



University of  
Stavanger

**Faculty of Science and Technology**

## **MASTER'S THESIS**

**Study program/ Specialization: Environmental  
Monitoring and Nature Management in the  
Northern Oil and Gas Producing Regions**

**Spring semester, 2016  
Open access**

**Writer:  
Maliheh Salimi**

.....  
**(Writer's signature)**

**Faculty supervisor: Dr. Roald Kommedal**

**External supervisor(s): Dr. Leif Ydstebø**

**Thesis title:**

**Sludge production in chemical precipitation**

**Credits (ECTS): 30**

**Key words: wastewater treatment, sludge  
production, TTS, COD, Ferric Chloride,  
alkalinity, chemical precipitation**

**Pages : 65**

**+enclosure**

**Stavanger: June 2016**

## **Acknowledgement**

I am very grateful to my adviser Dr. Leif Ydstebø for his precious support; guidance and mentoring through the theoretical and practical work as well as in writing the thesis From the very first day.

Thanks to Dr. Roald Kommedal for his academic guidance and support during my studying and writing the thesis.

Thanks to my colleague Eric Gramstad who helped me have a memorable time through the samples collecting and laboratory works.

I also appreciate laboratory and administration staff that supported me whenever I needed.

And finally my special thanks to the family, my parents and my sisters for their moral support.

## Abstract

Ferric chloride as in many other wastewater plants is used as a coagulant in wastewater treatment at Ivar (SNJ) since its multivalence nature has a significant effect on overcoming the stability of particles and consequently results in material precipitation by gravitational sedimentation process that concludes in proper removal of suspended solids as well as colloidal particles. This results in sludge production which should be treated before disposal. Prediction the amount of sludge produced during the chemical treatment is essential to estimate the volume and retention time required for the sludge treatment.

Observation at SNJ showed that the sludge production was not proportional with suspended solids removed or ferric chloride added. Laboratory-scale studies were carried out to investigate a corresponding relationship between the actual and expected sludge production during the coagulation and flocculation process.

For this purpose, jar tests were conducted and effect of ferric chloride dosage on pH, conductivity, TSS, TSS- removal, alkalinity and calculated and measured sludge production as well as comparison of those two last parameters was investigated. Results achieved in the laboratory showed an acceptable conformity between the measured and calculated sludge productions, particularly in dilute wastewater samples which resulted in lesser amounts of sludge.

In addition to laboratory experience, the result of full-scale plant that received from Ivar was reviewed and investigated to express the distinction between both scales.

## Table of content

1.	Introduction .....	1
1.1	Objectives.....	3
2.	Literature review.....	4
2.1.	History of wastewater treatment .....	4
2.2.	Wastewater characterization and origin of wastewater .....	5
2.3.	Physical and chemical treatment of wastewater.....	7
2.3.1.	Coagulation and flocculation .....	8
2.3.2.	Chemical precipitation by metal coagulants.....	9
2.3.3.	Theory of chemical precipitation .....	11
2.3.4.	Ferric chloride .....	12
2.4.	Sentralrenseanlegg Nord-Jæren (SNJ) .....	13
2.4.1.	Observation.....	17
3.	Materials and methods.....	18
3.1.	Materials .....	18
3.2.	Analytical methods .....	19
3.2.1.	Jar test.....	19
3.2.2.	pH and Conductivity.....	21
3.2.3.	Total suspended solids (TSS).....	22
3.2.4.	Alkalinity.....	23
3.2.5.	Chemical oxygen demand (COD) .....	25
3.2.6.	Measured sludge production.....	27
3.2.7.	Expected sludge production .....	27
4.	Results and discussion .....	28
4.1.	The labratoty results .....	28
4.1.1.	pH vs. ferric chloride dosage.....	29
4.1.2.	Conductivity vs. dosage of ferric chloride.....	30
4.1.3.	TSS and TSS removal vs. dosage of ferric chloride.....	31
4.1.4.	Alkalinity vs. dosage of ferric chloride .....	33
4.1.5.	Filtered COD vs. dosage of ferric chloride .....	34
4.1.6.	Measured sludge production vs. dosage of ferric chloride .....	35
4.1.7.	Calculated sludge production vs. dosage of ferric chloride.....	36
4.1.8.	Expected vs. measured sludge production .....	37
4.2.	The results of full scale at SNJ.....	44

5. Conclusion and recommendations .....	47
References .....	49
Appendix A .....	51
Appendix B .....	52
Appendix C .....	55

## List of Figures

Figure 2-1 Electrical double layer based on Stern's model .....	12
Figure 2-2 A schematic view of Ivar (Sentralrenseanlegg Nord-Jæren (SNJ)) in Randaberg	14
Figure 2-3 Ivar's process flow diagram .....	15
Figure 3-1 Jar tester .....	20
Figure 3-2 wastewater samples for jar test.....	21
Figure 3-3 portable pH and conductivity meter at UiS laboratory .....	22
Figure 3-4 the new alkalinity meter which was used for this study at UiS laboratory .....	24
Figure 3-5 Termoreactor TR 620.....	26
Figure 3-6 Spectroquant Pharo 300, Merck .....	26
Figure 4-1 Effect of ferric chloride on pH.....	30
Figure 4-2 Effect of ferric chloride on conductivity .....	31
Figure 4-3 Effect of ferric chloride on total suspended solids .....	32
Figure 4-4 Effect of ferric chloride on TSS removal .....	33
Figure 4-5 Effect of ferric chloride on alkalinity .....	34
<b>Figure 4-6</b> Effect of ferric chloride on COD .....	35
Figure 4-7 Effect of ferric chloride on measured sludge production .....	36
Figure 4-8 Effect of ferric chloride on expected sludge production .....	37
Figure 4-9 Calculated sludge production and measured sludge production .....	39
<b>Figure 4-10</b> Calculated sludge production and measured sludge production .....	40
Figure 4-11 Expected sludge production and measured sludge production .....	44

## List of Tables

Table 2-1 Chemicals used in wastewater treatment industries .....	10
<b>Table 2-2</b> Treatment requirements at Ivar (Sentralrenseanlegg Nord-Jæren (SNJ)).....	16
Table 4-1 Expected and calculated sludge producing vs. 55.56µl/l of ferric chloride .....	41
Table 4-2 Difference between expected and calculated sludge producing vs. 83.33µl/l of ferric chloride .....	42
Table 4-3 Distinction between expected and calculated sludge producing vs. 111.11µl/l of ferric chloride .....	42
<b>Table 4-4</b> comparison between expected and calculated sludge producing vs. 166.67µl/l of ferric chloride .....	43
Table 4-5 Difference between expected and calculated sludge producing vs. 222.22µl/l of ferric chloride .....	43
Table 4-6 Concentration of relevant parameters in the SNJ plant .....	45
Table 4-7 Consumption and formation of chemicals .....	45
Table 4-8 Estimated sludge production .....	46
Table 4-9 Sludge production measured in the plant .....	46

## **Abbreviations**

BOD: Biological oxygen demand

COD: Chemical Oxygen demand

TSS: Total suspended solids

SNJ: Sentralrenseanlegg Nord-Jæren (Ivar wastewater treatment plant)



## Chapter 1

### 1. Introduction

Wastewater treatment is the field of environmental engineering by which the main fundamentals of science and technology are utilized to solve the water pollution difficulties. As all other concepts of this category, the endmost intention is the conservation of the environment in a manner correspondent with public health and safety as well as social, economic and political regards (Tchobanoglous, Burton, Stensel, Metcalf, & Eddy, 2003).

A society's water supply is applied to flush and carry a diversity of wastes, therefore the wastewater comprises of more than 99.9% water, although the less than 0.1% solids are substantial due to their amount and potential influence on the society. Health of society wouldn't be guaranteed unless appropriate processes related to wastewater treatment such as collecting, treating, particles and solids removal and recycling of the products. The most important purpose of wastewater treatment consists of:

- Inhibition of morbidity and inconvenience
- Evasion of water reservoir contamination and filling up shippable waters
- Retaining clean waters for reproduction and aquatic organisms' survival and water conservation for future generation.

Chemical unit processes, despite the increasing desire for using the biological treatments, have still a significant role in evolving the separation methods in wastewater treatment. Chemical precipitation as one of the most usable

procedures in wastewater treatment consists of exploiting chemicals to modify the condition of dissolved and suspended solids to assist their separation by means of further sedimentation(Tchobanoglous et al., 2003).

Sludge as the main production of chemical precipitation is an integral component of wastewater treatment which ought to be treated appropriately, mainly by biological methods such as composting or anaerobic digestion before releasing to the environment. The produced sludge may contain some heavy metals and includes considerable amount of nutrients and organics that could be contemplated as a valuable source(Vesilind, 1979).

The amount of sludge produced during the chemical precipitation which has a direct corresponding to the quantity and quality of the raw wastewater and the dosage of added coagulant, can affect the cost of design and development of downstream units of plant. Creating larger particles which leads to enhanced further sedimentation, is the most striking feature of using chemicals such as alum or ferric chloride which are applied as coagulant in the mentioned process. Superior solid removal will result by using more (optimum) amount of chemicals, however; the larger volume of sludge production will enhance the load to the sludge treatment (biological) process. This study was one of the subjects proposed by Ivar (SNJ) and was done at University of Stavanger in cooperation with Ivar (the company and its activities will be introduced in chapter2).

## 1.1. Objectives

This research is to study sludge production from chemical precipitation with ferric chloride which is considered to be a function of various variables such as: the removal suspended solids (TSS), formation of  $\text{Fe}(\text{OH})_3$ , formation of  $\text{FePO}_4$  and precipitation of colloids. The main purpose of this study is to evaluate the measured (actual) and calculated (theoretical) amount of sludge production during wastewater treatment and to see how reliable our estimation could be. Beside this, diverse parameters related to chemical precipitation such as TSS, conductivity, alkalinity and COD are reviewed to illustrate the effect of ferric chloride on them. In addition to these results, the full scale's outcomes were discussed as well and finally all data presented in appendixes to support the study. The whole article is presented in five chapters:

- 1- Introduction
- 2- Literature review
- 3- Material and methods
- 4- Results and discussions
- 5- Conclusions and recommendations

## Chapter 2

### 2. Literature review

An overview of wastewater treatment, theoretical concept of chemical precipitation by means of coagulant, particularly ferric chloride, and sludge production in addition to a review of Ivar (SNJ) and its observations are compiled in this chapter.

#### 2.1. History of wastewater treatment

In the beginning of 1900s it was common to release the wastewater directly to the sea, ocean or any kind of water streams which resulted to reposition of sludge, noisome smell and phagosome situation. Constructing sewers and stablishing wastewater treatment industries were considered as the solutions for mentioned problems, however, the next challenge to prevail was how to get rid of the amount of sludge which was proportional to the mass of pollutants removed by the vigorous techniques of treatment(Tchobanoglous et al., 2003).

Development of wastewater treatment was the most obvious in the 20<sup>th</sup> century. Sewers were discussed as a risk possibility for Human health, however; the importance of human's excrement as a fertilizer was known beforehand. The surface water's quality appeared a new issue in the last half of 20<sup>th</sup> century, which was affected by eutrophication that means eruptive enhancement of algae and also other plants in water which happens because of fertilizing effect of the nitrogen and phosphorus evacuated to the rivers(Henze, 2008).

At the beginning wastewater treatment techniques were utilized to achieve public health and prevent adverse consequences due to release of wastewater to the environment. These techniques consist of physical/mechanical, chemical and finally biological methods(Tchobanoglous et al., 2003).

It is predicted that wastewater treatment industry in the new era will be defined by a substantial variety of wastewater sources which will be managed to be treated independently and individually and includes household, locality and intensive scales(Habermacher, Benetti, Derlon, & Morgenroth, 2015).

## **2.2. Wastewater characterization and origin of wastewater**

Perception of the specification of wastewater is very important for design and process of collection, treatment and discarding equipment. Understanding the physical, chemical and biological characteristics of wastewater will lead us to proper treatment method(Tchobanoglous et al., 2003). The quantity and quality of waste generated in households is affected by different parameters such as lifestyle and standard of living of society as well as technological and legal structure in which people are inscribed(Henze, 2008).

Based on the Urban Waste Water Directive of EU Council, the maximum allowable amount of discharge components from urban secondary wastewater treatment process are: maximum 25mg/l  $O_2$  for BOD5 at 20 °C, 125 g/l  $O_2$  for COD and 35mg/l for total suspended solids(EU Council Directive,1991).

The constituents which form the wastewater stream depend on the origin:

- 1- Sanitary wastewater from residential districts and urban areas and relevant facilities.
- 2- Industrial wastewater which mostly consists of industrial and manufacturing wastes.
- 3- Infiltration /Inflow water that usually contains the water from leaks, cracks and breaks as well as drain connections or manholes.(Tchobanoglous et al., 2003)

Societies produce different amount of wastewater based on sewage users. A usual volume for community wastewater stream is 450 lpcd (l/person.d) that expresses contemporary facilities are applied through the residential area. In such region the wastewater contains about 110 grams suspended solids and 90 grams BOD in case of organic matter per person per day. Industrial wastewater contributes to the community sewer flow after some pretreatment processes which could vary from a simple dilution of the residuals to removal of toxic metal ions. In case of recycling the residential wastewater, a particular emphasis should be placed on pretreatment procedure to prevent pollution's adverse impact on reused water(Hammer & Hammer, 2004).

The contamination of freshwater ecosystem by synthetic chemicals is an essential global problem which is increasing as a result of increasing world population and industrial development of nations. More than 100,000 chemical compounds are commercially registered in Europe which may be already entered to water bodies (Eggen, Hollender, Joss, Schärer, & Stamm, 2014).

### **2.3. Physical and chemical treatment of wastewater**

Physical treatments which are mostly based on operation by means of physical and mechanical forces are used in the first steps of wastewater treatment. Usually these operations consist of screening, mixing, sedimentation, settling, floatation, filtration, fluid transfer and so on (Tchobanoglous et al., 2003).

As a common device in many industries screens are applied for removal of large solid particles in the inlet stream. Generally sedimentation is the procedure through which suspended matters that are denser than water settle by gravity force resulting in separation of mainly suspended solids (Tchobanoglous et al., 2003).

In addition to an extensive utilization in drinking water treatment, recently, filtration is convenient for achieving auxiliary removal of suspended solids especially particulate BOD and also to eliminate precipitated phosphorous (Tchobanoglous et al., 2003).

A sufficient combination of physical and chemical treatment will lead to a proper separation before and after biological treatment.

Chemical unit processes that are based on chemical changes or reactions have continuity with both physical and biological treatment. In this industry, chemical precipitation adsorption and disinfection could be considered as some instances of this category. Chemical precipitation that will be expressed by detail later is defined by adding deliberate chemicals to shift the physical condition of dissolved and suspended solids and to assist it by sedimentation process.

Nowadays due to reaching to a higher quality of effluent, adsorption as a result of using activated-carbon has become more convenient and also disinfection represents the selective demolition of pathogenic organisms in water and wastewater treatment.

Physical and chemical treatment are becoming more essential in wastewater treatment industry, such as removal of phosphorous in activated sludge process as a chemical or chemical/biological treatment (Musvoto, Wentzel, Loewenthal, & Ekama, 2000).

### **2.3.1. Coagulation and flocculation**

Coagulation and flocculation are very significant in water and wastewater treatment whereas coagulation is the procedure by which destabilization of the solution is performed. The role of coagulation is to prevail the stability of the system and flocculation defines as a process in which destabilized particles are enforced to get closer to each other, encounter and as a result of that make bigger agglomerates. Metal coagulants such as alum, ferric sulphate and ferric chloride are used as primary coagulants in wastewater treatment to effect destabilization of the solution (Bratby, 2006).

Filtration, floatation and sedimentation are more efficient when the size of the particles in wastewater is bigger; however, if they are too small to be possible to remove by these methods, their size can be expanded by means of agglomeration and coagulation (Gregory & O'Melia, 1989).

Settling of tiny materials and colloidal particles is not a fast phenomenon and letting it by gravitational will cost a lot, therefore coagulation and flocculation are applied to separate them from wastewater (Hantanirina, 2010).



It is usual to apply chemicals to increase primary treatment through sedimentation as a result of coagulation and flocculation. This technique will lead to decreased capital costs and less space, as well as removal of phosphorus and toxic metal and effectual treatment in the case of storm incidents (Bratby, 2006).

The coagulation process has a high yield of removal of COD (chemical oxygen demand) and TSS (total suspended solids) by means of Al(III) or Fe(III) salts or calcium salts and by using some polymers as flocculants (Guida, Mattei, Della Rocca, Melluso, & Meriç, 2007).

### **2.3.2. Chemical precipitation by metal coagulants**

In wastewater treatment's process, chemical precipitation means the adding of some chemicals to change the physical condition of dissolved and suspended solids in the solution and to simplify the removal of them by sedimentation. Previously, chemical precipitation process was applied to increase the amount of suspended solids and BOD elimination, however; since the 70s chemical precipitation has been further considered in case of more entire removal of organic and inorganic compounds in wastewater. By the means of chemical unit process, treatment will be achieved by generating a chemical precipitate which tends to settle. Further separation process may include to handle the solid waste and chemical compound (Tchobanoglous et al., 2003).

Several chemical precipitants have been applied in wastewater treatment. A list of the most popular precipitants is presented in Table 2.1. The result of the treatment is a function of the amount of added chemicals and the following separation process.

Normally chemical precipitation results in a proper separation of suspended and colloidal solids. Considering gravitational sedimentation which bringing about 50-70% removal of total suspended solids and 30-40% of organic matter, it is possible to achieve to 80-90% removal of suspended solids, 40-70% of BOD<sub>5</sub>, 30-60% of COD and eventually 80-90% of bacteria by utilizing chemical precipitants.

**Table 2-1** Chemicals used in wastewater treatment industries

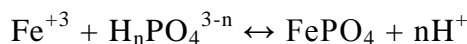
chemical	Formula	Molecular weight	Density, lb/ft <sup>3</sup>	
			Dry	Liquid
<b>Alum</b>	Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> · 18 H <sub>2</sub> O	666.7	60-75	78-80 (49%)
	Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> · 14 H <sub>2</sub> O	594.3	60-75	83-85 (49%)
<b>Ferric Chloride</b>	FeCl <sub>3</sub>	162.1		84-93
<b>Ferric sulfate</b>	Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>	400		
	Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> · 3H <sub>2</sub> O	454		70-72
<b>Ferrous sulfate</b>	FeSO <sub>2</sub> · 7H <sub>2</sub> O	278	62-66	
<b>Lime</b>	Ca(OH) <sub>2</sub>	56 as CaO	35-50	

Al(III) and Fe(III) as positively charged compounds made from hydrolysis process behave as beneficial coagulant for the removal of negatively charged matters. The anionic part on natural organic matter speeds up flocculation by means of producing complexes with positively charged aluminum and iron which results in their aggregation and precipitation processes (Shin, Spinette, & O'Melia, 2008).

Phosphorous will be integrated to both chemical and biological matters and consequently removed from wastewater. Metal salts are the most common chemicals for phosphorous treatment process and are normally applied in three phases known as pre-precipitation, co-precipitation and post-precipitation in which chemicals are

added either to raw wastewater, mixed in activated sludge or as a final polishing step after biological treatment, respectively.

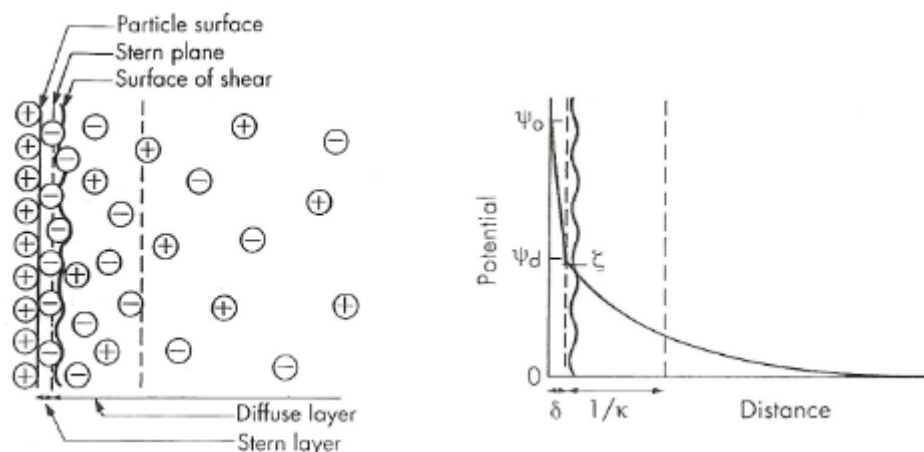
The general reaction of phosphate precipitation by iron is shown in equation bellow:



As it can be seen the mentioned equation displays an equal mole ratio of iron and phosphate, however, considering parallel reactions and many parameters such as pH, alkalinity, ligands and scarce matters which have adverse consequences, makes it arduous to estimates the dosage of coagulant and resulted materials, hence, using laboratory and full scales experiences are alternatives to theoretical concept.

### 2.3.3. Theory of chemical precipitation

Considering the complexity of nature of chemical precipitation which arises from incomplete main reactions and occurring many side reactions during the process makes it difficult to present a proper theoretical aspect for it. The colloidal particles in water solutions divided by two major groups of hydrophobic and hydrophilic particles. Stability as a result of particle's surface charge ought to be prevailed to make flocculation and sedimentation possible. The ions with contrary charge could attach to charged particle surface of colloids because of strong Van der Waals and electrostatic forces. This constant ion layer is covered by a spread layer to create a double layer in which the zeta potential declines from  $\psi_0$  to  $\psi_d$  and from  $\psi_d$  to 0 through compact and diffuse layer respectively as shown in Fig. 2-1.



**Figure 2-1** Electrical double layer based on Stern's model

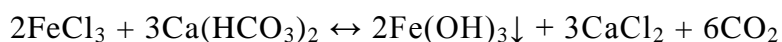
One of the techniques for making particles become associated is introduction the chemicals that result in hydrolyzed metal ions to reduce particle charge or minimize this effect. Applying potential-determining ions and electrolytes by the aim of decreasing the surface charge and zeta potential respectively, considered being the second solution and eventually using ionizable polymers (polyelectrolytes) with the purpose of preventing adsorption and bridging of particles (Tchobanoglous et al., 2003).

#### **2.3.4. Ferric chloride**

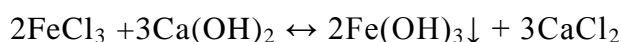
Natural and artificial components are used as coagulants, since the natural ones mostly contain starch and metals salts such as iron or aluminum. On the other hand, cationic, anionic and nonionic polymers can be used as well with significant efficiency but much more cost (Droste, 1997).

Ferric Chloride,  $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ , is applied essentially in wastewater coagulation. Commonly Ferric Chloride is made through chlorination of scrap iron and exists in both solid and liquid states.

In case of natural alkalinity of water, it reacts:



In case of adding lime or soda ash as alkaline chemicals, the reaction will be:



As  $\text{FeCl}_3$  is very corrosive, corrosion resistant facilities should be used. (Hammer & Hammer, 2004)

The removal of contaminants depends on many factors such as hydrolysis products, existence and reactivity of elements in complexation with iron species, hydrolysis kinetics between ferric chloride and other ligands, as well as mass transport rate of these components (Mosquera, 2014).

#### **2.4. Sentralrenseanlegg Nord-Jæren (SNJ)**

Sentralrenseanlegg Nord-Jæren (SNJ) which is located in Randaberg (about ten kilometer north of Stavanger) can be considered as one of the largest wastewater treatment plants in the country. Its operation was started in March 1992. The wastewater is received from residentials (sewage, rain and surface water) and industrial plants in municipalities of Randaberg, Stavanger, Sola, Sandnes and also Gjesdal. The plant was designed for a population equal to 240,000. The facilities for

wastewater treatment are placed in rock when other parts such as sludge treatment, landfill gas, workshops, laboratories and administration buildings are located outside. A 35 kilometer tunnel with a volume of 77,000 m<sup>3</sup> which acts as an equalizer carries the wastewater from initial destinations to Ivar and treated effluent evacuates to the Hastesinfjorden with a distance of 1.2 km from the shore and depth of 80 meters. Considering the population growth, it is anticipated to reach a wastewater amount of 500,000 population equivalent till 2050, so SNJ has planned for extending its plant and improving the capacity.



**Figure 2-2** A schematic view of Ivar (Sentralrenseanlegg Nord-Jæren (SNJ)) in Randaberg

Following there will be a short review of the process which is carried out in the plant:

Firstly, wastewater is pumped by means of four parallel pumps (each with a capacity of 1000 lit/sec) to the grid station for a pretreatment. Next stage is screening and

sand trap in which large particles are removed from the wastewater and the sands are separated through two similar aerated sand traps. In this step ferric chloride is injected to the stream to assist the formation of coarse particles, thereupon could be settled by the gravity.

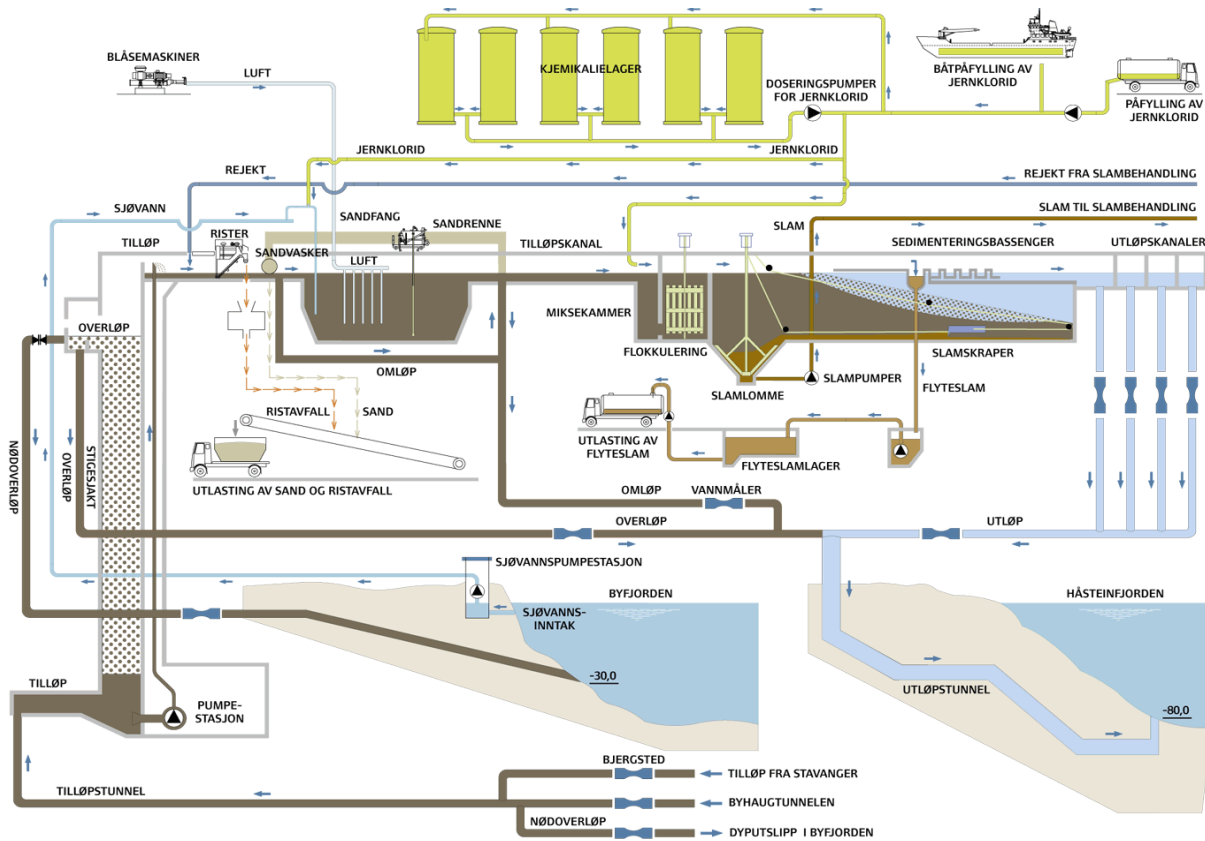


Figure 2-3 Ivar's process flow diagram

Through the sedimentation basins which consist of four vessels that have been formed from two tanks each, with the dimensions of 7m wide, 67.6m long and 4.8 meter depth. After this stage, treated effluent is evacuated to hasteinfjorden while the remained sludge with a consistency of 5 percent solids is pumped to anaerobic digester tanks. In these tanks anaerobic bacteria breaks down organic matter in the sludge, which results in production of biogas as a side stream product of SNJ with a

consistency of 60-70 percent methane. After a purification processes such as dehydration and defoaming, it can be sold to downstream industries.

The residual solids of the sludge passes through dewatering and drying plants which take place in the centrifuge drums and thermal dryers respectively and leave this stage by a consistency of about 85 percent. To achieve a product that can be easily handled, transported and stored, the produced sludge is compressed to small pellets which are suitable to utilize in non-agricultural lands. Finally thermal oxidation is applied in different sections for strong odor removal.

**Table 2-2** Treatment requirements at Ivar (Sentralrenseanlegg Nord-Jæren (SNJ))

Original requirements	
<b>Total P</b>	90 % removal and/or maximum 0.5 mg/l in effluent
<b>SS</b>	85 % removal and/or maximum 35 mg/l in effluent
New requirements	
<b>BOD*</b>	70 % removal and/or maximum 25 mg/l in the effluent
<b>COD**</b>	75 removal and/or maximum 125 mg/l in the effluent

\*: For BOD the effluent concentration exceeds the limit (36 vs. 25 mg/l) while the percentage removal is within the requirement (76 vs. 70 %).

\*\* : For COD the effluent concentration is within the limit (84 vs. 125 mg/l), while the percentage removal is below the limit (71 %).



### **2.4.1. Observation**

Based on observations in full scale at Sentralrenseanlegg Nord-Jæren (SNJ), the sludge production is not proportional with the SS(suspended solids) removal or  $\text{FeCl}_3$  (ferric chloride) added. Contributions from colloids and  $\text{Fe}(\text{OH})_3$  formations vary, depending on  $\text{FeCl}_3$  dosage and wastewater composition.

The objective of this study is to investigate the sludge production with different doses of  $\text{FeCl}_3$  and observe the relation between SS in effluent and sludge producing with added  $\text{FeCl}_3$ .

## Chapter 3

### 3. Materials and methods

This chapter presents an overview to the laboratory experience done for achieving the goals of this study. The wastewater samples were delivered from Ivar (SNJ) and following tests were carried out at university of Stavanger.

#### 3.1. Materials

The most important materials and instruments used for this research are listed here:

- Jar tester consists of 6 rotation paddles with the speed range of 0-140 rpm
- One liter beakers
- Analytical laboratory scale
- Syringes
- Stopwatch
- Sample and volumetric flasks
- Magnetic stirrer
- Graduated cylinders
- Glass microfiber filter, 1 $\mu$ m
- Vacuum filtering device
- Pipettes
- Burettes
- Automatic samplers

- Oven
- Desiccator
- pH and Conductivity meter
- Automatic titration device
- HCl 0.5 molar
- Ferric chloride (Appendix A)
- Termo reactor TR620
- Spectroquat pharo 300

### **3.2. Analytical methods**

The tests were done based on the procedures of standard methods for the examination of water and wastewater (Clesceri et al., 1998) and the best care was taken to be accurate and have all the solutions well mixed and all the instruments calibrated. Following the method for laboratory experiments and calculation basis are reported.

#### **3.2.1. Jar test**

It is common to analyze chemical precipitation of wastewater by means of coagulant in the laboratory by applying a jar test device which consists of several paddles for mixing different samples that has been added various dosages of coagulant.



**Figure 3-1** Jar tester

- 6 jars filled by wastewater were put on test-rack.
- Stirring at maximum speed for 30-60 sec while adding  $\text{FeCl}_3$  as coagulant.
- Slow mixing for 10 min (20-40 rpm); formation of flocs was observable in this phase.
- Sedimentation phase by stopping the mixer for 10 min.
- After 10 min, sampling by syringe was starting. (Collecting the sample from 1-2 cm below surface). Samples were taken in order to analyze different parameters such as TSS, pH, alkalinity and so on.



**Figure 3-2** wastewater samples for jar test

### **3.2.2. pH and Conductivity**

Both pH and conductivity were measured by using portable instrument of WTW Multi340i. Once a week before starting the tests, calibration of pH meter by means of standard buffer solutions of 4.01 and 7.00 was done manually. During the fast mixing, the pH probe was kept in the sample till reaching a constant number which could have been seen on the instrument's LED.

By changing the mode of WTW Multi340i portable instrument from pH to conductivity, conductivity of samples with different dosage of ferric chloride was measured.



**Figure 3-3** portable pH and conductivity meter at UiS laboratory

### 3.2.3. Total suspended solids (TSS)

This procedure was followed for both raw wastewater and jar test samples.

- Whatman GF/C glass microfiber filters with 1µm pore size were dried at 105°C, cooled and weighted.
- 100 ml of sample was transferred into a graduated cylinder and vacuum applied for filtering. (for being more accurate it was decided to use 150ml of samples in which 166.67 and 222.22 µl/l ferric chloride was applied respectively.)
- Filter was removed and dried for at least 2 hours in the oven at 105°C, then cooled and weighted for measuring the filter and solids weights.
- Total suspended solids (TSS) calculated from Equation 3.1.

$$TSS \left[ \frac{mg}{l} \right] = \frac{m_{filter + solids} - m_{filter}}{V_{sample}} \quad 3.1$$

### 3.2.4. Alkalinity

Generally alkalinity has defined as the capability of water to neutralize the acid, in the other words; alkalinity is the explanation of buffering capacity of a solution.

Hydroxides, carbonates and bicarbonates of calcium, magnesium, sodium, potassium and ammonia are the most important sources for alkalinity. During chemical and biological wastewater treatment, alkalinity could be considerable (Tchobanoglous et al., 2003).

It should be noticed that in this study, alkalinity was measured by two different procedures, manually through convenient method till 26<sup>th</sup> of January and by means of the new automatic titration device (TitroLine® 5000 Auto-Titration) as can be seen in Figure 3.4, after mentioned date.

The elements which constructed the automatic titration device comprised of acid container, stirrer unit, titration tip, display screen and measuring probe.



**Figure 3-4** the new alkalinity meter which was used for this study at UiS laboratory

For following the procedure, 50 ml of filtered sample (from TTS test) was located on stirrer unit to be mixed with a stable speed. Before starting the test pH was read and written down, titration was continued by adding a 0.05 molar solution of HCl (Lot No. 100317, Merck) to reach to pH 4.5. Corresponding amount of acid was recorded and eventually total alkalinity calculated from:

$$\text{Total Alkalinity [mg CaCO}_3\text{/l]} = ((\text{volume of HCl used[ml]} * \text{Normality of acid[eq/l]} * 50,000[\text{mgCaCO}_3\text{/eq}] / (\text{volume of sample[ml]}))$$

Since the volume of filtered sample was chosen 50 ml for all the tests and the molarity of acid was selected to be 0.05 mol/l (with a Hydrogen equivalent of 1), the alkalinity in this case would be calculated easily by measuring the amount of Hydrochloric acid used during the titration.



### 3.2.5. Chemical oxygen demand (COD)

COD is known as a measure of the matter that oxidizes chemically and normally is declared in terms of oxygen equivalents which means the amount of oxygen that can be reduced by electrons released among the oxidation process and it can be observed by soluble COD (sCOD) and total COD (tCOD).

For this study, filtered COD was conducted for wastewater samples before and after adding different dosages of ferric chloride. Filtered samples were collected every day after TSS test and kept in the freezer, and then the COD test was done for the preserved samples by using special vials (production No. 114895) particular for COD range of 15 and 300 mg/l. The procedure was conducted by following steps:

- After shaking very well and getting homogenized, 2 ml of sample was transferred to a COD vial by a volumetric pipette.
- Sample was digested in thermo reactor that can be seen in Figure 3.5, at 148°C for 2 hours. After removing it was left to be cooled in a metal test tube rack to room temperature and then put in spectrometer cell compartment which illustrated in Figure 3.6.
- After selecting the correct measuring method, COD was read.
- COD vial was placed in prescribed container (the content should not have done empty as the reagents contain strong acids and may include Hg).
- Dissolved COD was calculated from following equation:

$$sCOD = sCOD_{read} \frac{V_{sample} + V_{wash}}{V_{sample}}$$



Figure 3-5 Termoreactor TR 620



Figure 3-6 Spectroquant Pharo 300, Merck

### 3.2.6. Measured sludge production

Sludge production of samples was analyzed through the formula:

$$\text{Measured sludge production} = \text{TSS}_1 \cdot V_1 + \text{TSS}_2 \cdot V_2.$$

In which  $\text{TSS}_1$  was measured for the effluent gained from jar test, since the remained wastewater sample in graduated cylinder was mixed completely and  $\text{TSS}_2$  was evaluated with considering the  $V_2 = 0.9 - V_1$  (the remained wastewater in the cylinder after deducting  $V_1$ , considering the total volume of primary wastewater samples was 0.9 liter). Then the total amount of sludge production within coagulation process could be measured from the mentioned formula that can be considered as real or practical sludge production.

### 3.2.7. Expected sludge production

In this study calculated sludge production is a function of difference in influent and effluent suspended solids, formation of  $\text{Fe}(\text{OH})_3$ , formation of ferric phosphate and precipitation of colloids which appears as difference of filtered COD before and after precipitation with excess Fe, in other word:

Calculated sludge production =

$$V * [(\text{TSS}_0 - \text{TSS}_e) + \text{Fe}(\text{OH})_3 + ((\text{COD}_0 - \text{COD}_e) / (\text{COD} / \text{VSS}) + \text{FePO}_4]$$

In this formula,  $\text{TSS}_0$  and  $\text{COD}_0$  are corresponded to the parameters before applying ferric chloride while  $\text{TSS}_e$  and  $\text{COD}_e$  are related to effluent streams. The ratio of  $\text{COD} / \text{VSS}$  is to converting the COD basis to mass basis and based on the practical data from Ivar (SNJ), it is estimated around 1.2 gCOD/gTSS.

## Chapter 4

### 4. Results and discussion

In this chapter the results from laboratory and full scale plant are expressed and analyzed. The samples were received from Sentralrenseanlegg Nord-Jæren (Ivar) during January till April 2016 and different tests were done during this period of time. Based on the condition, the samples could be ‘morning’ wastewater which refers to wastewater collected during the night that is relatively dilute because of less activity of people in the residential and industrial areas. The ‘evening’ wastewater refers to wastewater collected in the afternoon/evening when the waste production is at its maximum due to the residents activities and is the most concentrated wastewater.

#### 4.1. The laboratory results

All the laboratory results such as ferric chloride dosage, pH, conductivity and temperature, total suspended solids (TSS), removal TSS, alkalinity, chemical oxygen demand (COD), removal COD, measured sludge production and calculated sludge production have been collected in table in appendix B.

Likewise, the data from Sentralrenseanlegg Nord-Jæren in 2015 prepared by Leif Ydstebø is gathered in another table in appendix C.

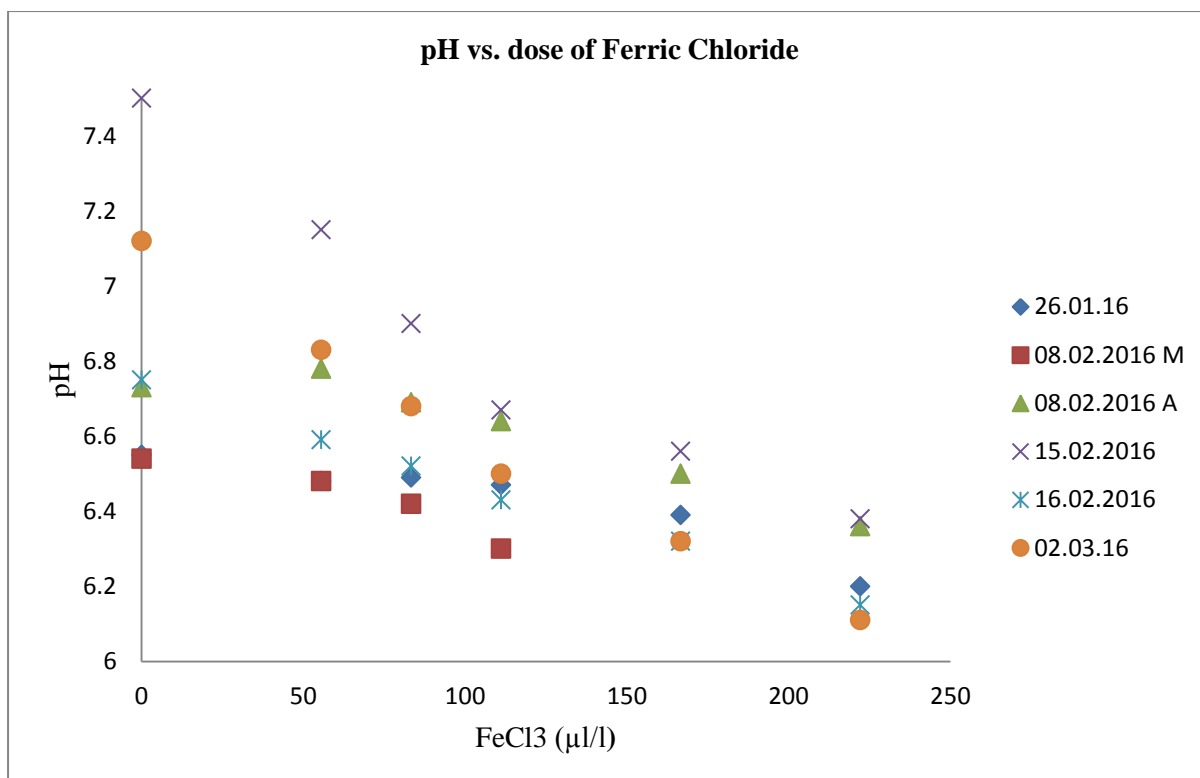
Totally 18 sets of test were carried out in the laboratory, however 6 of them were chosen to be continued to the whole procedure for measuring the sludge production,

so the following graphs will focus on these selected dates: 26.01.16, 08.02.16 (two tests were done in this day named M and A for morning and afternoon respectively), 15.02.16, 16.02.16 and 02.03.16. The samples of 26.01.2016, 15.02.2016 and 02.03.2016 were evening wastewater since the others were morning ones.

A special emphasis could be placed on various weather conditions during laboratory experience, which was rainy on 8<sup>th</sup> February, resulted to diluted samples and dry weather on 26<sup>th</sup> of January and 15 and 16<sup>th</sup> of February, expected to follow by denser samples, however, on 15.02.2016 the sample was dilute.

#### **4.1.1. pH vs. ferric chloride dosage**

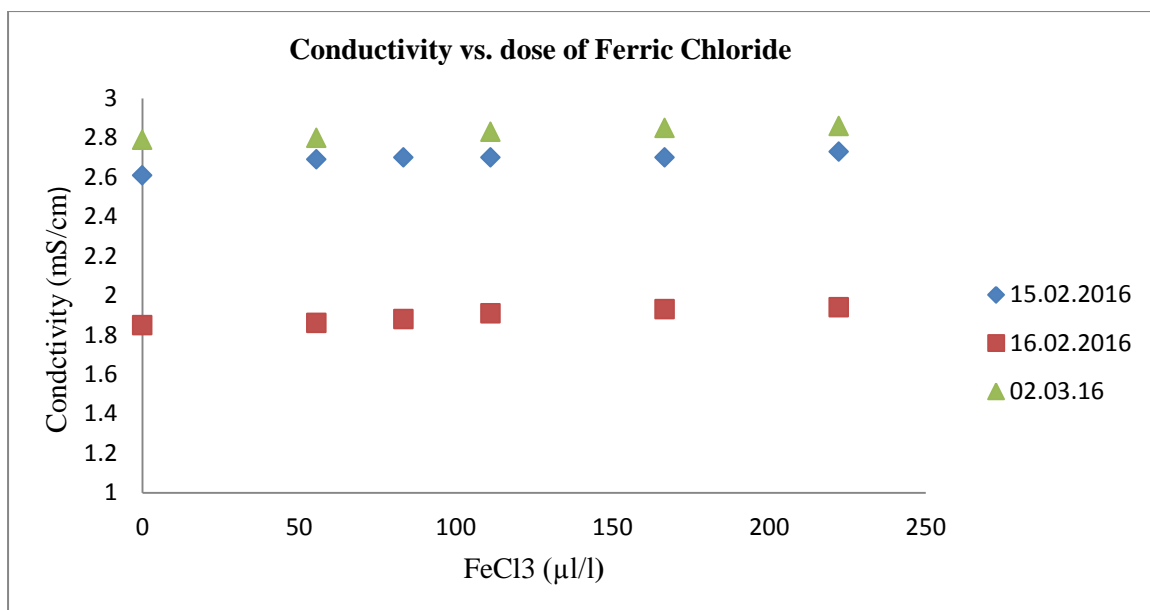
The first item measured before and after adding ferric chloride, was pH and as can be seen in the Figure 4.1, ferric chloride significantly affects pH by means of acidic quality it contributes to the solution after hydrolyzing. Almost all the samples followed the same decreasing trend, although the difference between two samples of same day of 08.02.2016 could be explained by 2mmol/l of NaHCO<sub>3</sub> added to 08.02.2016A to increase its alkalinity. Therefore as it is vivid, the addition of coagulant wasn't able to overcome the stability obtained due to usage of bicarbonate on this sample as well as 08.02.2016M which didn't utilize NaHCO<sub>3</sub>. In contrast to 08.02.2016M, the pH of 15.02.2016 was slightly higher than the others.



**Figure 4-1** Effect of ferric chloride on pH

#### 4.1.2. Conductivity vs. dosage of ferric chloride

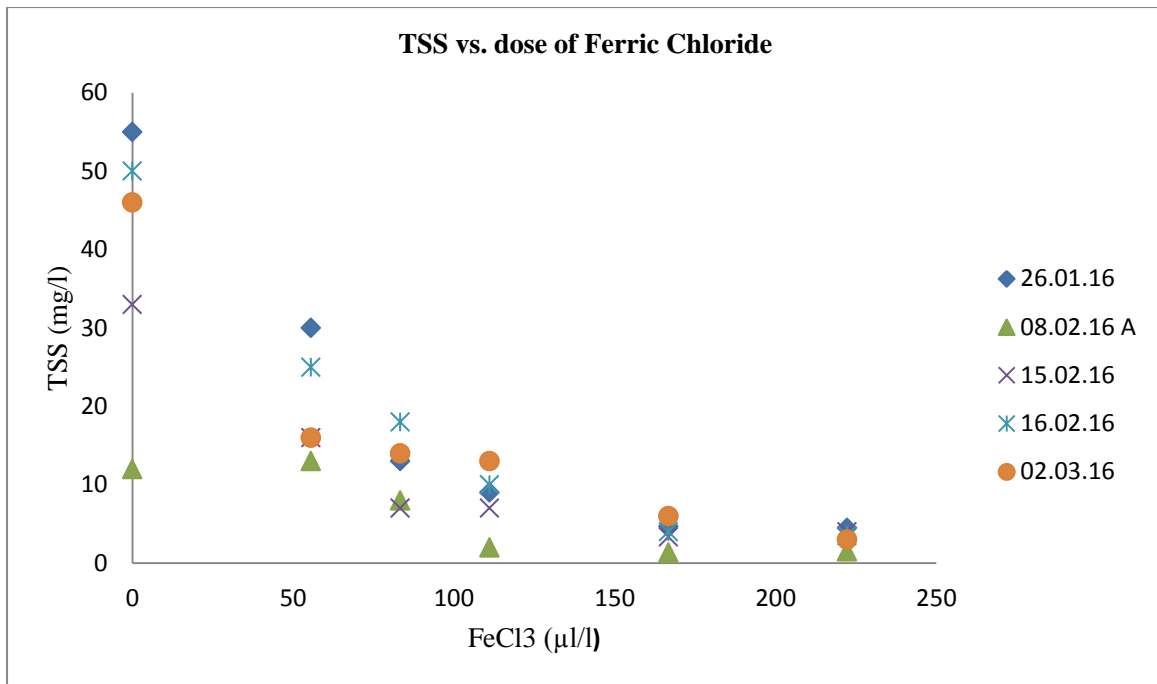
Since there was a problem with the probe for measuring the conductivity, the reliable data was measured just after 09.02.2016 and as can be observed from Figure 4.2 conductivity to some extent remained stable during the procedure for each sample in mentioned dates; however, there is a considerable difference between the results on 16.02.2016 in which the sample belonged to morning wastewater in dry weather and 15.02.2016 and 02.03.2016 through which samples pertained to evening time.



**Figure 4-2** Effect of ferric chloride on conductivity

#### 4.1.3. TSS and TSS removal vs. dosage of ferric chloride

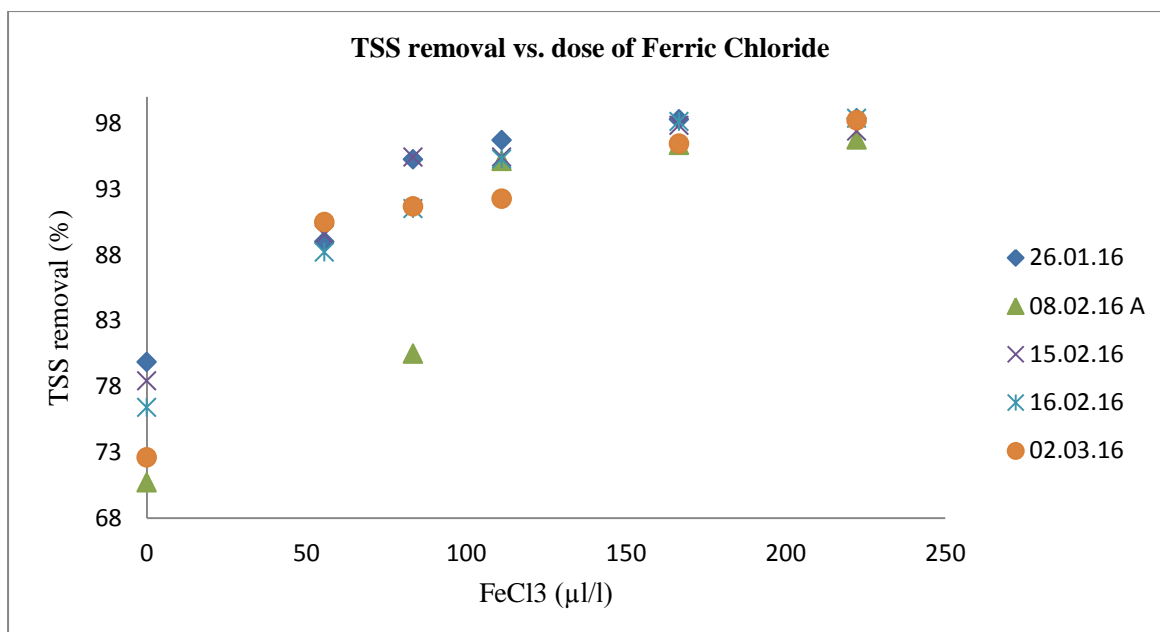
Treatment of each sample by means of different amount of ferric chloride in terms of total suspended solid has been provided in Figure 4.3. The predicted decreasing trend for all samples is vivid; however, the evening wastewaters (26.01.2016, 15.02.2016 and 02.03.2016) presented a better reaction to ferric chloride applied. The most drastic decline happened through adding the first and second dosages of FeCl<sub>3</sub>: 55.56 and 83.33µl/l respectively following by a steady pattern afterward which confirms that the extra amount of coagulant could have an unessential effect on the process.



**Figure 4-3** Effect of ferric chloride on total suspended solids

Additionally the projected data in the Figure 4.4 depicts the percentage of TSS removal based on ferric chloride dosage. Evidently there is an indication of the rise in all samples with sharp slope in the beginning and slight approach to complete treatment at the end. A particular emphasis could be placed on precipitation in absence of coagulant and by means of natural gravity in which the most dilute (08.02.2016) and dense (26.01.2016) wastewaters showed minimum and maximum percentage of separation as 70.73 and 79.85% respectively. Finally, it is obvious that all the samples met easily the required standard point for final TSS which is 35mg/l.

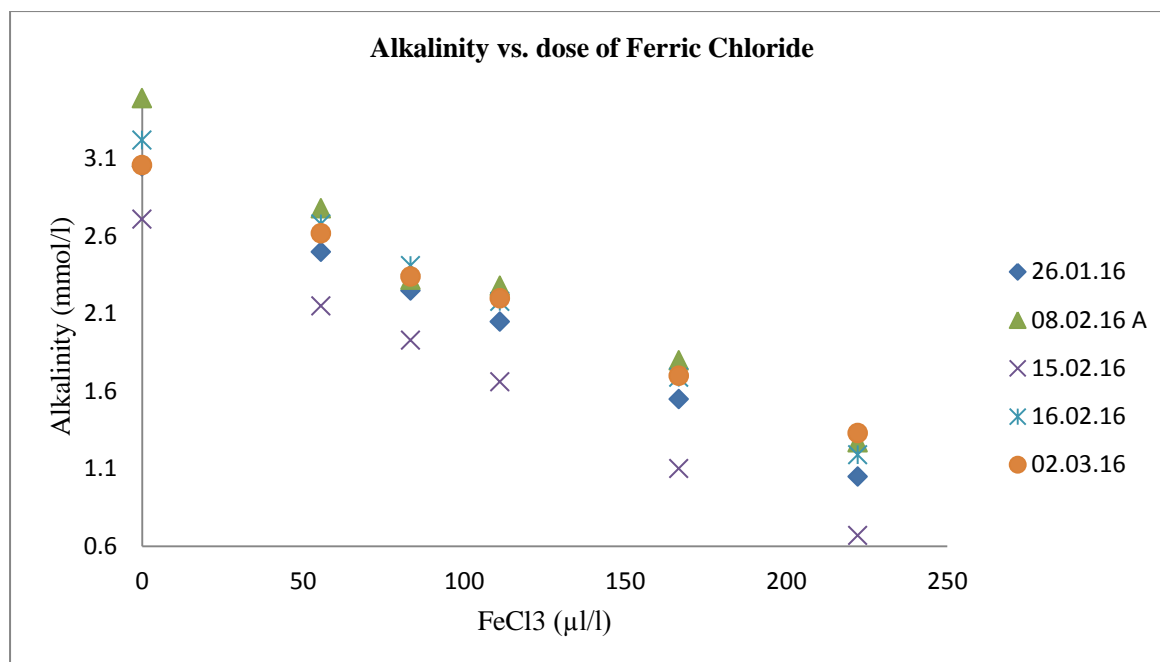




**Figure 4-4** Effect of ferric chloride on TSS removal

#### 4.1.4. Alkalinity vs. dosage of ferric chloride

The alkalinity of samples before and after adding FeCl<sub>3</sub> has been prepared in Figure 4.5. As an overall view, a reduction tendency of all samples is estimated through adding ferric chloride. The sample of 08.02.2016A which was treated with 2 mmol/l bicarbonate, expressed the highest alkalinity among all samples which is easily defined by the resistance of alkalinity against acidification. On the other hand 15.02.16 had marginally lower than others, started from 2.71mmol/l without applying coagulant to 0.67mmol/l with 222.22µl/l of ferric chloride by a sharp falling trend.

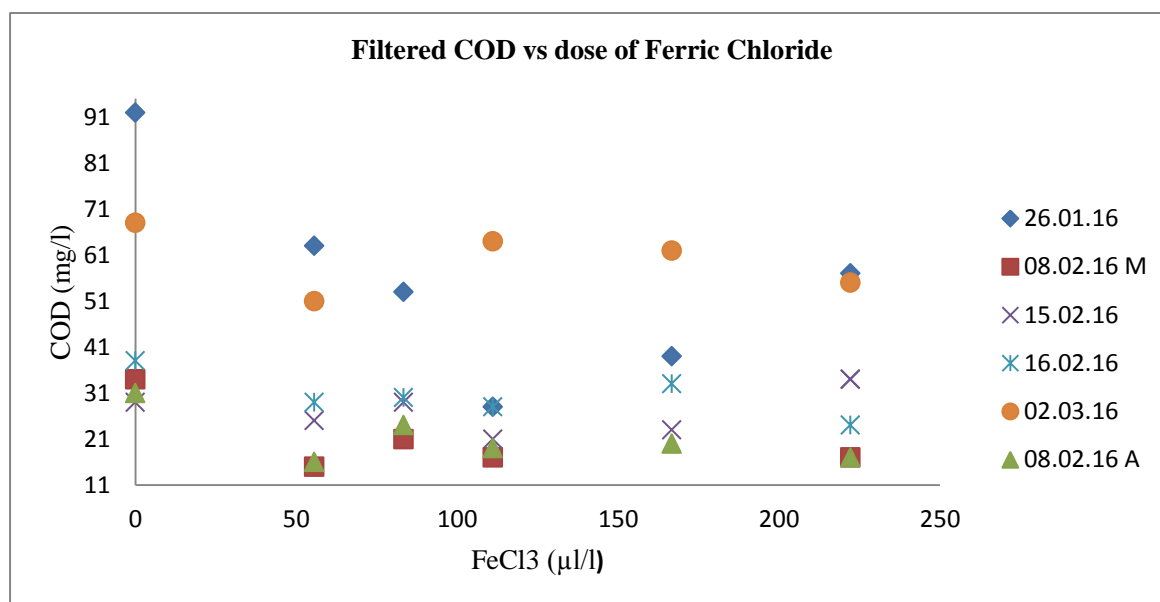


**Figure 4-5** Effect of ferric chloride on alkalinity

#### 4.1.5. Filtered COD vs. dosage of ferric chloride

Filtered COD of wastewater samples was measured through the mentioned procedure in previous chapter and was expressed in Figure 4.6. All in all, the samples indicate a slight dip of COD with some fluctuation among added coagulant, although it is easily visible that on 26<sup>th</sup> of January and 2<sup>nd</sup> of March, the graphs demonstrate significantly higher quantities in compare to the other days. On the other hand, on 8<sup>th</sup> of February both samples, with and without bicarbonate faced lowest amount of COD which can illustrate the fact that dense wastewater in a dry weather contains more COD content while the dilute wastewater which has a larger percentage of rain and surface water, presents lower concentration of COD. On 26.01.2016 and 15.02.2016 adding higher dosage of coagulant has resulted to decrease the COD which can be explained by attraction of organic matters by excess ferric hydroxide. The point should be considered in this test is that filtrate samples after filtering to

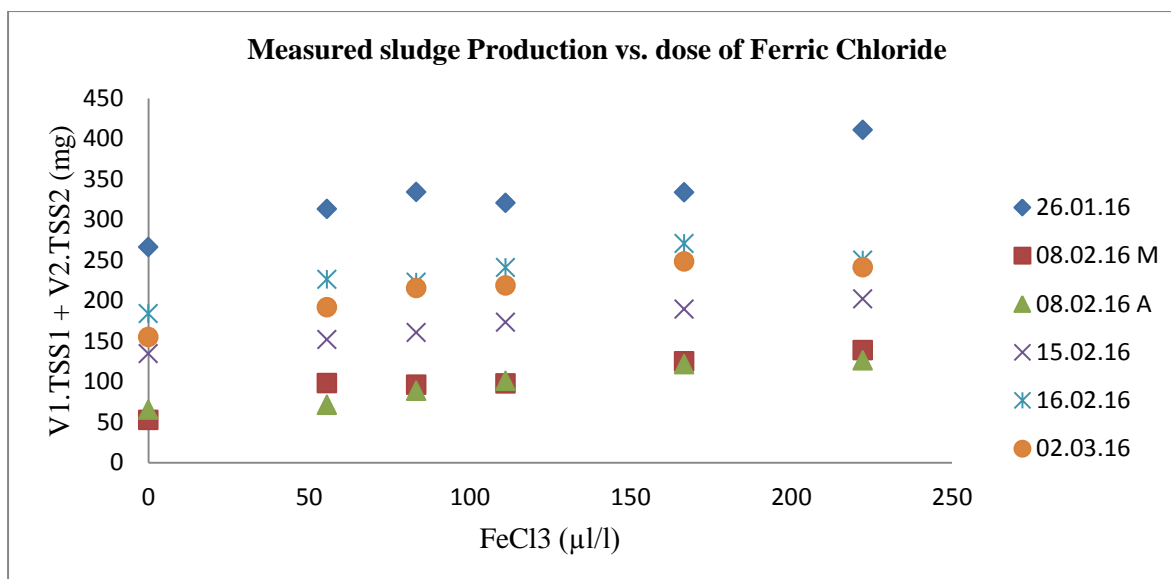
measure TSS, were kept freezing for a while and then all the COD tests were done together, so it can be a possibility of having an significant influence on these results.



**Figure 4-6** Effect of ferric chloride on COD

#### 4.1.6. Measured sludge production vs. dosage of ferric chloride

The outcomes are presented in Figure 4.7 and as expected the denser samples and dry weather contributed to higher values of sludge while there wasn't any impressive difference between use and non-use of bicarbonate in dilute sample of 08.02.2016 in terms of producing sludge. Furthermore all the graphs experienced a very smooth slope of increasing trend among adding ferric chloride in which the first step of coagulant added showed the most rising course continued with a steady pathway and a slow decline by adding the last extra amount of FeCl<sub>3</sub> however on 26<sup>th</sup> of February after reaching from 266.3mg to average of 325.5, it went up to 411.1mg as a result of 222.22µl/l coagulant.



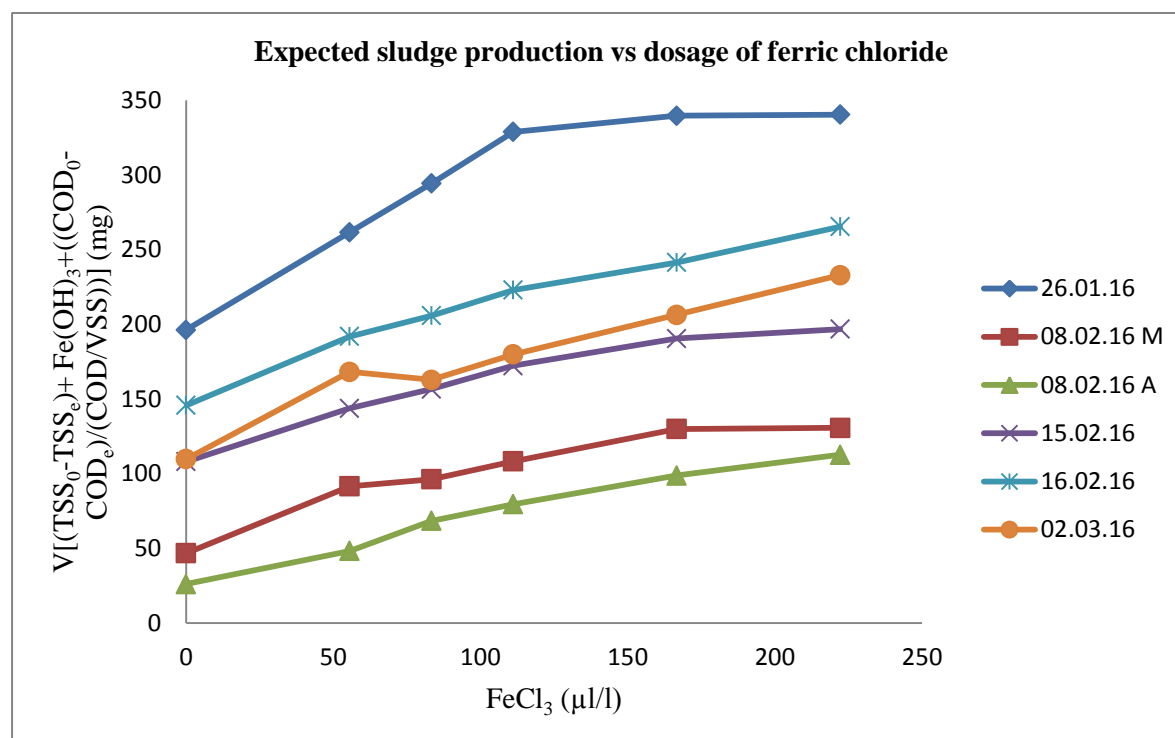
**Figure 4-7** Effect of ferric chloride on measured sludge production

#### 4.1.7. Calculated sludge production vs. dosage of ferric chloride

Sludge production as a combination of difference in influent and effluent suspended solids, formation of  $\text{Fe}(\text{OH})_3$  and precipitation of colloids (difference of filtered COD before and after precipitation) is showed in Figure 4.8 as a function of ferric chloride usage. As it is vivid, the similar regime with the previous figure was obtained for expected sludge production where all the samples had an increasing procedure with a decelerating slope. 26.01.2016 presented by far the highest amount of sludge production as 340.33 mg (after adding 222.22µl/l  $\text{FeCl}_3$ ) while 08.02.2016 showed the minimum amounts as 112.63 and 130.63 mg with and without bicarbonate respectively.

In addition to the mentioned parameters which form the calculated sludge production, formation of ferric phosphate should be considered, however; due to the slight effect of this factor, it has been decided to ignore testing that. Later the

estimated value of  $\text{FePO}_4$  will be discussed from the results followed from full scale plant.



**Figure 4-8** Effect of ferric chloride on expected sludge production

#### 4.1.8. Expected vs. measured sludge production

The modification of sludge production in terms of expected amount has been provided in Figure 4.9 to contrast such statistics with measured sludge production in the laboratory at University of Stavanger. As an overall view, it is obvious that most days indicate a proper adaptation between calculated and practical values of sludge produced followed with some fluctuation mostly on 15.02.2016 and 08.02.2016

In this study the formation of ferric phosphate as a part of sludge precipitation wasn't carried out in the laboratory based on its inconsequential effect compared to other constituents. According to the average value of total phosphate in influent and

effluent as 2.8 and 0.3 mg/l respectively, and by assuming the free phosphate as 50% of total amount in influent (the next 50% would be a part of suspended solids), the formation of  $\text{FePO}_4$  could be considered as 6.8 mg/l equal to 7.6 mg through intended volume (0.9 lit). Therefore it could be acceptable to ignore this fraction of total sludge production, however; by affirming this fact, the difference between measured and calculated sludge production could be even smaller. On the other hand it could be approved that by assuming a complete reaction between phosphate and iron, less amount of ferric hydroxide will be produced as a result of deficiency of available iron in the system. So it can be considered that a combination of  $\text{Fe}(\text{OH})_3$  and  $\text{FePO}_4$  together which results a net value of even fewer of ferric phosphate that eventually confirms our hypothesis of negligible effect of it on sludge production.

Based on the results achieved in the laboratory, there is a relatively good correspondence between the measured and calculated sludge production, especially in lower amounts of sludge which corresponds to more dilute wastewater samples which presented in Figure 4.9. To make it easier to have an observation, all the data from mentioned dates are gathered together in Figure 4.10 where a proper synchrony between achieved data and the linear expected trend could be noticed.

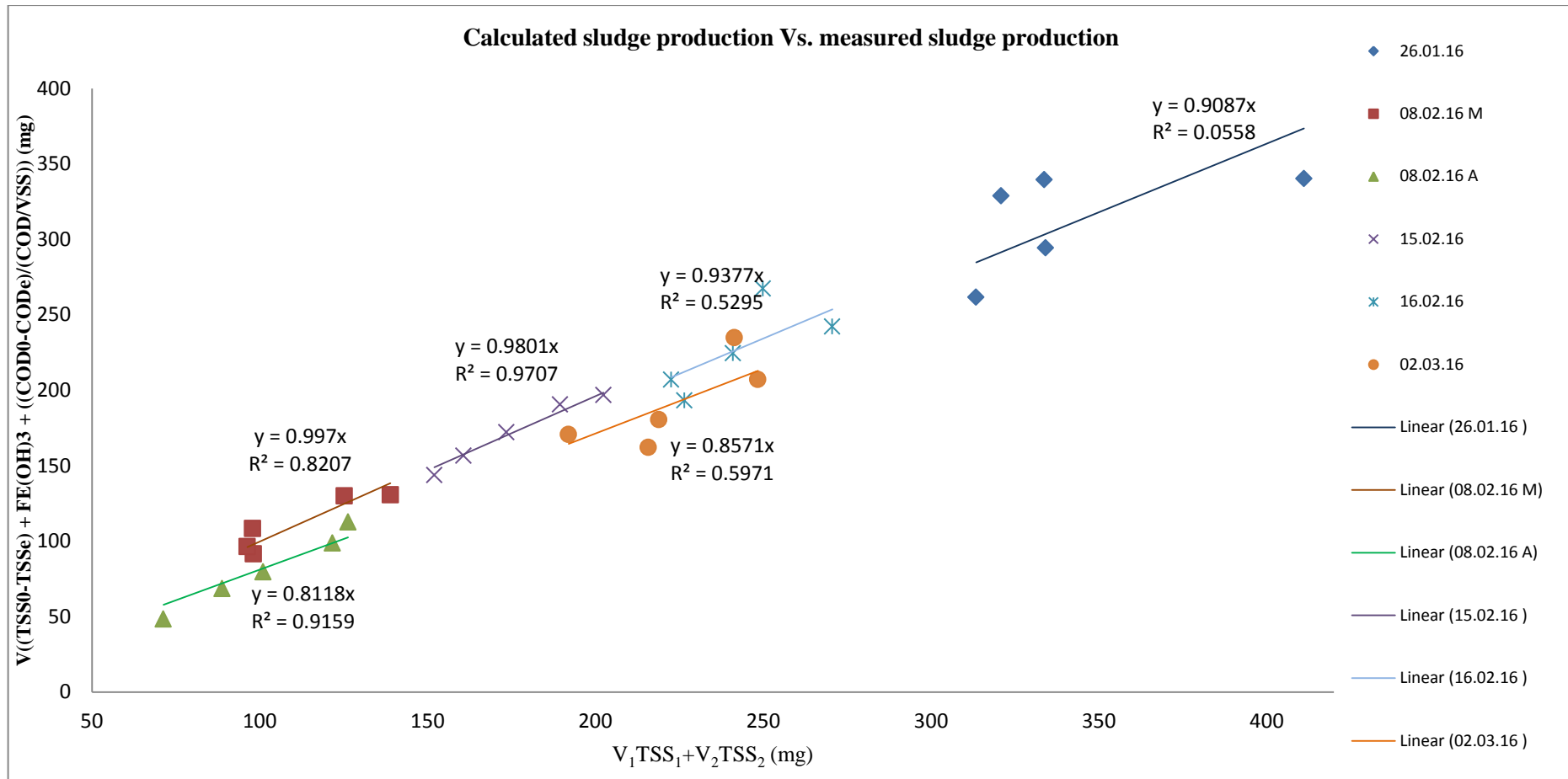
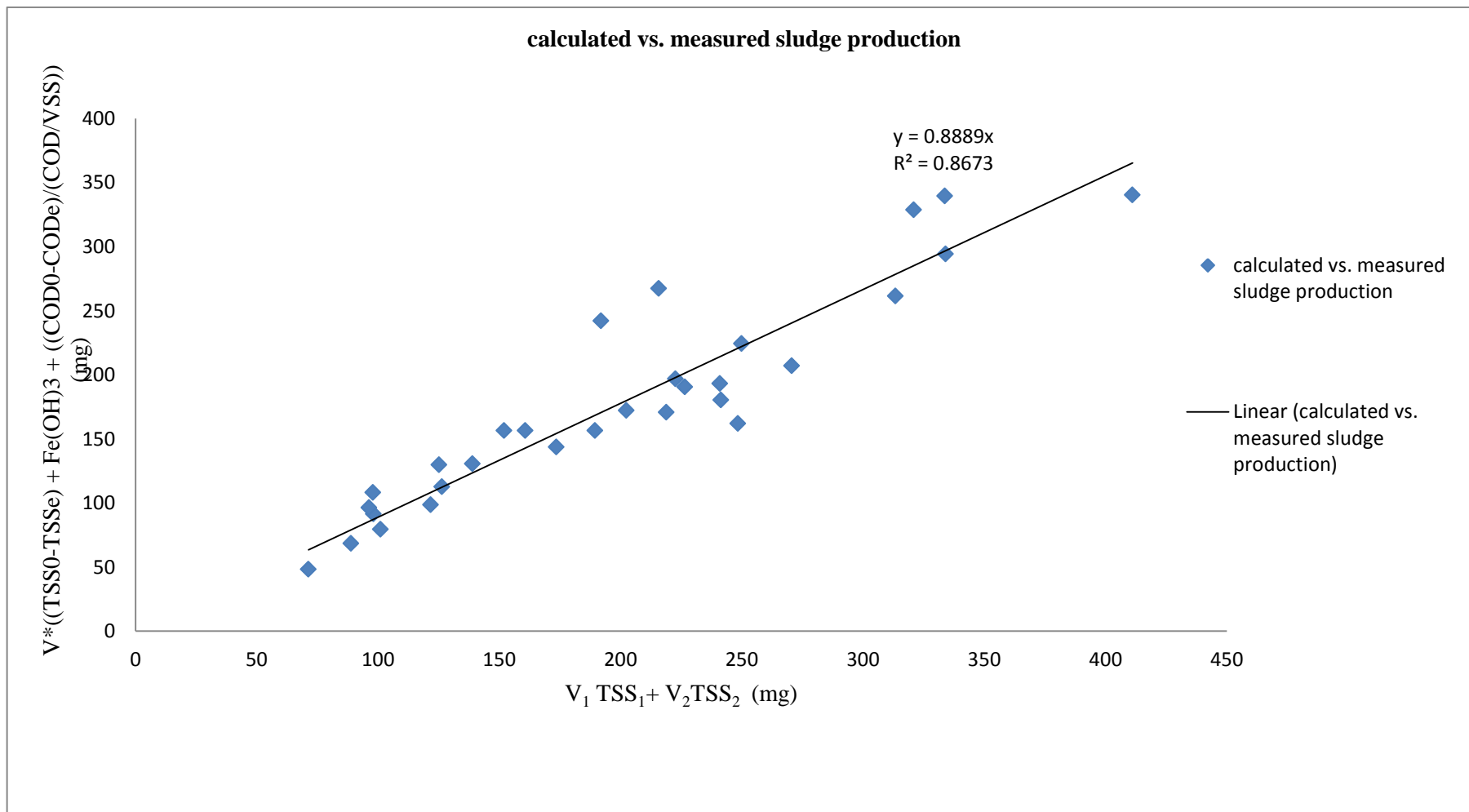


Figure 4-9 Calculated sludge production and measured sludge production



**Figure 4-10** Calculated sludge production and measured sludge production

(An overall view)



The measured and calculated sludge productions by means of same dosage of ferric chloride are reported in Tables 4.1 to 4.5. As it can be seen in Table 4.1 in all tests the sludge calculated from summation of suspended solids difference, ferric hydroxide formation and precipitated colloids is lower than what was measured. Although by considering the errors occurred during the experimental works in the laboratory and ferric phosphate formation, there would be an acceptable adaptation between estimated and real sludge production.

**Table 4-1** Expected and calculated sludge producing vs. 55.56 $\mu$ l/l of ferric chloride

<b>Date</b>	<b>Measured sludge production(mg)</b>	<b>Calculated sludge production(mg)</b>	<b>Percentage of difference (%)</b>
<b>26.01.16</b>	313.4	261.5	16.6
<b>08.02.16M</b>	98.1	91.5	6.7
<b>08.02.16A</b>	71.3	48.3	32.3
<b>15.02.16</b>	152	143.7	5.5
<b>16.02.16</b>	226.5	193.2	14.7
<b>02.03.16</b>	192	170.8	11

It can be observed from Table 4.2 that using 83.33 $\mu$ l/l of FeCl<sub>3</sub> may result in lower average of differences compared to 55.56 $\mu$ l/l; however in both cases the wastewater sample for 08.02.2016 afternoon displays by far the highest distinction during the other dates.

**Table 4-2** Difference between expected and calculated sludge producing vs. 83.33 $\mu$ l/l of ferric chloride

Date	Measured sludge production(mg)	Calculated sludge production(mg)	Percentage of difference (%)
26.01.16	334.1	294.3	11.9
08.02.16M	96.3	96.3	0
08.02.16A	88.8	68.4	23
15.02.16	160.7	156.6	2.6
16.02.16	222.6	207	7
02.03.16	215.8	162.1	11.6

By using coagulant of 111.11 $\mu$ l/l as shown in Table 4.3 the higher values of calculated sludge was not seen for 26.01.16 and 08.02.16 morning, which indicates theoretical sludge production exceeded the measured, likewise 08.02.16 afternoon has the same behavior as seen in the previous tables.

**Table 4-3** Distinction between expected and calculated sludge producing vs. 111.11 $\mu$ l/l of ferric chloride

Date	Measured sludge production(mg)	Calculated sludge production(mg)	Percentage of difference (%)
26.01.16	320.9	328.8	-2.5
08.02.16M	97.9	108.3	-10
08.02.16A	101	79.5	21.3
15.02.16	173.5	172.2	0.8
16.02.16	241	224.4	6.9
02.03.16	218.9	180.4	17.6

Similar to Tables 4.3, Table 4.4 (applying 166.67 $\mu$ l/l ferric chloride) displays the bigger amount of calculated quantities in comparison with measured; however, it could be an indication of undesirable errors during the Laboratory activities.

**Table 4-4** comparison between expected and calculated sludge producing vs. 166.67 $\mu$ l/l of ferric chloride

Date	Measured sludge production(mg)	Calculated sludge production(mg)	Percentage of difference (%)
26.01.16	333.7	339.6	-1.8
08.02.16M	125.2	129.9	-3.7
08.02.16A	121.7	98.7	18.9
15.02.16	189.5	190.5	-0.5
16.02.16	270.6	242.1	10.5
02.03.16	248.4	207.2	16.6

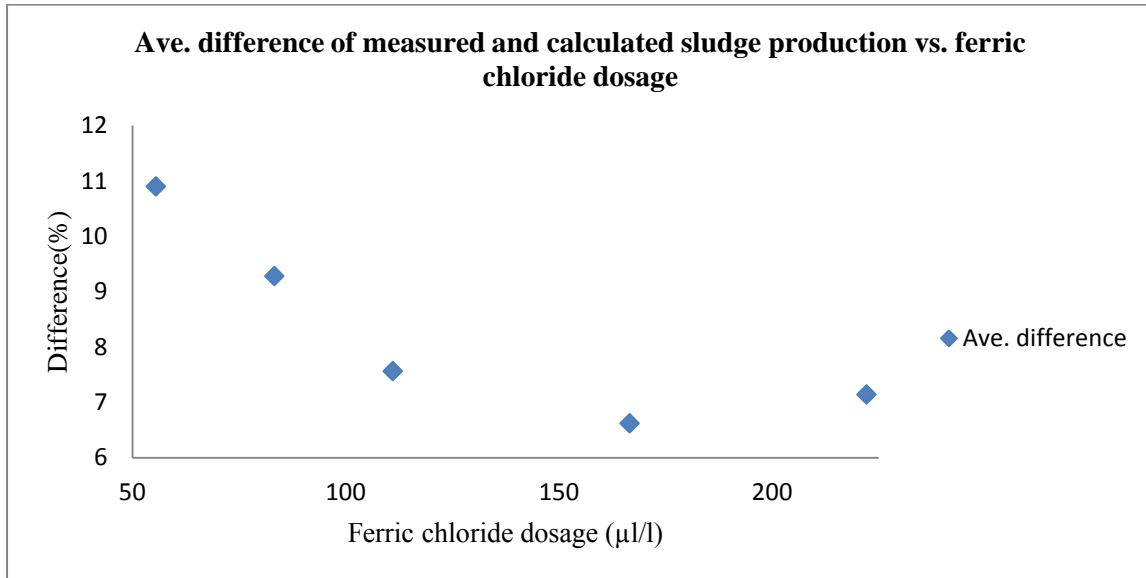
As expressed in Table 4.5 as well, it is noticeable that all tests on 8<sup>th</sup> of February afternoon which treated by 2 mmol/l bicarbonate showed marginally higher discrepancy between estimated and real sludge production.

**Table 4-5** Difference between expected and calculated sludge producing vs. 222.22 $\mu$ l/l of ferric chloride

Date	Measured sludge production(mg)	Calculated sludge production(mg)	Percentage of difference (%)
26.01.16	411.1	340.3	17.2
08.02.16M	138.9	130.6	6
08.02.16A	126.3	112.6	10.8
15.02.16	202.4	196.8	2.8
16.02.16	249.9	267.4	-7
02.03.16	241.4	234.8	2.7

Based on information achieved from the previous tables, the average values of differences between measured and calculated amount of sludge production have been presented in Figure 4.11, in which by paying less attention to dosage of 111.11 $\mu$ l/l of FeCl<sub>3</sub>, it is visible to consider a falling trend of the difference by increasing the ferric chloride added for treatment. The average distinction could be marginally

lower by ignoring the results from 08.02.16 afternoon, since it wasn't possible to find a convincing relationship between added alkalinity and the observed higher interval among the measured and calculated sludge productions.



**Figure 4-11** Expected sludge production and measured sludge production

## 4.2. The results of full scale at SNJ

In this section the data from SNJ through 2015 has been presented to compare with the laboratory result. The following information was prepared by Leif Ydstebø. Based on the mentioned information the total amount of wastewater treated chemically during 2015 was around 41,534,162 m<sup>3</sup>/year corresponding to 113,792 m<sup>3</sup>/day. The average concentration of relevant parameters of influent and effluent streams has been gathered in Table 4.6. Suspended solid is measured manually once a week in the laboratory in addition to daily online monitoring of the process. Removal colloids parameter is calculated from equation below:

$$\text{Removal colloids} = (\text{COD}_{\text{filt,in}} - \text{COD}_{\text{filt,out}}) / (\text{COD} / \text{TSS})$$

Where; COD/TSS=1.2 gCOD/gTSS

**Table 4-6** Concentration of relevant parameters in the SNJ plant

Parameter	Influent (mg/l)	effluent (mg/l)	Removal (mg/l)
<b>TSS</b>	200	20	180
<b>TSS online</b>	200	28	172
<b>COD</b>	300	66	234
<b>COD<sub>filt</sub></b>	70	46	24
<b>BOD</b>	193	31	162
<b>BOD<sub>filt</sub></b>	30.7	18.2	12.5
<b>colloids</b>	20	0	20

Table 4.7 indicates the chemicals added and produced during chemical treatment of wastewater in the plant at 2015. As it can be seen the average dosage of ferric chloride used in SNJ is equal to 108.1µl/l.

**Table 4-7** Consumption and formation of chemicals

Parameter	Quantity	Unit
<b>Consumed ferric chloride</b>	4500 (12.3)	m <sup>3</sup> /year (m <sup>3</sup> /day)
<b>Ferric chloride dosage</b>	108.1	ml/m <sup>3</sup>
<b>Ferric Chloride dosage</b> (Density=1.5kg/l)	162.1	g FeCl <sub>3</sub> /m <sup>3</sup>
<b>Iron dosage</b> (Iron content=0.115g/g)	18.6	g Fe/m <sup>3</sup>
<b>Ferric hydroxide formation</b> (Mw=107g/mole)	35.7	g Fe(OH) <sub>3</sub> /m <sup>3</sup>

Sludge production as a combination of suspended solids and colloids removal and ferric hydroxide formation which gathered from Table 4.6 and Table 4.7 is expressed in Table4.8. Conversion of ferric chloride to ferric hydroxide was considered to be complete which may have overestimated the sludge production estimation.

**Table 4-8** Estimated sludge production

Parameter	Total (kg TS/d)	VS/TS	Organic (kg VS/d)	Inorganic (kgFS/d)
<b>SS removal</b>	20483	0.85	17410	3073
<b>Colloid removal</b>	2275	0.85	1934	341
<b>Ferric hydroxide</b>	4062	0	0	4062
<b>Total</b>	26820	0.72	19344	7476

Based on the data prepared in Sentralrenseanlegg Nord-Jæren (SNJ), by assuming the usual TS content of sludge (5%) in settling tanks which pumped by a rate of 386 m<sup>3</sup>/d, the produced sludge would be 19300 kg TS/d that indicates lower than the calculated amount. On the other hand, as it is obvious from Table 4.9, the 5% TS content seems to be underestimated as the sampling is done during the morning when the sludge appears most dilute, while a more realistic value is 5.5% results in a decline of 20.9% or the amount of 21230 kg TS/d.

**Table 4-9** Sludge production measured in the plant

Parameter	Quantity	Unit	Difference in sludge production
<b>Sludge from treatment</b>	26280	kg TS/d	-
<b>Sludge pumping</b>	386	m <sup>3</sup> /d	-
<b>TS content</b>	5	%	-
<b>Sludge production</b>	19300	kg TS/d	28.1% lower
<b>TS content</b>	5.5	%	-
<b>Sludge production</b>	21230	kg TS/d	20.9% lower

## Chapter 5

### 5. Conclusion and recommendations

Chemical precipitation with ferric chloride in the laboratory-scale was carried out in order to investigate diverse parameters affecting the process.

Six samples in different dates and weather condition were chosen, considering the effect of  $\text{FeCl}_3$ , it indicated that pH was varied from 6.11 to 7.15 as a result of applying 222.22 $\mu\text{l/l}$  and 55.56 $\mu\text{l/l}$  of mentioned coagulant respectively, observing a declining trend of pH.

Decreasing of TSS by adding higher dosages ferric chloride indicates increasing tendency of TSS removal with maximum separation of 79.85% for the most dense wastewater sample on 26.02.2016.

Akin to TSS, alkalinity demonstrates a falling trend through rising the amount of  $\text{FeCl}_3$ , however, unlike TSS and alkalinity, filtered COD expressed very slight change in the process with a sharp slope of reduction at the lowest dose of coagulant, while for the remaining higher doses small changes was observed.

Both measured and calculated sludge production increase as ferric chloride increases and are also affected by denser wastewater sample of 26.01.2016 showed the maximum amount of sludge production.

By comparing actual and theoretical sludge productions it was obvious that a good correlation between them could be seen, particularly in the case of more dilute wastewater samples and also the average difference declined by using higher dosages of  $\text{FeCl}_3$ .

As it was predictable the data prepared in SNJ observed a bigger difference between measured and calculated sludge production.

For further studies it is recommended to investigate the conceivable reactions which may occur during chemical precipitation and affect this process and thereby have an adverse consequence on sludge production. Moreover a particular attention could be placed on the effects of adding the bicarbonate to see the effects of undesirable reactions and matters that derived from.



## References

- Bratby, J. (2006). *Coagulation and flocculation in water and wastewater treatment* (2nd ed. ed.). London: IWA Publ.
- Clesceri, L. S., Greenberg, A. E., Eaton, A. D., American Public Health, A., Water Environment, F., & American Water Works, A. (1998). *Standard methods for the examination of water and wastewater* (20th ed. ed.). Washington: American Public Health Association.
- Droste, R. L. (1997). *Theory and practice of water and wastewater treatment*. New York: Wiley.
- Eggen, R. I. L., Hollender, J., Joss, A., Schärer, M., & Stamm, C. (2014). Reducing the discharge of micropollutants in the aquatic environment: the benefits of upgrading wastewater treatment plants. *Environmental science & technology*, 48(14), 7683. doi:10.1021/es500907n
- Gregory, J., & O'Melia, C. R. (1989). Fundamentals of flocculation. *Critical Reviews in Environmental Science and Technology*, 19(3), 185-230.
- Guida, M., Mattei, M., Della Rocca, C., Melluso, G., & Meriç, S. (2007). Optimization of alum-coagulation/flocculation for COD and TSS removal from five municipal wastewater. *Desalination*, 211(1), 113-127. doi:10.1016/j.desal.2006.02.086
- Habermacher, J., Benetti, A. D., Derlon, N., & Morgenroth, E. (2015). The effect of different aeration conditions in activated sludge - Side-stream system on sludge production, sludge degradation rates, active biomass and extracellular polymeric substances. *Water research*, 85, 46. doi:10.1016/j.watres.2015.08.002
- Hammer, M. J., & Hammer, M. J. (2004). *Water and wastewater technology* (5th ed. ed.). Upper Saddle River, N.J: Prentice-Hall.

- Hantanirina, J. M. O. (2010). Improving BOD removal at SNJ wastewater treatment plant by biological treatment: University of Stavanger, Norway.
- Henze, M. (2008). *Biological wastewater treatment : principles, modelling and design*. London: IWA Publ.
- Mosquera, M. (2014). Chemical precipitation and treatment control parameters in wastewater treatment: University of Stavanger, Norway.
- Musvoto, E. V., Wentzel, M. C., Loewenthal, R. E., & Ekama, G. A. (2000). Integrated chemical–physical processes modelling—I. Development of a kinetic-based model for mixed weak acid/base systems. *Water research*, 34(6), 1857-1867.  
doi:10.1016/S0043-1354(99)00334-6
- Shin, J. Y., Spinette, R. F., & O'Melia, C. R. (2008). Stoichiometry of coagulation revisited. *Environmental science & technology*, 42(7), 2582.
- Tchobanoglous, G., Burton, F. L., Stensel, H. D., Metcalf, & Eddy. (2003). *Wastewater engineering : treatment and reuse* (4th ed. revised by George Tchobanoglous, Franklin L. Burton, H. David Stensel. ed.). Boston: McGraw-Hill.
- Vesilind, P. A. (1979). *Treatment and disposal of wastewater sludges* (2nd ed. ed.). Ann Arbor, Mich: Ann Arbor Science Publ.

## Appendix A

FeCl<sub>3</sub> certificate receiving by Ivar.

# Kemira

## ANALYSESERTIFIKAT

### PIX-318

**KUNDE: IVAR**

**ANALYSEDATO: 5-2-16**

**LEVERINGSDATO: uke05**

PIX 318 er analysert ved vårt laboratorium i Fredrikstad og er godkjent i følge våre spesifikasjoner. Analysene er utført i henhold til våre standard analysemetoder. Disse er beskrevet i vårt kvalitetssystem, som er sertifisert etter ISO 9001:2008 standarden.

Referanseprøve av denne leveransen vil bli oppbevart hos oss i 6 måneder etter leveranse.

ANALYSEN GA FØLGENDE RESULTATER:

SPESIFIKASJON		ANALYSE
Jern Fe <sup>3+</sup> %	11,6 ± 0,3	11,6
Jern Fe <sup>2+</sup> %	< 0,3	0,19
Uløst stoff %	< 0,05	<0,05
Tetthet g/cm <sup>3</sup>	1,46-1,54	1,512

Analysert av  
Ebj

Kvalitetsingeniør  
Tore Hunn

## Appendix B

### Laboratory results

Date	Sample	FeCl3 (µl/l)	pH	Conductivity (µS/cm)	TSS1 (mg/l)	TSS <sub>0</sub> - TSS <sub>e</sub> (mg/l)	removal TSS%	TSS2 (mg/l)	V <sub>1</sub> .TSS <sub>1</sub> + V <sub>2</sub> .TSS <sub>2</sub> (mg)	Fe(OH) <sub>3</sub> formation (mg/l)	Alkalinity (mmol/l)	COD (mg/l)	COD <sub>0</sub> -COD <sub>e</sub> (mg/l)	V*((TSS <sub>0</sub> -TSS <sub>e</sub> ) + Fe(OH) <sub>3</sub> + ((COD <sub>0</sub> -COD <sub>e</sub> )/1.2)) (mg)
26.01.16	0	0			273	0	0		245.7	0	3	92	0	196.2
	1	0			55	218	79.85	326	266.3	0	3.05	-	-	-
	2	55.55			30	243	89.01	388	313.4	18.66	2.5	63	29	261.59
	3	83.33			13	260	95.24	416	334.1	27.99	2.25	53	39	294.29
	4	111.11			9	264	96.7	400	320.9	37.32	2.05	28	64	328.79
	5	166.67			4.67	268.33	98.29	444	333.7	55.99	1.55	39	53	339.58
	6	222.22			4.5	268.5	98.35	586	411.1	74.65	1.05	57	35	340.33
08.02.16 M	0	0	6,63		69	0	0		62.1	0	1.43	34	0	46.8
	1	0	6,54		17	52	75.36	64	52.9	0	1.42	-	-	-
	2	55.55	6,48		5	64	92.75	122	98.1	18.66	0.91	15	19	91.49
	3	83.33	6,42		3	66	95.65	120	96.3	27.99	-	21	13	96.29

	4	111.11	6,30		3	66	95.65	122	97.9	37.32	0.48	17	17	108.29
	5	166.67	5,10		4.67	64.33	93.23	166	125.2	55.99	0.07	10	24	129.88
	6	222.22	3,50		15.5	53.5	77.53	194	138.9	74.65	0	17	17	130.63
08.02.16 A	0	0	6,67		41	0	0	-	36.9	0	1.43	31	0	26.1
	1	0	6,73		12	29	70.73	80	65.2	0	3.49	-	-	-
	2	55.55	6,78		13	28	68.29	100	71.3	18.66	2.78	24	7	48.29
	3	83.33	6,69		8	33	80.49	110	88.8	27.99	2.32	16	15	68.39
	4	111.11	6,64		2	39	95.12	126	101	37.32	2.28	19	12	79.49
	5	166.67	6,50		1.33	39.67	96.76	162	121.7	55.99	1.8	17	14	98.69
	6	222.22	6,36		1.5	39.5	96.34	180	126.3	74.65	1.27	20	11	112.63
15.02.16	0	0	6,93	2.59 (mS/cm)	153	0	0	-	137.7	0	2.66	29	0	108
	1	0	7,5	2.61(mS/cm)	33	120	78.43	164	134.5	0	2.71	-	-	-
	2	55.55	7,15	2.69 (mS/cm)	16	137	89.54	188	152	18.66	2.15	25	4	143.69
	3	83.33	6,9	2.7 (mS/cm)	7	146	95.42	200	160.7	27.99	1.93	29	0	156.59
	4	111.11	6,67	2.7 (mS/cm)	7	146	95.42	216	173.5	37.32	1.66	21	8	172.19
	5	166.67	6,56	2.7 (mS/cm)	3.33	149.67	97.82	252	189.5	55.99	1.1	23	6	190.49
	6	222.22	6,38	2.73 (mS/cm)	4	149	97.39	288	202.4	74.65	0.67	34	-5	196.78
16.0 2.16	0	0	7,5	1818	212	0	0		190.8	0	3.18	38	0	145.8

	1	0	6,75	1851	50	162	76.42	224	184.2	0	3.22	-	-	-
	2	55.55	6,59	1865	25	187	88.21	280	226.5	18.66	2.68	29	9	191.84
	3	83.33	6,52	1881	18	194	91.51	276	222.6	27.99	2.41	30	8	205.79
	4	111.11	6,43	1908	10	202	95.28	300	241	37.32	2.18	28	10	222.89
	5	166.67	6,32	1928	4	208	98.11	360	270.6	55.99	1.69	33	5	241.33
	6	222.22	6,15	1940	3.5	208.5	98.35	356	249.9	74.65	1.19	24	14	265.33
02.03.16	0	0	7.05	2.87 (mS/cm)	168	0	0	-	151.2	0	3.03	68	0	109.8
	1	0	7.12	2.84 (mS/cm)	46	122	72.62	188	155	0	3.06	-	-	-
	2	55.55	6.83	2.86 (mS/cm)	16	152	90.48	238	192	20.74	2.62	51	17	168.21
	3	83.33	6.68	2.87 (mS/cm)	14	154	91.67	268	215.8	31.1	2.34	73	-5	162.84
	4	111.11	6.5	2.87 (mS/cm)	13	155	92.26	272	218.9	41.47	2.2	64	4	179.82
	5	166.67	6.32	2.89(mS/cm)	6	162	96.43	330	248.4	62.21	1.7	62	6	206.28
	6	222.22	6.11	2.91 (mS/cm)	3	165	98.21	344	241.4	82.94	1.33	55	13	232.89

## Appendix C

Full scale (Ivar wastewater treatment plant, SNJ) results (2015)

Dag	Influent						Effluent						Flow
	COD	COD <sub>fit</sub>	BOD	BOD <sub>fit</sub>	SS	Tot-P	COD	COD <sub>fit</sub>	BOD	BOD <sub>fit</sub>	SS	Tot-P	
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	m <sup>3</sup> /d
07/01/2015	148	43	101	21	104		51	26	24	13	25		178551
14/01/2015	141	42	90	23	87		44	27	24	14	21		132560
21/01/2015	373	75	183	37	181		66	50	33	21	19		96659
28/01/2015	117	29	68	14	87		40	12.5	22	9	32		212479
04/02/2015	321	84	200	39	217	3.85	70	50	38	29	21	0.478	89916
11/02/2015	409	76	189	37	192		68	49	33	19	21		99627
19/02/2015	175	45	104	21	128		45	28	23	15	19		183343
26/02/2015	171	46	90	17	136		53	34	22	13	26		169432
04/03/2015	197	56	130	29	116		51	35	26	16	18		132049
11/03/2015	256	67	160	35	179		56	46	28	23	15		123576
18/03/2015	375	93	214	42	246		70	61	36	23	15		88458
25/03/2015	239	71	132	38	146		55	47	28	26	11		125716
31/03/2015	301	60	205	44	184		67	46	32	21	18		116932
08/04/2015	439	105	340	42	257		80	66	32	28	14		85001
15/04/2015	107	55	62	26	41	1.72	49	35	28	10	21	0.386	158567
22/04/2015	392	95	242	46	267		85	57	42	27	22		70639
28/04/2015	426	88	259	45	302		81	59	41	24	20		100767
06/05/2015	262	65	191	33	163		54	38	27	10	15		103523
12/05/2015	196	62	129	28	117		55	40	29	21	19		177288
20/05/2015	236	61	146	29	160		53	34	30	10	22		121874
27/05/2015	306	66	166	31	192		64	39	28	10	19		108413
03/06/2015	187	53	107	10	114		49	33	22	10	17		133943
10/06/2015	299	89	208	46	190		77	55	40	29	21		88521

<b>17/06/2015</b>	304	75	186	32	236		64	50	32	24	17		124407
<b>24/06/2015</b>	195	96	107	35	89	3.29	83	66	37	25	20	0.3	68010
<b>01/07/2015</b>	495	101	299	51	306		94	74	51	39	27		70532
<b>08/07/2015</b>	251	79	132	26	137		78	57	27	10	23		76867
<b>15/07/2015</b>	354	82	200	33	204		77	56	32	25	21		64980
<b>23/07/2015</b>	309	72	189	29	186		68	54	28	10	14		74651
<b>29/07/2015</b>	319	78	200	30	246		76	56	28	24	17		71316
<b>05/08/2015</b>	439	75	220	34	271		73	51	35	23	15		92719
<b>12/08/2015</b>	392	89	242	39	300		83	60	28	26	21		75814
<b>19/08/2015</b>	321	80	186	27	196	4.04	74	51	38	21	18	0.321	88574
<b>26/08/2015</b>	195	60	155	21	117		56	38	23	10	15		129395
<b>02/09/2015</b>	161	50	101	10	108		60	39	24	10	24		142729
<b>09/09/2015</b>	450	104	389	48	353		101	64	54	32	31		76014
<b>16/09/2015</b>	344	69	451	26	257		73	45	37	10	25		101983
<b>23/09/2015</b>	509	72	360	34	355		64	46	32	10	17		94537
<b>30/09/2015</b>	486	95	343	43	371		91	64	43	26	29		83095
<b>07/10/2015</b>	392	73	287	31	308		76	51	37	22	29		96522
<b>14/10/2015</b>	544	104	344	52	340		89	65	51	32	20		74303
<b>28/10/2015</b>	402	87	324	46	451	4.17	72	59	40	23	20	0.356	89890
<b>04/11/2015</b>	433	114	388	55	287		94	74	51	25	25		75998
<b>11/11/2015</b>	306	55	228	10	253		58	34	29	10	27		136717
<b>18/11/2015</b>	159	51	99	10	102		63	40	22	10	23		188695
<b>25/11/2015</b>	191	45	104	10	118		55	31	25	10	25		169856
<b>03/12/2015</b>	231	52	113	24	157		64	35	27	10	30		173956
<b>09/12/2015</b>	116	38	65	10	69	1.33	42	12.5	10	10	21	0.373	183336
<b>16/12/2015</b>	344	58	200	27	229		64	36	31	10	18		121081
<b>21/12/2015</b>	146	45	104	10	156	1.54	39	12.5	10	10	13	0.202	186908
<b>28/12/2015</b>	239	62	127	29	168		64	45	27	10	17		120896



<b>Sum</b>													
<b>Average</b>	296.1	70.3	193.3	30.7	199.5	2.8	66.2	45.8	31.3	18.2	20.6	0.3	116698.3
<b>Max</b>	544	114	451	55	451	4.17	101	74	54	39	32	0.478	212479
<b>Min</b>	107	29	62	10	41	1.33	39	12.5	10	9	11	0.202	64980