5.6 MASS BALANCE MODELLING

Mass balance modeling is a tool for establishing quality of collected data. It is preferably used as an indicator. As described in section 3.6 there are three possible balances to investigate; nitrogen, phosphorus and COD. COD is only measured in Rustorp and Headingley, and neither biogas nor sludge measurements are available. It is therefore not possible to calculate any mass balance for COD. Unfortunately none of the WWTPs covered in this thesis have measurements (or sufficient measurements) of sludge to perform mass balance calculations to ensure the quality of logged data. Mass balance for phosphorus is not possible due to lack of sampling in the sludge.

5.7 ACCURACY IN PERFORMANCE INDICATORS

It is difficult to know exactly how accurate the value of the PIs is but it is important to have a dialogue with employees at the WWTPs to get an idea of how reliable measurements are. There may be changing degree of errors embedded in calculated PIs but the primary function is visualizing performance patterns and not the exact numbers. It is important when analyzing PIs to know what data they are based on and have a critical eye when calculating PIs.

5.8 CATEGORIZING WASTEWATER TREATMENT PLANTS

One possible function of PIs is benchmarking between WWTPs. Due to the different available designs of WWTPs it is difficult to compare plants with each other. The requirements on effluent wastewater from authorities are also different depending on the recipient. Some WWTPs have limits for nutrients while others do not. Normally, for benchmarking between WWTPs, a yearly basis is enough detail in the PIs and that is also the recommended time-interval in this thesis. One other possible approach for more detailed PIs could be for plants with large seasonal variation to also have a quarterly basis (not necessarily a calendar quarter but rather four periods in a year with similar behavior). An example of this could be Ptot for Sternö in Figure 14 where March, April and May show a pattern. This study covers four WWTPs, which is too few to make any generalizations but it is a foundation for mapping of performance and energy efficiency PIs.

5.9 EVALUATION OF PERFORMANCE INDICATORS

Here the most important results from each WWTP will be summarized with respect to the four main foci for the PIs in this thesis.

5.9.1 Organic matter

Sternö WWTP has continuous sampling of BOD7 and as Table 3 shows, the annual mean of BOD7 is well below restriction limits. BOD7 does not vary much during the year of collected data, see Figure 12. Due to the problems with the BOD-test, mentioned in section 2.3.3, it would be better to start measuring COD, but since legislation is stated in BOD they have no incentives to change the sampling method. TOC is a parameter of organic matter that has greater variation during the investigated time period and one possible reason for this could be variation in temperature. The correlation between TOC and temperature is however small, see Appendix. Most of the BOD7, Table 7, (96.7 percent) is removed in the secondary treatment step, which shows the efficiency in this treatment step. BOD7 values at Rustorp vary more than for Sternö but are more stable for 2011 than for 2012 (Figure 17). Rustorp is also well under legislated restrictions, however, if future changes in legislation require more stringent restrictions, a solution could be to treat bypass wastewater since 17 percent of effluent BOD7 is discharged with the bypass wastewater to the recipient (Table 11). Rustorp also samples COD (Figure 18) and COD values are higher (which is not surprising since more compounds can be oxidized chemically) but they follow the behavior of the BOD7 values. There is a greater variation in removal of COD. Headingley has legislated restrictions for CBOD and is well below those, Table 5. The values for CBOB are consistent during the time of collected data. Kimmswick has samplings of BOD5 with consistent high removal (Figure 27) and is well below restricted values (Table 6).

To sum up, all the WWTPs in this study are well below their restriction limits and have little variation in the efficiency of removal of organic matter. PIs referring to organic matter with a monthly basis in the denominator may not be necessary since the monthly variation is small. In this study, a yearly basis in the denominator was sufficient. There is an economic incentive to decrease energy usage (due to energy bills) and with regard to organic matter there is a large difference between legislated amounts and discharged amounts, making it possible to increase the effort for making the process more energy efficient without risking the limits.

5.9.2 Nitrogen

Nitrogen removal has shown to be the parameter that varies the most during the year. Since this parameter is the one most affected by temperature and all WWTPs in this study are geographically located with seasonal temperature variations this result is not surprising. Results from Sternö show a correlation between temperature and nitrogen removal (Appendix), and this is also supported by the literature, see section 2.3.2 and 2.3.4. Sternö has a large removal of ammonia in the secondary treatment (Table 7). A relatively large portion of the nitrogen still remains in effluent wastewater at Sternö (Table 8). The remaining nitrogen is thus a mix of organic nitrogen that is hard to transform and residues from an incomplete denitrification. From Figure 12 it is seen that February, March and April are months where the effluent values are near the limit values. Since the limits are defined on a yearly basis and the rest of the months are well below the limit it is acceptable, but if the future brings more stringent limits these months are a period of concern. From Figure 14 it is also seen that the reason for high total nitrogen is high ammonia nitrogen during the same time period. It is thus the lack of efficiency of nitrification that is responsible for the high discharge values. Total nitrogen removal and ammonia nitrogen removal at Rustorp follow the same behavior. The removal of both parameters is slightly less in springtime (with a small shift in which month has the lowest value). Table 11 and Table 12 shows that bypass of wastewater does not affect the removal of total nitrogen especially much. The bypass is responsible for 5 and 6 percent in 2010 and 2011 respectively of total nitrogen discharged to the recipient. This indicates that organic nitrogen and ammonia nitrogen are not a large fraction of total nitrogen discharged. Figure 17 shows typical behavior in 2010, with more efficient nitrification in the warmer months, but the curve for 2011 deviates from that behavior and instead shows a quite consistent improvement during the year. Figure 21 shows that NOx-N (nitrite and nitrate aggregated) at Headingley is relatively low during the time period (except for the value in January). Figure22 show that the fraction of organic nitrogen in effluent wastewater always is a small percentage of total nitrogen (except for August). NO2-N is always a relatively small percentage of total nitrogen since it rarely accumulates and the fraction of NO3-N is quite consistent during the time period. It is the fraction of ammonia nitrogen that affects if effluent total nitrogen is high or low. The values for nitrogen at Kimmswick vary greatly during the data collecting period (Figure 29). The values for NOx-N vary inconsistently during the period, which indicates varying efficiency for denitrification. Ammonia nitrogen is consistently low, except for January. Organic nitrogen varies greatly during the sampling period, which indicates that ammonification is not functioning as it should.

To sum up, all the WWTPs in this study show a similar behavior, supported by literature, that the efficiency of nitrification is highly dependent of temperature. The need for aeration is met since the nitrification is significantly more efficient when not affected by temperature. When temperature is not affecting the rate of nitrification, the residuals of denitrification are the largest fraction in nitrogen discharged to the recipient. Rustorp has a deviant removal behavior for 2011 and Kimmswick has an overall deviant behavior of nitrogen removal, largely caused by very uneven effluent values for organic nitrogen. Since the process of nitrogen removal, in this study, shows a seasonal vulnerability through being affected by the seasons and by being close to restricted values it therefore recommended to have a monthly denominator for those PIs.

5.9.3 Phosphorus

Phosphorus removal for Sternö is quite consistent (Figure 12). The yearly effluent values for Sternö is 0.01 kg/pe, year in the investigated time period and a 98 percent removal (Table 8), which is a high efficiency for their biological phosphorus removal process. The removal of total phosphorus seems not to be affected by temperature (Figure 15). The effluent values of total phosphorus continuously increase with every month until May (Figure 12), thereafter the effluent values decrease and remain low. One possible explanation for this could be the upgrade of the equipment, which might have improved the volume of the anaerobic zones hence increase the efficiency of the removal of soluble orthophosphate. The values for Rustorp show a similar, but less marked, decrease in removal during springtime for both 2010 and 2011 (Figure 17). The percentage removal of total phosphorus is lower for Rustorp than for Sternö. Table 11 and Table 12 show that the bypass of wastewater is responsible for a large fraction of the discharge of phosphorus to the recipient. Thus, a separate treatment of bypass wastewater is to prefer if future limits are more stringent, rather than changing the process in the secondary treatment. Figure 14 shows that there is a peak in effluent values for Rustorp during the first calendar quarter; thereafter the effluent values stay relatively constant during the rest of the year. Lack of samples for influent phosphorus makes it difficult to calculate percentage removal for Headingley but removal seems to vary (Figure 26). The correlation between effluent orthophosphate and effluent total phosphorus is small, Figure 26. There is no clear seasonal variation, possibly the efficiency of removal is slightly less during winter. Kimmswick does not have legislated limits or monitoring requirements but there are some samples of effluent phosphorus (Figure 30). Values for effluent phosphorus are low with an exception of two abnormally large values in July and August.

To sum up, the WWTPs in this study have different requirements (or none at all) regarding phosphorus discharged to recipient. Sternö has the most efficient phosphorus removal; the others have a smaller gap between phosphorus limit and discharge relatively to the other parameters. A yearly denominator for PIs is probably sufficient for monitoring phosphorus. Rustorp could increase the removal of phosphorus by treating the bypass wastewater, which corresponds to 18 percent of effluent phosphorus.

5.9.4 Energy

The energy usage for the secondary step has proven to be the greatest challenge in this Master Thesis since energy measurements are rare, it is common just to pay the bill. Sternö was the only plant with energy sampling but that situation was unique due to experiments at the plant. With solely the old equipment, Sternö would have energy usage for aeration that would be the same as suggested by the literature study (Table 10). The upgrade of one of the lines results in 18 percent lower energy usage for the upgraded line relative the line with the old equipment. As seen in Figure 17, there is a lower energy usage for both lines in springtime. A probable explanation for this could be the decreased efficiency of nitrifying bacteria during the same time period, hence requiring lower aeration. The other WWTPs unfortunately do not have energy sampling but by sample some other parameters and make some assumptions a rough value can be calculated. Table 13 shows a sensitivity analysis of energy use and how different parameters affect the result. Aeration at Rustorp has an approximately 22 to 28 percentage of total energy use at the plant, comparing to 36 percent for Sternö. By using the equations described in Appendix A and some assumptions (depending on which data is available) rough numbers for energy usage in conjunction with aeration in the secondary treatment step may be calculated.

What can be concluded is that all WWTPs in this study are performing well and discharge effluent concentrations of organic matter and nutrients that are well below legislated limitations. The gap between actual effluent values and limit values enables the plants to reduce aeration and hence reduce energy usage. What is important to remember is that changes in control may change the performance of the different processes in various degrees, depending on which process configuration is in use.

OCP is a way to estimate the aggregated process performance of a WWTP. Figure 32 shows the effluent kg OCP/ pe, month for the different plants in this study. The x-axes correspond to the time period of data sampling that has been available. Since Headingley do not log BOD5 but CBOD instead, the OCP values for Headingley are based on CBOD. Equation (11) was used when calculating OCP values.

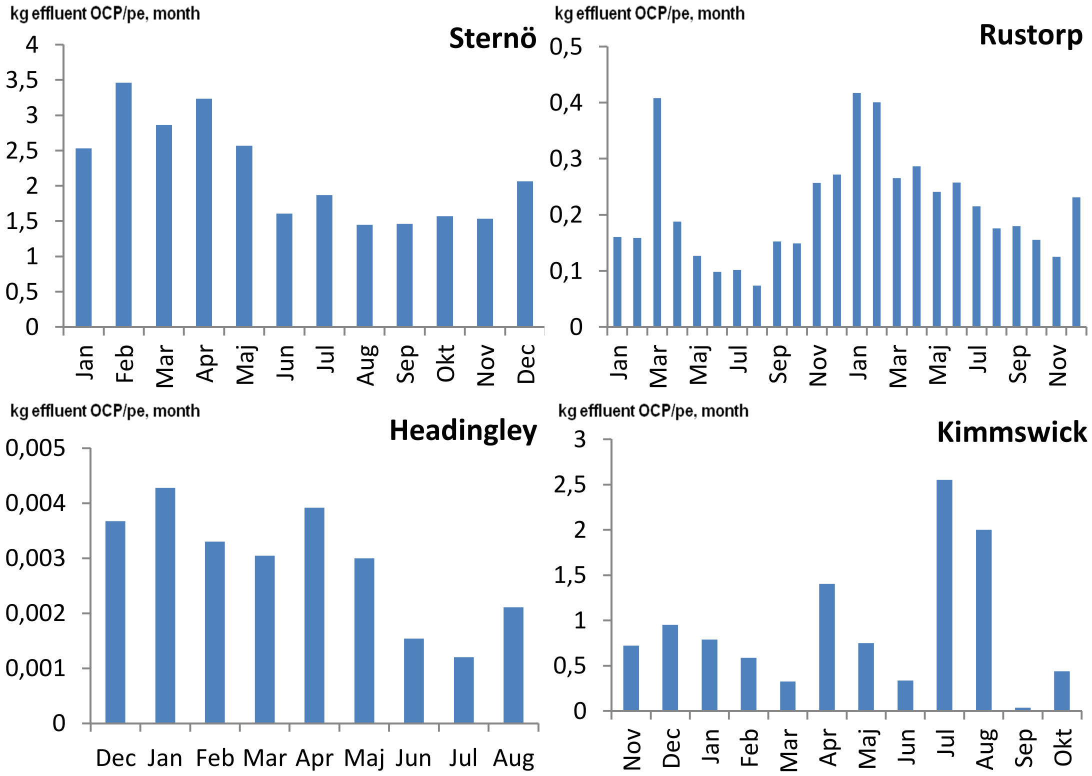

Figure 32. *Oxygen consumption potential (kg/pe, month) in the effluent water for the data sampling periods at the different WWTPs in this study. Note the different scale on the y-axes.*

Three of the graphs above show similar seasonal variation, with higher OCP in the colder months, especially in spring, due to a decrease in nitrification catalysed by a colder wastewater temperature. Kimmswick shows no obvious pattern and has peak values in July and August because of the high total phosphorus values during those months. Headingley has by far the lowest values and Sternö has the highest. It is important to remember that these WWTPs have different limitations on effluent wastewater, so even if Sternö has highest OCP values the values are still well below their limits.

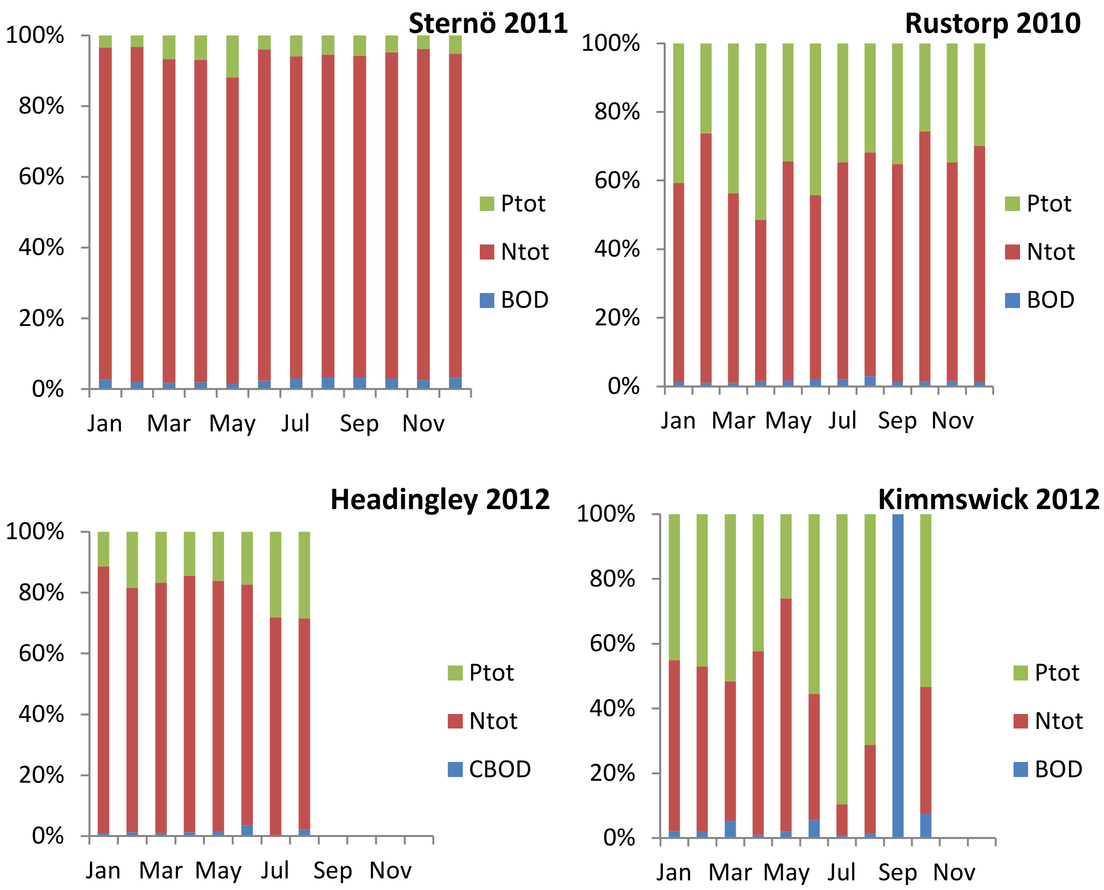

Figure 33. *Dispersion of the weighted fractions that together sums up to OCP of effluent wastewater. All graphs are for a year (January to December). At Kimmswick, BOD is the only measurement for September and therefore equals 100 percent.*

From Figure 33 it is evident that the discharge of nitrogen is the parameter that affects the oxygen demand of the effluent water the most and to lessen the impact on the recipient, nitrogen should be the focus to remove. The exception is Kimmswick, where the recipient is equally affected by the discharge of nitrogen and phosphorus (bear in mind that Kimmswick have no legislated effluent requirements regarding nitrogen and phosphorus).

Table 14. *Energy need for aeration per kg OCP removed at Sternö and Rustorp.*

	Sternö 2011	**Rustorp 2010**
kWh/kg OCP red	550	600

In Table 14 a rough calculation of energy need for aeration per kg OCP removed from the process is displayed. Due to lack of data, this calculation was only possible to do for Sternö and Ronneby. This PI is a measure of efficiency in the secondary treatment step. Since Sternö uses less energy to remove OCP Sternö has a more efficient secondary treatment step.

5.10 ELECTED PERFORMANCE INDICATORS

With the literature study as a basis, several performance indicators may be chosen, see Table 2. Due to scarcity of exhaustive data sampling, only the PIs that have brought valuable information and were possible to calculate in this study were elected for evaluation in this master thesis.

Table 15 shows the PIs of importance in this master thesis. OCP is, as explained in section 2.2.3, a weighed value of the total oxygen consuming processes that organic matter and nutrients give rise to in the recipient.

Table 15.*The performance indicators evaluated for the four WWTPs. Every PI might not be applicable for all the plants due to different data availability.*

Chosen performance indicators	**Unit**
$BOD_{red,eff}$	% ; kg/pe, year; kg/pe, month
$COD_{red,eff}$	% ; kg/pe, year; kg/pe, month
$TN_{red,eff}$	% ; kg/pe, year; kg/pe, month
$TP_{red,eff}$	% ; kg/pe, year; kg/pe, month
$energy_{aeration}$	kWh/kg red. parameter; kWh/pe, year; (kWh/pe, month)
energy/red	kWh/kg OCP_{red}

When sampling organic matter, COD is the most reliable parameter but since BOD and sometimes CBOD are measured, both these parameters are relevant. If the plant has logged some samples of both COD and BOD, it is possible to calculate a plant-specific quotient to use when benchmarking between WWTPs. TOC is an unreliable parameter why it is not included in Table 15. Ntot and Ptot are valuable in benchmarking between WWTPs but the different fractions of nitrogen and phosphorus are also valuable for the individual plant when they want to evaluate the process performance. Energy used for aeration is the most important energy parameter to evaluate since it is responsible for the largest portion of the total energy usage at the plant. This parameter is almost never sampled and therefore requires calculation based on different amount of data and assumptions (depending on how much data are available). Energy used for mixing of wastewater in the secondary treatment step is also not sampled but since it is a significantly smaller portion of total energy use at the plant and the calculation includes many uncertainties this PI is not investigated further. The yearly basis is suitable in comparison between WWTPs and the monthly basis is suitable when a single WWTP wants to compare itself from year to year. When a single WWTP wants to compare process performance over time, it is valuable to look at the monthly variations of the different fractions of nitrogen. This gives a good indication of the performance in the nitrogen removal processes, since these are the processes that vary the most during a year.

6 DISCUSSION

This chapter will discuss factors that affect the value of calculated PIs and other PIs that have not been evaluated in this master thesis due to delimitations in the scope of the thesis.

6.1 OTHER PERFORMANCE INDICATORS

In fast-growing cities, where square meters are expensive, the area a WWTP need is important for investors. Footprint (pers. comm. Larsson, 2012) is a term related to area needed for a WWTP to handle the load. One example of footprint PI could be m^2/kg removed OCP. In large metropolitan areas where new WWTPs are planned, or where an existing WWTP will expand to handle higher loads, footprint is an important PI. Operating expenditure (OPEX) is also an important PI to get an idea of what the costs are for running the WWTP. One possible OPEX PI could be cost/ kg removed OCP, but with monetary PIs it is important to be aware of inflation when benchmarking over time. Capital expenditure (CAPEX) is a measure of expenditures creating future benefits, e.g. when Sternö invests in new equipment that requires a lump sum but generates payoff in terms of a more energy efficient process. A possible PI for CAPEX could be saved kWh/ year.

Since the main focus for WWTP in general is to keep within the limits, PIs could be normalized against effluent limits, to be presented as percentage below limits.

6.2 SOURCE OF ERRORS

There are many factors that affect the result and feasibility of this master thesis. The selection of WWTPs may not be representative. The WWTPs were chosen to be middle sized and to have good sampling routines, so it was possible to evaluate as many PIs as possible. These standards were not always met due to difficulty to find WWTPs that fitted the description and wanted to participate in the study.

If the standards were chosen differently, the result may have been different. It might have been more meaningful to study several WWTPs with the same plant and process configuration.

Errors may exist in the datasets. Data for calculations have, as far as possible, been collected from accredited laboratories. When data was scarce, so called in-house samples were used. .

6.3 VARIABLES THAT AFFECT THE OUTCOME

The composition of influent wastewater affects the efficiency of the processes and toxic compounds may also affect the treatment. Different plants have different conditions that are important to be aware of; climate and topography at the plant are examples. It is important to remember what information lies behind the PI or is embedded in the PI when benchmarking between WWTPs. PIs are a useful tool to reveal patterns and the exact number of the PI is less important because they contain simplifications and assumptions.

7 CONCLUSIONS

The variation in percentage removal and effluent organic matter during a year was insignificantly small. The removal of organic matter was high in all investigated WWTPs. A PI regarding the removal of organic matter with a yearly basis in the denominator should therefore be sufficient.

The removal of phosphorus was high for every WWTP, in this study, that had legislated limits concerning phosphorus.

Low nitrification was responsible for the largest nitrogen fraction to recipient during lower temperatures; otherwise it was residuals from denitrification that was the largest nitrogen fraction to the recipient.

Nitrogen was the parameter responsible for the major fraction of the OCP value and therefore it was the effluent nitrogen that affected the oxygen demand in the recipient the most. From an environmental point of view, the effluent nitrogen should be the main focus to reduce for the WWTPs in this study.

Nitrogen is the substance that has shown to be closest, in this study, to restriction values and also the parameter that follow a yearly pattern. Nitrogen and fractions of nitrogen were the most interesting PI to study with a monthly basis in this thesis.

Sternö WWTP has, comparing to Rustorp WWTP, a slightly more efficient secondary treatment step. Efficiency was difficult to calculate due to scarcity of measurements so it is always important to be aware of which assumptions are embedded in the result.

The unit in which to measure PIs may vary. It is suitable to use a yearly basis when comparing WWTPs with each other, thus eliminating the effect the geographic position of the WWTP might have on variation in process performance. A monthly basis is suitable when a single WWTP wants to compare its process performance over time.

If a plant has high effluent values of organic matter and phosphorus it could be correlated to diverting water through bypass at the plant and treating the bypass water could be a solution.

All of the studied WWTPs were performing much better than they were legislated to do. This enables the WWTPs to try and become more energy efficient without risking their limits.

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APPENDIX A

The following equations were used to calculate energy need:

ACTUAL OXYGEN REQUIREMENT (AOR)

Actual oxygen requirement is the oxygen requirement during the conditions in the secondary treatment and is calculated through equation (A1).

$$AOR = Q(X(BOD_{5,in} - BOD_{5,eff}) + Y(NH_{4,in} - NH_{4,eff})) \tag{A1}$$

where,

AOR = actual oxygen requirement [kg O_2/d]
Q = flow at WWTP [m^3/d]
X = oxygen need for oxidation of organic matter [kg O_2/kg BOD_5]
Y = oxygen need for oxidation of ammonium [kg O_2/kg NH_4^+]
BOD_5 = BOD_5 influent and effluent at the WWTP [kg/m^3]
NH_4^+ = NH_4^+ influent and effluent at the WWTP [kg/m^3]

Oxygen need for oxidation of organic matter is 1.0 and oxygen need for oxidation of ammonium is 4.57 (see equation (8)). Influent and effluent samplings of BOD and NH_4^+ are required.

OXYGEN TRANSFER RATE (OTR_f)

To be able to compare oxygen requirements between WWTPs, corrections must be done so that AOR is adjusted to standard conditions from field conditions (OTR_f) using equation (A2).

$$OTR_f = AOR + (Q \times DO) \tag{A2}$$

where,

OTR_f = field oxygen transfer rate [kg/d]
Q = flow in tank [m^3/d]
DO = dissolved oxygen concentration in tank [kg/m^3]

Dissolved oxygen is sometimes measured but, at least, the operators have a rough estimate of DO in the tank.

STANDARD OXYGEN TRANSFER RATE (SOTR)

SOTR is the oxygen transfer rate converted to zero DO, a standardized temperature of 20°C, atmospheric pressure (101.3 kPa) and an oxygen transfer coefficient of clean water (K_La).

$$SOTR = \frac{OTR_f \cdot C^*_{\infty 20}}{\alpha F \theta^{(T-20)}(\Omega \tau \beta C^*_{\infty 20} - C)} \tag{A3}$$

where,

SOTR = standard oxygen transfer rate [kg/d]
α = process water K_La / clean water K_La [-]
F = process water K_La of diffuser after given time / process water K_La of new diffuser [-]
θ = correction factor for temperature on K_La [-]
T = temperature [°C]
$C_{\infty 20}^*$ = steady-state DO saturation concentration at infinite time for a given diffuser at 20°C and 1 atm [kg/m^3]
C = process water DO concentration [kg/m^3]
Ω = field atmospheric pressure / mean sea level atmospheric pressure [-]
τ = correction factor for temperature on $C_{\infty 20}^*$ [-]
β = process water $C_{\infty 20}^*$ / clean water $C_{\infty 20}^*$ [-]

Approximations were made after discussions (pers. comm. Nordenborg, 2012); F=1, $\alpha=0.65$ and $\Omega=1$. $\Theta=1.024$ and $\beta=0.98$ were values from literature (Tchobanoglous, et al., 2003).

$C_{\infty 20}^*$ is possible to calculate with equation (A4) if depth of diffusers are known.

$$C_{\infty 20}^* = C_{s20}^*(1 + \frac{P_{water}}{P_{water}+P_{msl}}) \qquad \text{(A4)}$$

where,

C_{s20}^* = tabular value from (ASCE, 2007) of DO surface saturation concentration [kg/m^3]
P_{water} = water pressure [Pa], calculated according to (A5)
P_{msl} = mean sea level atmospheric pressure [Pa]

$$P_{water} = \rho \cdot g \cdot h \qquad \text{(A5)}$$

where,

ρ = density of water [kg/m^3]
g = acceleration of gravity [m/s^2]
h = diffuser depth [m]

STANDARD OXYGEN TRANSFER EFFICINCY (SOTE)

Standard oxygen transfer efficiency is the fraction of oxygen that is dissolved in the wastewater under standard conditions and is calculated by equation (A6).

$$SOTE = \frac{SOTR}{\rho_{air} \cdot [O_2] \cdot Q_{air}} \qquad \text{(A6)}$$

where,

SOTE = standard oxygen transfer efficiency [-]
ρ_{air} = density of air [kg/m^3]

$[O_2]$ = concentration of oxygen in the air [-]
Q_{air} = airflow [m^3/d]

SOTE from equation (A6) is estimated from brand-specific information from manufacturer homepages in this master thesis. If SOTR is calculated, airflow can be solved from equation (A6).

The calculated airflow is divided by total airflow and a linear relationship is assumed between airflow and power, which is supported by samplings in Sternö, Figure A1.

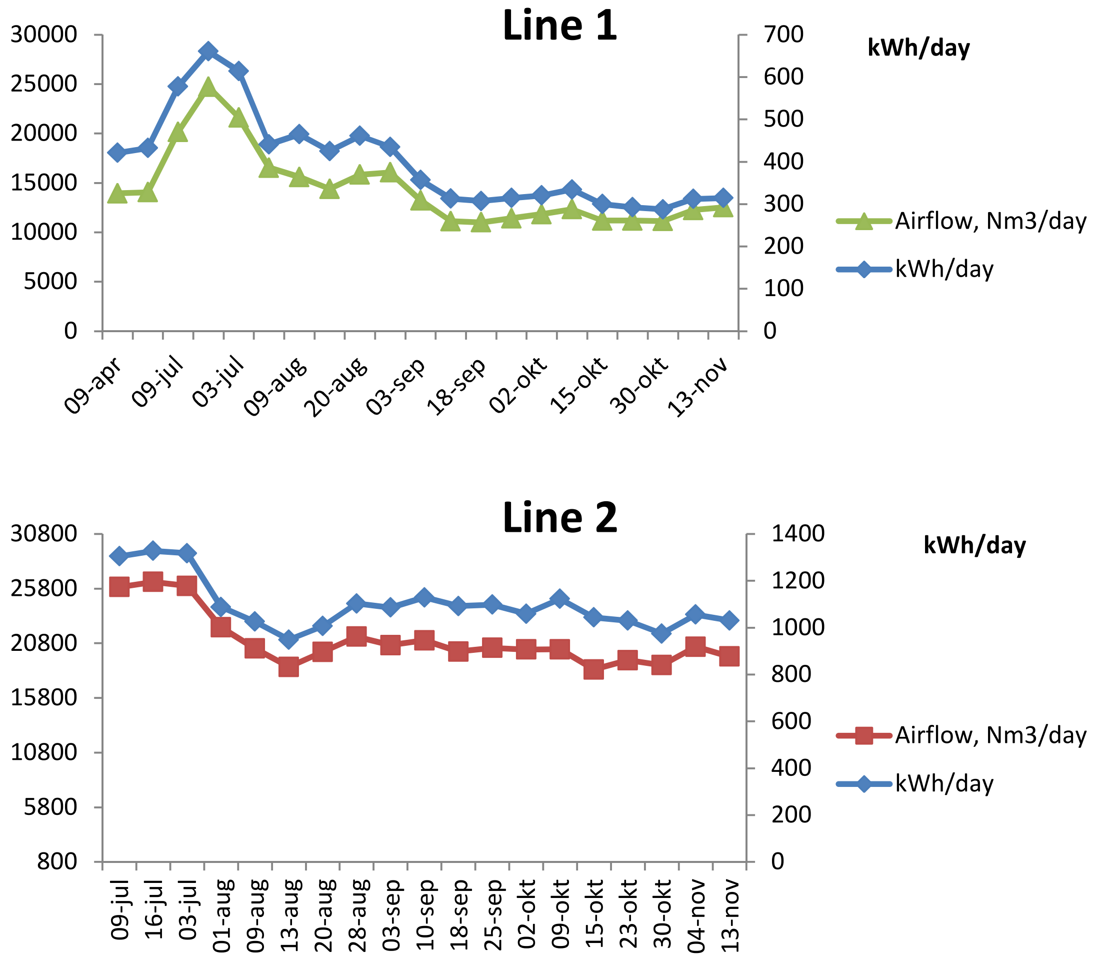

Figure A1.*Airflow and energy use in line 1 and line 2 at Sternö WWTP.*

When the quota between calculated and total airflow is known, the same quota is applied for the motor power of the blowers, multiplied by hours it is running. This results in a rough calculation of energy need in kWh/time-interval.

APPENDIX B - STERNÖ

Of the parameters in Figure 12, the ones that seem to be correlated to temperature is nitrogen and total organic carbon.

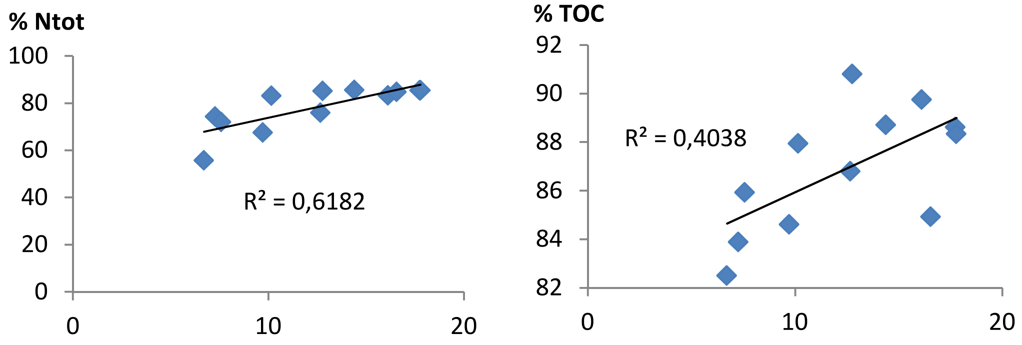

Figure B1. *Correlation chart between temperature, total nitrogen removal and total organic carbon removal.*

The positive correlation, Figure B1, between removal of total nitrogen and temperature is 0.62, which indicates that there is a relationship between the parameters. There also seems to be a slight positive correlation between temperature and removal of TOC, albeit less.

Figure B2 shows only total nitrogen and temperature to better visualize the dependence.

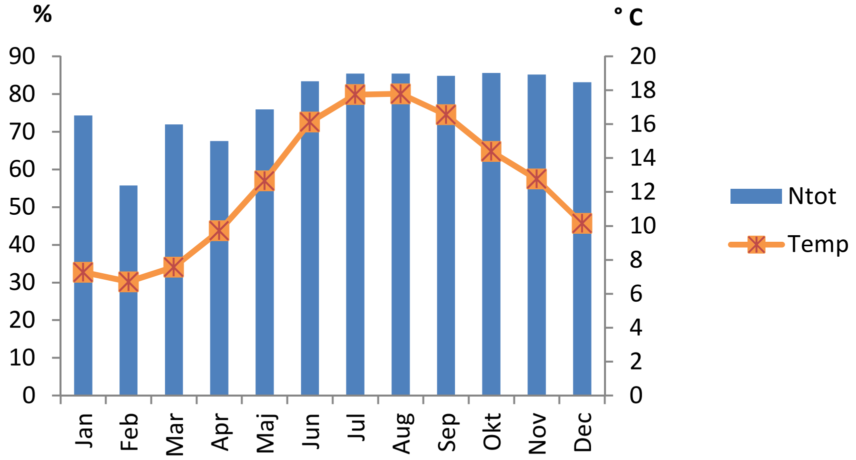

Figure B2. *Total nitrogen removal versus temperature for 2011. In spring, when temperature is low, nitrogen removal is lower.*

The lowest value for N-tot removal is in February at 55 % and after June the removal is constantly at about 85 %. Why removal of nitrogen still is relatively high from October to January is unclear. The high removal rate at the end of the year has a probable explanation in the upgrade of the plant but that is not an explanation for the value in January.

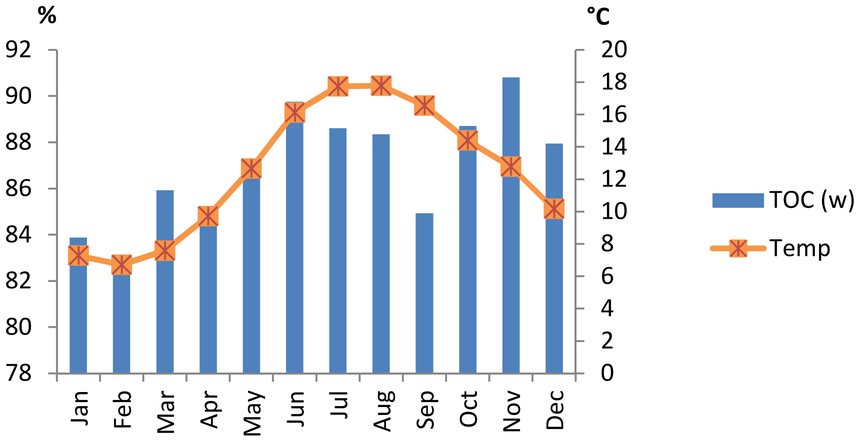

Figure B3. *Total organic carbon removal and temperature for 2011.*

Total organic carbon is visualized in Figure B3. The removal of TOC varies between 83 – 91 % during 2011 and the removal is lowest in January to May but September also shows a low removal rate.

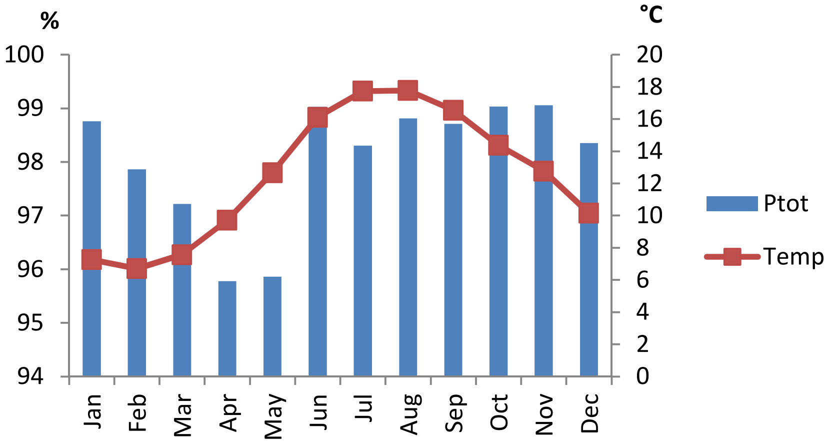

Figure B4. *Total phosphorus removal in percent during 2011 and temperature variations in influent wastewater during the same period. The left axis starts at 94 percent.*

Phosphorus removal at Sternö is consistent and above 98 percent except during the period February to May. There is no apparent correlation between temperature and phosphorus removal. The variability in percent removal of phosphorus is much less than the variability in percent removal of nitrogen, see Figure B4.

APPENDIX C - HEADINGLEY

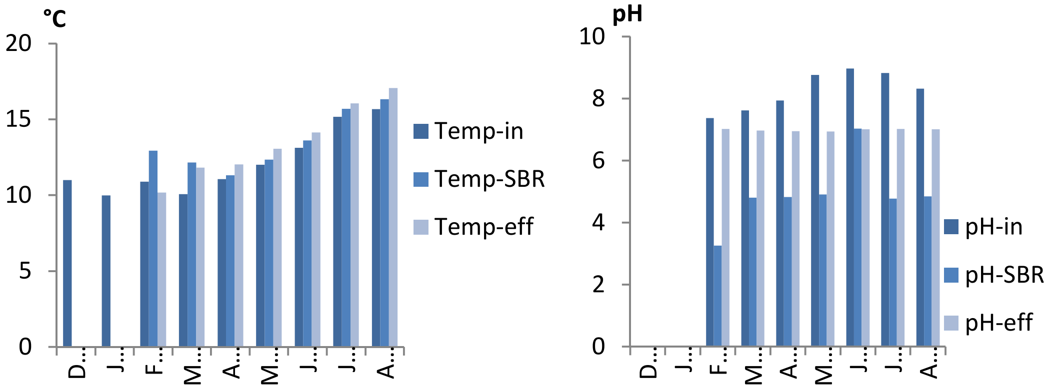

Figure C1. *Temperature and pH in influent, SBR-basin and effluent.*

The temperature rises continuously through the process, Figure, an explanation for that could be latent energy from aeration and biological processes. pH decreases from influent to SBR-basin, a possible cause for the decrease could be the carbonic acid released in nitrification (pH rises through denitrification but maybe not enough), see section 2.3.4.