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**OPTIMIZATION OF HIGH
PHOSPHORUS LOADED
POST-PRECIPITATION AND
SEPARATION PROCESS**

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Abstract		
<p>This research was aimed to achieve maximum efficiency of post-precipitation and separation process at existing in-situ pilot plant project installed inside Viikinmäki Wastewater Treatment Plant in Helsinki, Finland. The pilot plant is a part of HSY's individual RAVITA program, which is about phosphorus recovery form wastewater. The pilot plant included extra-phosphorus addition to the influent water to simulate the process without chemical or bio-phosphorus removal, followed by coagulation, flocculation and disc filtration stages.</p>		
<p>The main purpose of the thesis was to find out which parameters are correlated in the process of chemical post-precipitation and separation and how to adjust them. Every step of the process was analyzed, designed and multiple laboratory- and pilot-scale tests were conducted to obtain formulated goals and positive results. The aims represented themselves optimization of chemical additions, mixing intensities and retention time so that effluent total phosphorus is 0.5 mg/l when the inlet is 3-5 mg/l and BW% (parameter for discfilter operation capacity) of the discfilter is not more than 50–60%. Moreover, the idea to use the sludge formed during the process as coagulation aid (sludge recirculation) has been implemented and researched.</p>		
<p>During the current research, optimum chemical addition amounts were determined for different inlet P concentrations, parameters affecting discfilter were observed, sludge recycle enhanced the process of post-precipitation in a positive way and should be considered as useful coagulation aid in this process.</p>		
<p>Using the results of this research, it would be possible to estimate the amounts of chemicals to be added in post-precipitation while different inlet phosphorus concentrations and adjust the filtering capacity of the discfilter in the future. The obtained results would be used as a basis for further development and enlargement of the pilot and RAVITA process, since the formed thickened sludge during chemical precipitation has to be treated and it is an attractive source for further nutrient recovery.</p>		
Keywords		
phosphorus, precipitation, disc filtration		

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Appendix 1: Results from laboratory scale tests.

Appendix 2: Results from pilot test runs.

Appendix 3: Results from pilot test runs with sludge recycle implemented into the process.

NOMENCLATURE

BW% backwash percentage

COD chemical oxygen demand

DF discfilter

EBPR enhanced biological phosphorus removal

HCl hydrogen chloride

HRT hydraulic retention time

HSY Helsingin seudun ympäristöpalvelut -kuntayhtymä (Helsinki Region Environmental Services Authority)

NaOCl sodium hypochlorite

R&D research and development

SS suspended solid

TP total phosphorus

TSS total suspended solids

UWWT urban wastewater treatment

WWTP wastewater treatment plant

1 INTRODUCTION

Nowadays the process of wastewater treatment is reaching to be as developed, innovative and complete as it is possible. That is why the tertiary or so-called advanced treatment procedures are being researched and implemented now in many wastewater facilities. After the primary and secondary treatment steps, that are mainly included in the majority of wastewater treatment plants (WWTP), the wastewater can be proceeded further to the possible tertiary stage, where it still contains some value of suspended solids, nutrients (mainly phosphorus and nitrogen) and other fine particles.

It is highly important, already regulated, prescribed by legislation and different directives that effluent flows from WWTPs should contain the lowest possible amount of nutrients. The reason for that is a long term threat to the environment in addition to eutrophication of natural waters. The implementation of advanced treatment technologies inside modern WWTPs helps to significantly remove eutrophying substances, but the rejected sludge containing lots of phosphorus is the baseline for nutrients recirculation and reuse.

Since the main source of P, the phosphate rock, has been named a critical raw material by European Commission (Proposal for a Regulation of the European Parliament and of the Council relating to cadmium in fertilizers, 2014), one of the possibilities is to recover phosphorus from the sludge formed in WWTPs. This process is not economically efficient yet and it does need a lot of research and development (R&D) programs to be conducted around it. On the other hand, WWTPs are interesting and promising sources for the phosphorus recovery since the amounts of continuously produced substance are great and concentrated at one place. Further, recovered phosphorus can be recycled for agriculture uses, for instance for the fertilizer industry and several others.

This thesis contains a wide description of research and development work conducted to optimize and adjust the pilot plant, which has been installed inside Viikinmäki WWTP. The pilot is the first phase of HSY's (Helsinki Regional Environmental Services Authority) individual RAVITA project and represents itself

high phosphorus loaded post-precipitation and separation process during the wastewater treatment. This step has to be optimized to guarantee the efficient P recovery in the next phase. The main idea in RAVITA project is to make the process of nutrient recovery available for the majority of WWTPs, since no digestion or biological removal is needed. It is done by shifting the precipitation from simultaneous to post-precipitation step and further separation of the formed chemical sludge with high P recovery potential (hsy.fi/ravita, 2017.) It should be noticed, that when coagulation and flocculation have occurred and separation of sludge has been done, there is a need in the polishing step to ensure the low possible phosphorus content in effluent.

The idea to use sludge as a coagulation aid has been implemented, analyzed and reported on possible findings. The assessment of the process has been done analyzing the key variable parameters: chemical types and their amounts, retention time and structure optimization. The efficiency of the adjustments has been controlled with the phosphate reduction value, filtering capacity and qualities of the formed sludge.

Several research questions have been answered during current thesis work, the overall question of this R&D project looks as follows: "How to achieve the maximum efficiency of the pilot work?" Such question literally represents the whole thesis paper, but to make the study more constructive and specific, it was essential to start with answering the question: "Which parameters are depended on each other in the process of chemical post-precipitation and separation and how to adjust them?" The recirculation of sludge formed inside the pilot plant was about to enhance the process of flock formation and make the flock more dense, solid and easily removed by the filter. After this process had been implemented and researched, the question "Does sludge recirculation-enhance the efficiency of post-precipitation and separation via discfilter?" has been answered and discussed as well.

2 PHOSPHORUS CONTAMINATION OF MUNICIPAL WASTEWATER

2.1 Effects and risks of phosphorus

Phosphorus is an important and indispensable nutrient, which is used in all living organisms' processes such as conversion of the sunlight into the energy, and cells' growth and reproduction. Phosphorus is located in the number of the 20 most frequently occurred elements in the solar system and the 11th in the crust of Earth (Nutrients: Phosphorus, Nitrogen Sources, Impact on Water Quality, 2008.) Moreover, P fertilizers are in a huge demand to grow enough food for the world population, which is continuously enlarging with great potential.

The eutrophication of waters, well known as nutrient enrichment appearing in the water, is caused by overloading water bodies with nutrient substances, particularly phosphorus and nitrogen. Such phenomenon might occur from both point and non-point sources of pollution. Point sources could represent for instance wastewater discharges from manufactures and non-point ones are leakages of the surface waters with high fertilizer content from the farms. (Yang et al., 2008)

Excessive content of the nutrients in water bodies brings several serious problems, such as structural and functional destruction of coastal areas' ecosystems and appearances of algae blooms on the water surfaces. The "experienced molecular formula" of algae is " $C_{106}H_{263}O_{110}N_{16}P$ ", as it can be seen the phosphorus together with nitrogen relate to the smallest proportions of the whole substance. Especially P plays a role of the limiting element to control the reproduction and distribution of the algae in the water body. According to the paper of Zhao in 2004, 80% of all eutrophied water bodies worldwide have been overloaded mainly by the phosphorus and only other 20% by nitrogen and other relative limiting factors. Talking about all lakes and reservoirs in the world, from 30 to 40% of them have been exposed to eutrophication in varying degrees, as it has been investigated by United Nation Environmental Protection. (Yang et al., 2008)

Referring to the actual risks that can occur from the enrichment of water bodies with nutrients, the damage can be directed to all participants of the water ecosystem, which leads to the degradation of all the vital functions. Particularly, the effects can result in decreasing the water quality and turbidity, thus the sunlight cannot come through the upper layers of water surface, and the photosynthesis process appears to be weakened or even impossible. Another risk is the lack of dissolved oxygen in water, since the process of eutrophication intakes a great amount of O₂ for the regeneration and reproduction of algae. This fact can result in death of the large number of aquatic animals. Moreover, the formed thick layer of algae on the surface can release some amounts of toxic substances, and the organic matter can be transferred into harmful gases that again might damage the aquatic ecosystem. (Yang et al., 2008)

Water eutrophication has gradually become an important problem, which needs great attention and actions to prevent this phenomenon to happen. The Urban Wastewater Treatment (UWWT) Directive (adopted in 1991) is a prescription which regulates how well wastewater has to be treated before discharges to the natural waters. The division of the requirements is being done in accordance to the population of the area. The member states under this Directive must provide collecting systems for wastewater for the agglomerations of population more than 2000 people (p.e. – population equivalent). If such areas discharge the treated water into the fresh waters, the secondary treatment process must be applied. The agglomerations with the population higher than 10000 p.e. are prescribed with special requirements touching several parameters to be controlled and assessed: Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Total Nitrogen (N_{tot}) and Total Phosphorus (TP). (Council Directive concerning urban waste-water treatment 91/271/EEC)

The Water Framework Directive (WFD) which was a basement for the UWWT Directive requires the estimation and identification of substances that support and enhance the process of eutrophication. The requirements for the eutrophying substances, phosphorus and nitrogen, represent the concentration and minimum

percentage of reduction depending on the population of the agglomerate. (Table 1)

Table 1. Requirements for the phosphorus and nitrogen removal in UWWT (Council Directive concerning urban waste-water treatment 91/271/EEC)

Parameters	Concentration	Minimum percentage of reduction
Total phosphorus	3 mg/l (less than 2,000 p.e.)	80%
	2 mg/l (2,000-100,000 p.e.)	
	1 mg/l (more than 100,000 p.e.)	
Total nitrogen	15 mg/l (10,000-100,000 p.e.)	70%
	10 mg/l (more than 100,000 p.e.)	

2.2 Phosphorus characteristics

Phosphorus in the water is divided into two main forms: particulate (insoluble) and dissolved (soluble) as it is presented in the scheme below (Figure 1). The most frequently appearing form is ortho phosphorus, the same type is the most attractive for algae and living species in the aquatic systems. Talking about discharges from WWTPs, the treated wastewater contains mainly dissolved forms of phosphorus. (Bartsch, 1972)

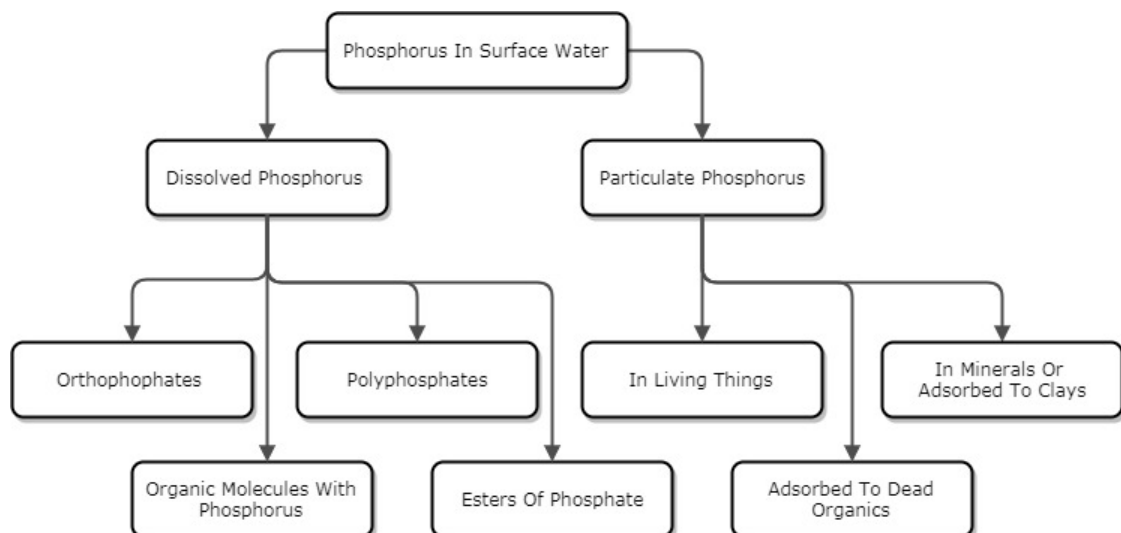


Figure 1. Schematic of phosphorus forms (modified from "Phosphorus: Sources, Forms, Impact on Water Quality, 2007")

Particulate phosphorus on its turn has the ability to cycle from one form to another depending on several conditions of the medium. For instance, whilst microbial decomposition of organics takes place in some water body, organic particulate phosphorus can be transferred to the dissolved one. Some minerals also contain particles of P that due to some physical-chemical changes in the bottom of the water reservoirs can be cycled to the soluble form. That is why it is mostly advisable to make the analysis of TP while assessing the nutrient discharges to the natural waters that can cause eutrophication.

(Bartsch, 1972)

2.3 Techniques for phosphorus removal

Phosphorus can be removed from wastewater using biological or physical-chemical methods. The ideas of both types of treatment include the incorporation of P into the TSS and further removal of phosphorus from this dry matter. In the case of chemical process, the phosphorus is incorporated into chemical precipitates. It is done by adding metal coagulants and mixing them with wastewater so the inorganic forms of phosphorus are removed in a great scale. In the role of coagulant, several metal salts can be used: calcium, aluminum and iron. (Metcalf et al., 2003)

In order to enhance the process, different coagulant aids can be implemented to create heavy and tough precipitate. Such formed floc will settle faster and will not be destructed while mixing so it can be easily separated from the water. In this study the addition of polymer and sludge will be described further, but in other cases, lime, clay, activated silica and other acids and alkalis can be used as coagulant aids. (Metcalf et al., 2003)

During the biological process of phosphorus removal, P is incorporated into biological solids, such as microorganisms. So-called phosphorus accumulating organisms grow in special reactors, intake and accumulate the P from the wastewater in both anaerobic and aerobic conditions. Schematic process of Enhanced Biological Phosphorus Removal (EBPR) is depicted in the Figure 2. As it can be seen, chemical costs are reduced in comparison with chemical

precipitation in addition to the lower amount of sludge produced (Metcalf et al., 2003.) The main disadvantage of the bio-removal method is that it is not quite stable and reliable. Taking into consideration Nordic countries, low temperatures and high flows of the influent wastewater create disturbances in the process and the needed low concentrations of phosphorus in effluent are hard to be achieved due to those upsets. (Panasiuk, 2010)

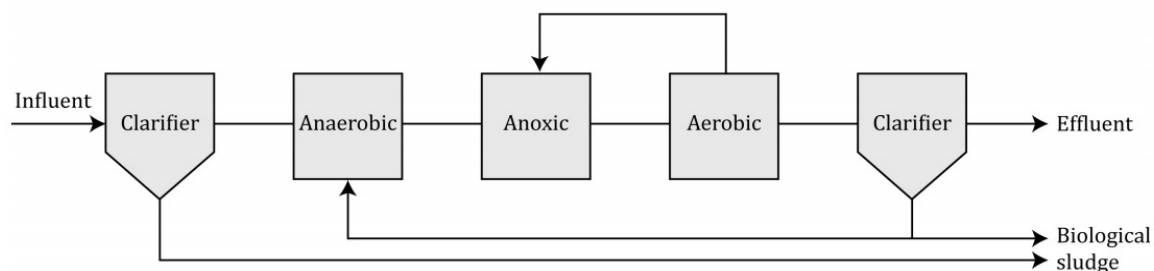


Figure 2. EBPR process (Panasiuk, 2010)

This thesis study has been conducted to optimize the physical-chemical phosphorus removal method and it contains tests where the salts of Al and Fe have been used for coagulation. The actual process description will be represented in Chapter 3.

2.4 Current situation in Europe

Advanced wastewater treatment is implemented quite widely nowadays. Taking a look at the European part of the world, Finland is the one of the leaders of the tertiary treatment procedures in UWWTPs over the whole Europe. By this means it essentially removes great amounts of nutrients and organic matter before discharges into natural waters. The Nordic Countries, in their turn, implement and use the tertiary treatment more than Central, Southern or Eastern parts. It has to be noticed, that wastewater from around 70% of citizens in Northern Europe is treated in WWTP with implemented advanced treatment processes. (European Environment Agency, 2017)

Talking about the situation in Europe considering an average phosphorus content in municipal wastewater, the value equals to 10 mg/l of P or less. As it was shown earlier in chapter 2.1, the minimum reduction percentage for the

phosphorus in effluent from WWTPs has to be at least 80%. In real situations, according to the standards of 0,5-1 mg/l of P, the 90% reduction has to be executed. Scandinavian countries' discharges are being even more strictly controlled by special permits – from 0,2 to 0,3 mg/l of P as threshold values. In these cases, the chemical precipitation is used instead or along with the biological phosphorus removal to get maximum efficiency. Central Europe mainly implements only biological P removal in their WWTPs technologies, which allows to get good but not perfect quality of effluent (P concentrations from 0,5 to 1 mg/l). So currently it is considered that the chemical precipitation together with bio-removal is the best combination for P removal from wastewater. (Stark, 2004)

Touching the theme of phosphorus recovery from the sludge, such process brings a great possibility to recirculate and reuse the P in sustainable and economically-efficient manner. The technologies are just developing nowadays in this field, so the costs of implementations are sometimes more expensive than the profit from the recovered P. This means that the motivation of each country in Europe varies in this direction. Some would find such technologies environmentally attractive, as for instance the Nordic countries and the Netherlands do, while other countries would find it unattractive since the market value of phosphorus taken from sludge is much higher than for instance phosphate rock. (Stark, 2004)

3 CHEMICAL PRECIPITATION STEPS

Since this research is about optimizing the chemical precipitation method, there is a need in deep explanation by the theory how the process is adjusted and how it actually goes.

3.1 Destabilization via coagulation

Starting with the definition, coagulation is the process where the system is destabilized from the stable state. In terms of the wastewater treatment, the particles (or colloids) contaminating the water are transferred to the unstable phase. The term stability in this case can be described as ability of particle to

remain as an individual entity. Such characteristic is conditioned by surface charge appearing between liquid and colloid in addition to different hydration levels of colloidal surfaces. (Bratby, 2006)

There are hydrophobic (has a water repellent effect) and hydrophilic (affined to water particles) colloids being present in the dispersion, both types of particles can exist together in substance. Moreover, both hydrophilic and hydrophobic areas can co-occur on the colloids. It is essential to mention, how the surface charge of colloids originated since the destabilization of particles, which occurs while coagulation, is strongly dependent on such factor. (Bratby, 2006)

According to Stumm and Morgan (1987), the surface charge might originate from chemical reactions appearing on the surfaces of solids, mainly by degree of ionization of functional, e.g. carboxyl or amino, groups. Other two reasons are disturbances of lattice structure (replacements of atoms) and adsorption of ions. When the surface charge appears on the colloid, the electrical double layer is situated simultaneously.

In the Figure 3 below, the concept model of an electrical double layer developed by Otto Stern in 1924 is shown. The negatively charged particle has the Stern layer of positively charged surface, together they make up an inner region. The diffuse region consists of counter- and co-ions placed inside the diffuse layer representing the liquid surrounding the colloid. Electrical potential surrounding the colloid is called zeta potential, which is used to estimate the degree of the double layer charge. (Bratby, 2006)

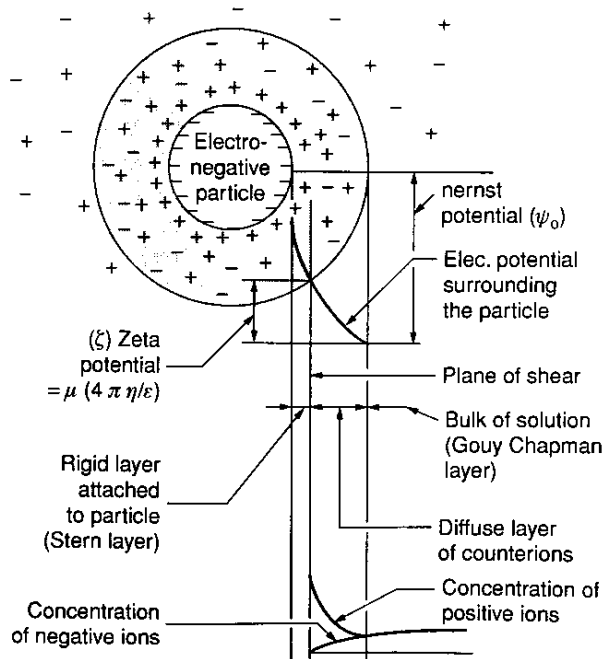
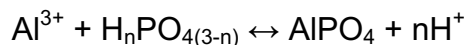


Figure 3. Concept of electrical double layer (Bratby, 2006)

The stability of a certain colloid can be explained in terms of the double layer structure, particularly such structure allows to estimate the energy of interaction and energy of repulsion between the particles. They are calculated mainly by London-van der Waals forces. If the maximal potential energy is larger than thermal kinetic energy of the colloids, then the system is stabilized. Otherwise the particles will consolidate. (Bratby, 2006)

The destabilization of particles that remains in a stable state can be done by an addition of needed concentration of simple electrolyte, so the electrical double layer would be repressed. Adsorption of ion on the surface of the particle involves several steps including removals of ion from solution and solvent from the particle, followed by the attachment of the ion onto the surface of the colloid. During this study, metal coagulants together with polymers will be used for precipitation. The most relatively cheap, available and effective are aluminum and iron coagulants. Their main benefit is the enhancement of the adsorption process due to the formed polynuclear complexes in the medium. (Bratby, 2006)

As for the aluminum, different forms of such are used as coagulants: alum, aluminum phosphates and hydrated aluminum sulphates are the most common ones. The reaction, that occur during the process, looks as follows:



It should be noticed that this is a simplified view on the reaction of coagulation, such factors as pH, alkalinity, possible trace elements and other reactions in the medium should be considered. As it can be also seen, the rate of the coagulant loading is the function of the required P removal. In the same way, iron salts are used in coagulation, namely chlorides, sulphates and ferrous sulphates. The simplified reaction is represented below, the ions of iron in combination with P form ferric phosphates: $\text{Fe}^{3+} + \text{H}_n\text{PO}_{4(3-n)} \leftrightarrow \text{FePO}_4 + n\text{H}^+$ (Metcalf et al., 2003).

It has to also be noticed that the obligatory condition for the coagulation process is the rapid mixing of wastewater flow with coagulant. Such step helps to obtain uniform dispersion of added chemical and increase the probability for particular contact of colloids. (Bratby, 2006) It is important to mention certain parameters that can affect coagulation process. The list of them includes characteristics of the wastewater itself: temperature, pH, suspended solids and P content. Other factors are amount of the added coagulant with its type, mixing intensities in the basins and retention time of coagulation, all of listed parameters can be adjusted (Bratby, 2006.) During the thesis work, all of the mentioned parameters have been changed, tested and optimized, excluding pH and temperature. These two factors were stable and could not be changed during the process.

3.2 Flocculation

Flocculation itself is implemented after the system has already been destabilized by coagulant and the particles have been formed during coagulation. Added flocculant into the suspension induces such particles (floc) to agglomerate together to form bigger, thicker and more strength floc. Along with such characteristics, filterability, settleability and compressibility parameters are being improved as well during the flocculation step. (Bratby, 2006)

Different flocculants can be used during precipitation process. In this study synthetic polymers were used as flocculants and recycled sludge was in a role of additional coagulation aid. Polyelectrolytes represent themselves as special group of polymers with functional groups that can be ionized. When such groups dissociate, other molecules start to be positively or negatively charged, respectively referring to anionic or cationic polyelectrolytes. (Bratby, 2006)

The process of flocculation takes place in gentle mixing conditions and consists of two important stages: perikinetic and orthokinetic flocculation. The first one is happening straight after the destabilization in the colloidal dispersion has occurred. This is a randomly appearing process of floc merge and agitation, it is originated from the Brownian movements of particles. An orthokinetic flocculation is the following step where the final amount of agglomerated floc is being formed. With induced mixing intensity, more floc is being formed but the size of them would be relatively small due to the breakdown of larger floc particles. The lower velocity gradient prevents the floc destruction; however longer time is needed to reach the needed size of floc. Thus, the time for flocculation and velocity gradients are two main parameters for flocculation adjustments. Settings can vary depending on the next proceeding of formed precipitate, the aim could be to reach the maximum settling rate of the floc or for example to increase its filterability. (Bratby, 2006)

3.3 Sludge recirculation

The usage of formed chemical sludge as coagulation aid has been mainly described in literature sources by the term “ballasted flocculation”. For such process, the micro-sand is used in most of the cases, but sludge recycle has been mentioned as a suitable substance as well. The ballasted flocculation represents the process of metal-salt coagulant addition to achieve the destabilization of the system, followed by the addition of polymer and micro-sand (or returned sludge). Such coagulation-aid substances create more surfaces for suspended solids to contact via polymer bridges and consequently the probabilities for colloidal agglomerations increase. As a result, noticeable

improvements in TSS removal from the influent are obtained, in addition denser and easily handled sludge is formed. (Wateronline.com, 1998)

Usually, such technique has been used to increase the settling rate of formed floc, since the greater weight of agglomerates acts as a ballast while precipitation. The sludge can be easily collected from the bottom of sedimentation basin and proceeded further into, for instance, hydrocyclone-separator as it is done during Actiflo® process (Figure 4). (Wastewater Technology Fact Sheet Ballasted Flocculation, 2003)

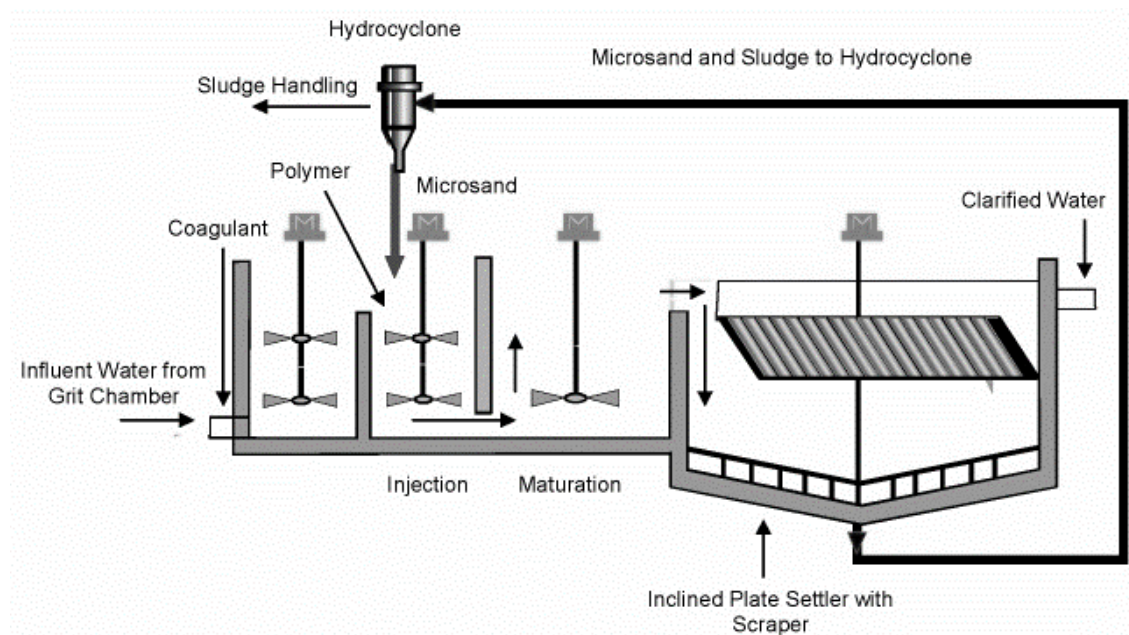


Figure 4. Schematic Actiflo® process (Wastewater Technology Fact Sheet Ballasted Flocculation, 2003)

During this thesis work sludge recycle has been tested in order to observe how ballasted flocculation would be working with surface filtration method, particularly discfilter. In this case, the settling rate of floc formed during gentle mixing is not as important as its filterability. Theoretically, it has been estimated that larger agglomerates of floc would be more efficiently sieved through filter media. Thus, backwash water from the discfilter would have increased amount of SS and thickened sludge would be denser and reach by nutrients as well. Suspended solids content in the effluent would be decreased too. Practical results from pilot-tests are represented further in chapter 8.1.3.

4 SEPARATION

4.1 Filtration methods

After the coagulation and flocculation stages have successfully been proceeded, the next step is to remove formed organic and inorganic colloids and suspended solids (SS). This process is usually done by separation techniques, particularly different types of filtration. The common classification of filtration methods is represented in the Figure 5.

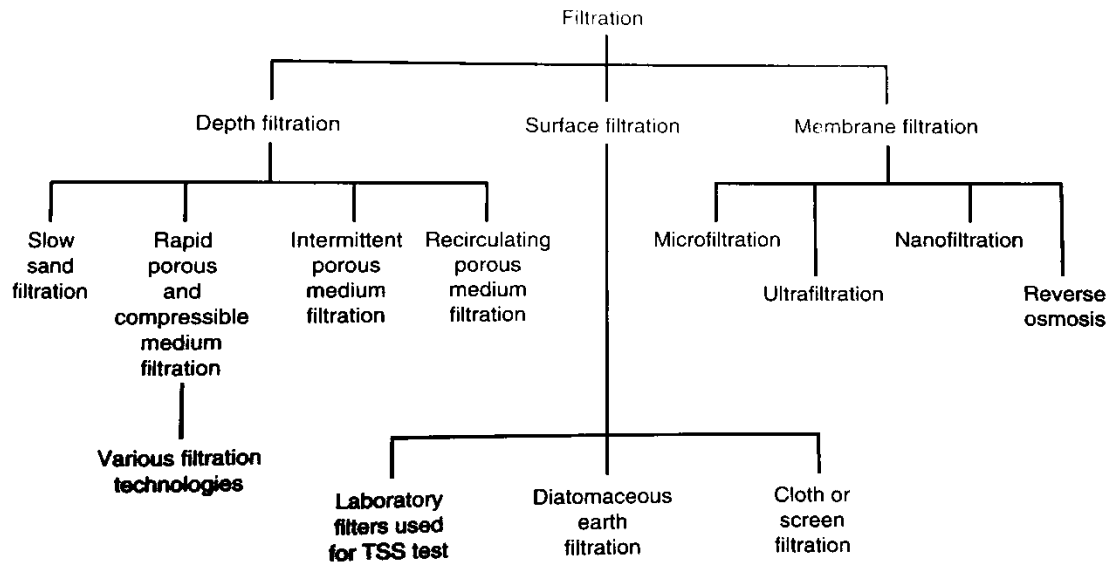


Figure 5. Different methods for filtration (Metcalf et al., 2003)

As it is depicted, there are three common groups of techniques: depth, surface and membrane filtration. The key feature of depth filtration is the filter bed, where removal of precipitate is taking place within or on the surface of it. Surface and membrane methods for separation are somehow similar, in these cases the removal of suspended solids being done by filtering the water flow through a straining surface (for instance filter cloth or thin membrane). (Metcalf et al., 2003)

During this thesis study, discfilter has been used for the removal of precipitate material from the wastewater flow, description in detail of such is presented in the next paragraph 4.2.

4.2 Disc filtration

Disc filter (DF) is the device working by the principal of surface filtration method, so the wastewater stream is sieved through the thin septum. DF usually represents itself set of the discs that support the filter cloth, each of them is linked to the feeding tube. Material used for filter media is preferably polyester or stainless steel (316). Talking about actual operation, the schematic principle of work is depicted on the Figure 6 below. The influent water with formed floc can enter the discfilter either via the central feeding tube or outside of it and runs outward trough the filtering cloth. Normally from 60% to 70% of the disc area is submerged with wastewater and the disc rotates from 1 to 9 rounds per minute depending on the settings and loads. (Metcalf et al., 2003)

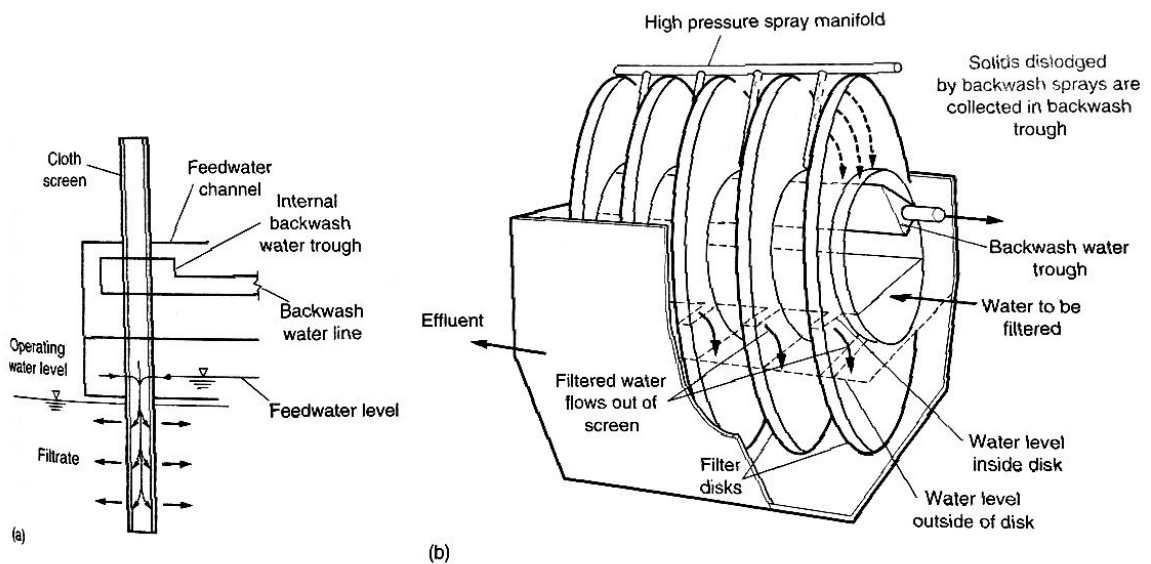


Figure 6. Disc schematic (Metcalf et al., 2003)

DF is able to work in continuous or intermittent backwash modes depending on the inlet flow and amount of suspended material in it. While the continues mode, influent wastewater runs through filter media, discs continuously rotate capturing suspended solids from the flow and high-pressurized sprays start to flush the precipitate from the cloth media. The mix of backwashed water and SS is being washed away from the discs and collected into the separated channel, from where the mixture is pumped further into the process. After discs have been washed with nozzles, the filtering cycle can be started from the beginning.

Intermittent backwash mode allows setting the certain submerging level of filters. It is controlled by pressure level meter, so the backwashing only starts when the certain level has been achieved. (Metcalf et al., 2003)

5 CASE STUDY AT VIIKINMÄKI WWTP

5.1 Viikinmäki WWTP

Currently, Viikinmäki WWTP is the largest treatment plant in Finland and in the Nordic Countries. Viikinmäki WWTP treats the wastewater from approximately 800,000 residents of Capital Region and some parts of Greater Helsinki. The actual treatment process at the plant is based on the activated sludge method separated into three parts: mechanical, biological and chemical. Biological filter is being used for enhanced nitrogen removal via denitrification bacteria. Phosphorus is removed by simultaneous precipitation with addition of the ferrous sulphate (Figure 7). (Hsy.fi, 2017)

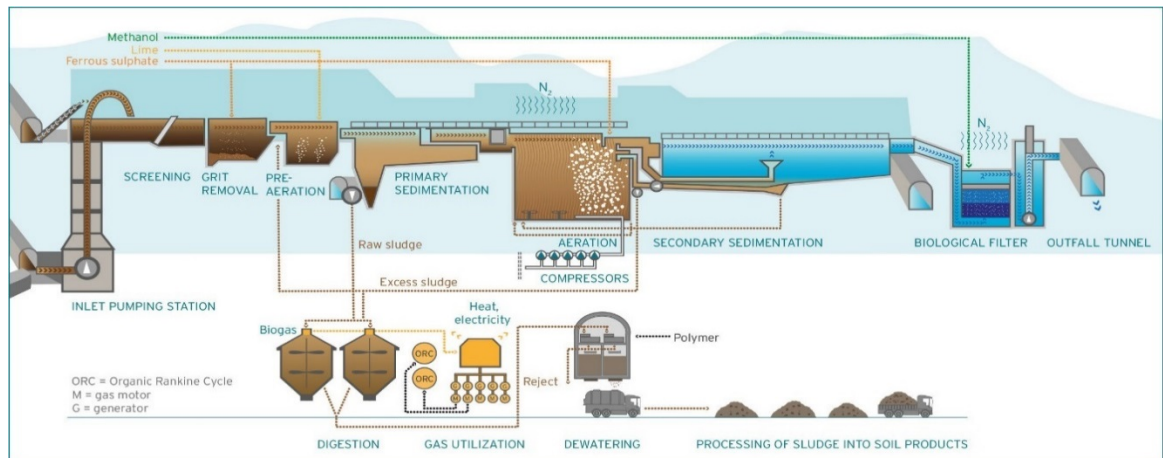


Figure 7. Process description of Viikinmäki WWTP (Hsy.fi, 2017)

Formed amounts of organic matter in sludge are utilized using digestion, around 60,000t of dried sludge is being produced in Viikinmäki WWTP per year. Produced biogas from sludge is used for energy production on the site, it makes the plant fully self-efficient with heat production and 70% self-efficiency for electricity needs. Digested and dried sludge is utilized further in the composting field in Sipoo, where green soils and fertilizers can be produced. (Hsy.fi, 2017)

Viikinmäki WWTP is operating under the European and national regulations regarding the minimal levels of wastewater treatment. Moreover, it has its own plant-specific permits with threshold values for effluent water parameters, solid wastes and air emissions. Based on the open information from HSY's 2016 annual report, in the Table 2, the limiting values and the results can be outlined. All values are quarterly averaged, except total nitrogen, which is calculated as annual average value. (Hsy.fi, 2016)

Table 2. Parameters of outgoing wastewater from Viikinmäki WWTP (modified from annual report of HSY, 2016)

	BOD _{7ATU}	Total nitrogen	Total Phosphorus	COD _{Cr}
	mg/l	% reduction	mg/l	mg/l
Limit values	≤10	≥80	≤0,3	≤75
Results	4,9	92	0,21	41

5.2 RAVITA-process and pilot plant

Pilot plant which was built inside Viikinmäki WWTP in 2014 is a part of HSY's individual RAVITA-process for the phosphorus recovery. The main idea of RAVITA is to transfer precipitation step from the simultaneous to the end of the wastewater treatment process (hsy.fi/ravita, 2017.) Current pilot plant represents the first step of the planned process, it includes advanced chemical precipitation of high P loaded wastewater, followed by the separation procedure. The separation is being currently done via the disc filtration technique, since it has been considered to be tested at first. (Rossi, 2014) The whole schematic RAVITA-process is presented in the Figure 8 including the post-precipitation, separation and actual recovery phases.

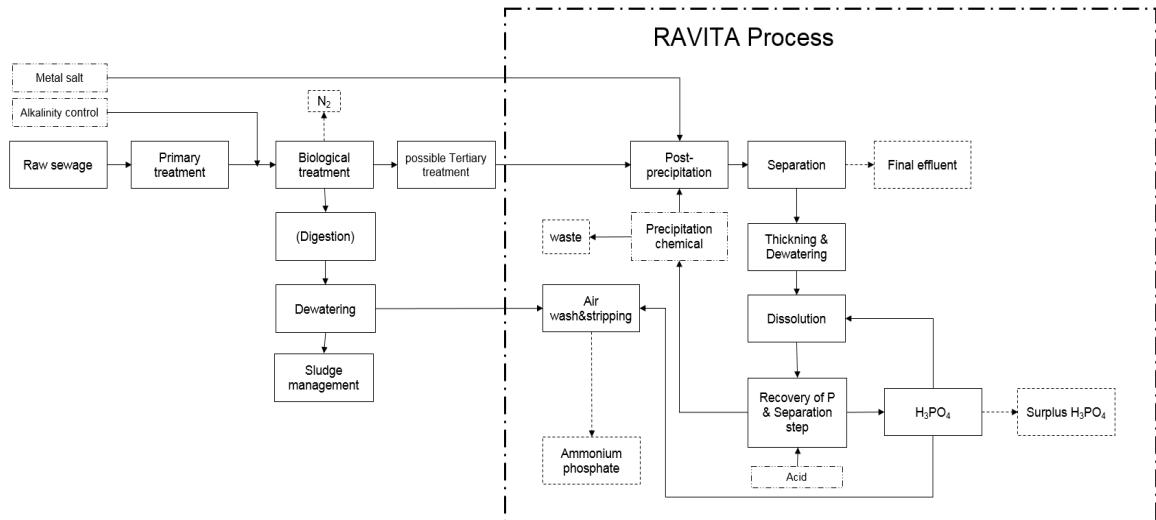


Figure 8. RAVITA -process added to a conventional wastewater treatment process. (Rossi, 2017)

The pilot plant is the unit of RAVITA where the actual optimization work for the thesis has been conducted. Its structure and description is explained further in chapter 6.5 and it looks as follows in the Figure 9.



Figure 9. Pilot process

6 MATERIALS AND METHODS

The study can be separated into two parts: conducted laboratory- and pilot scale tests and analysis of the obtained results.

6.1 Applied chemicals

The following metal-salt coagulants presented in the Table 3 have been tested both in jar tests and in pilot tests runs.

Table 3. Applied coagulants

Coagulant	PAX XL100	PIX-105
Supplier	Kemira Oy	Kemira Oy
Concentration (%)	30-40	35-45
Metal content (%)	9.3±0.3 (Al)	11.7 ±0.5 (Fe)
Density at 20°C (g/cm ³)	1.36-1.42	1.45-1.55
Form	Liquid	Liquid

Two different types of polymers have been applied both in laboratory and pilot scales represented in Table 4.

Table 4. Applied polymers

Polymer type	A-100	C-492 VP
Supplier	Kemira Oy	Kemira Oy
Charge	Anionic	Cationic
Bulk density (kg/m ³)	800±50	750
Relative Molecular weight	High	High
Form	Solid	Solid

Chemicals that have been used for maintenance and washing the equipment, such as discfilter and lenses of online turbidity meters: HCl (10%) and NaOCl (5%).

6.2 Calculations

6.2.1 Mass and molar concentration

Formulas for mass and molar concentrations have been used as follows to control the amounts of added chemicals (Equation 1.)

$$C = \frac{m}{V}; \quad C = \frac{n}{V}; \quad n = \frac{m}{M} \quad (1)$$

C	molar or mass concentration (mmol/L or mg/L)
M	molar mass (mg/mmol)
m	mass (mg)
n	quantity of moles (mol)
V	volume of the substance (L)

6.2.2 Amount of product to be added

To be able to conduct laboratory jar tests, the amounts of chemicals to be added should be recalculated manually for the product, namely Aluminum based PAX XL100 and Iron based PIX-105, using following formula (Equation 2.)

$$F_c = \frac{c(Me) \cdot F_s}{\frac{\%(Me)}{100} \cdot d(metal)} \quad (2)$$

F_c	inlet flow of chemical coagulant (ml/h)
$c(Me)$	metal concentration (mg/l)
F_s	inlet flow of water (m ³ /h)
$\%(Me)$	metal content (%)
$d(metal)$	product density (g/cm ³)

6.2.3 Molar ratio between phosphorus and loaded coagulant

In order to control the molar ratio between Phosphorus and loaded coagulant (Al or Fe), following set of equations have been used for calculations (Equation 3.)

$$\begin{aligned}
 TP \text{ in (mmol/l)} &= TP \text{ in (mg/l)} / M(P) \\
 Al \text{ or Fe in (mmol/l)} &= TP \text{ in (mmol/l)} * (\text{mol Al or Fe:mol P}) \\
 Al \text{ or Fe in (mg/L)} &= Al \text{ or Fe in (mmol/l)} * M(Al \text{ or Fe})
 \end{aligned} \quad (3)$$

TP_{in}	TP content in the inlet (mmol/ or mg/l)
Al_{in}	Aluminum content in the inlet (mmol/ or mg/l)
Fe_{in}	Iron content in the inlet (mmol/ or mg/l)
$M(Al)$	Molar Mass of Al (mg/mmol)
$M(Fe)$	Molar Mass of Fe (mg/mmol)
$M(P)$	Molar Mass of P (mg/mmol)
$(mol Al: mol P)$	Molar Ratio between Al and P
$(mol Fe: mol P)$	Molar Ratio between Fe and P

6.2.4 Backwash percentage

The backwash percentage (BW%) represents itself the actual washing time of one wash cycle conducted by the discfilter divided by the period of time between previous and next washing. Such value gives the percentage of the disc working time from the total amount of the time. Less BW% means less energy consumption and less need in disc maintenance in the future perspective. Below it can be seen how the BW% is calculated from the received data (Equation 4.)

$$BW\% = \frac{t_{wash}}{t_{tot}} \cdot 100 \% \quad (4)$$

$BW\%$	backwash percent
t_{wash}	washing time (s)
t_{tot}	total filtration time, wash+cycle (s)

6.2.5 Hydraulic retention time

For various adjustments related to optimization of the total coagulation and flocculation time of the process, hydraulic retention time (HRT) has been calculated as follows (Equation 5.)

$$HRT = \frac{V_{basin}}{Q} \quad (5)$$

HRT	hydraulic retention time (min)
V_{basin}	volume of the flocculation basin (m ³)
Q	inflow (m ³ /h)

6.3 Mass balance calculations

The theoretical estimation about the amount of sludge that is about to be recirculated inside the pilot has been done using mass-balance analyses with the help of the obtained values of suspended solids concentrated in backwash water. The mass balance analysis is used in a great amount of systems mainly when there is a need in account of the entering and leaving materials or substances and their flows. The key principal of such method is that a certain matter cannot disappear or eventually appear inside the system. (Metcalf et al., 2003)

The Figure 10 represents the SS flow in the system. The value Q means the volume of the substance and SS the suspended solids amounts. As it can be seen, the inlet water (Q IN and SS IN) comes to the discfilter, 71% of SS removed and collected in the sludge sump (SS total BW=171%). Part of this accumulated sludge, which has 100% amount of SS inside is being circulated back to the process (SS sludge cycle). Other part (SS out BW) is pumped to the thickener for further proceedings.

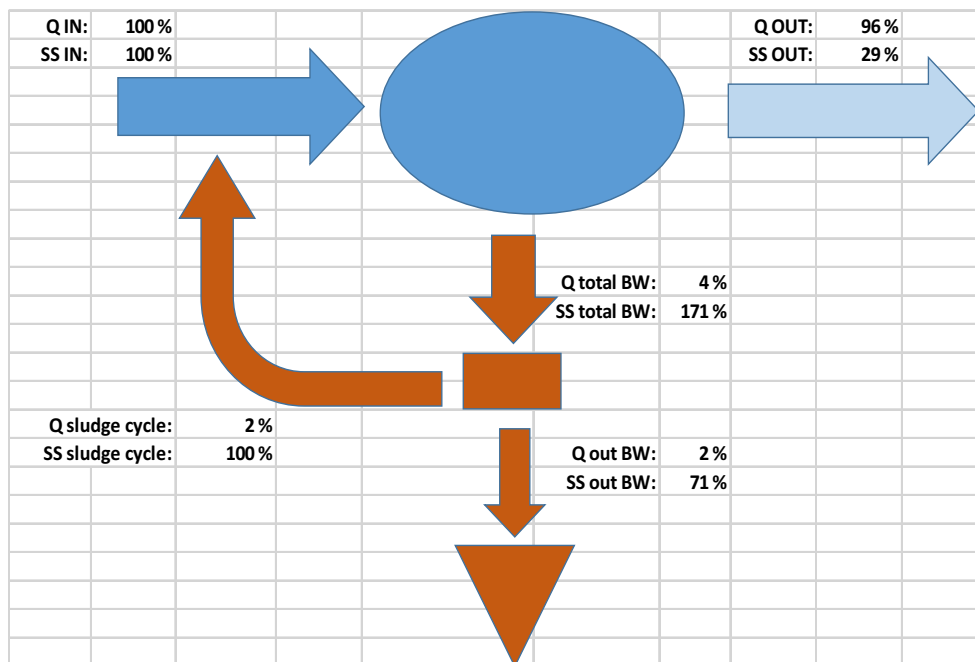


Figure 10. Mass-balance calculations for sludge recirculation

As it is represented in the Table 5, it has been estimated that the concentration of suspended solids entering the pilot from the backwash water is doubled in

comparison with the original precipitate amount. After mass balance analysis of the sludge recycle was conducted, it was found out that around 58% of the backwash water by volume has to be returned back to the process to achieve the improvement in the coagulation and flocculation steps.

Table 5. Calculations for sludge recirculation

changeable values, others are calculated					estimated SS recirculation multiplier:	2
Q=quantity						
	part (%)	Q (m ³ /d)	SS (mg/l)	SS (kg/d)	SS incoming part	Q incoming part
INLET		100	20	2,00	100 %	100 %
INLET+CYCLE		102		4,00	200 %	102 %
OUT		96	6	0,58	29 %	96 %
BACKWASH, out		1,66		1,4	71 %	2 %
BACKWASH, all	4 %	4	856	3,42	171 %	4 %
SLUDGE CYCLE	58 %	2,34	856	2,00	100 %	2 %

6.4 Laboratory scale tests

In order to conduct any possible modification of the pilot, it was highly reasonable and advisable to imitate the process in the laboratory scale beforehand.

Moreover, some analysis can be done in the laboratory to estimate the feasibility and efficiency of certain changes implemented during test-runs.

6.4.1 Jar-tests for chemical optimization

After the theoretical estimations of the chemicals' type and amount have been done via equations (1) and (3), their volumes for jar-tests had to be calculated. Formula (2) provides the calculation method for test products' amount. Lab-scaled coagulators, presented in the Figure 11, were used for such cases of pre-testing, where it is possible to adjust time and mixing velocities. The injections of chemicals were done manually.



Figure 11. Lab-scaled coagulator with raw water mixing

In most of the cases intense mixing after addition of coagulant was done at 400 rpm for about 1 min and following slow mixing straight after polymer injections – 50 rpm for 3 min. Figure 12 shows how the destabilization and floc formation processes can be visually noticed. Thus, it is possible to see how dense the floc looks like. Additionally, it helps to recognize is the floc floating or settling too much and other parameters that can help with chemical optimization in the better way.



Figure 12. Coagulation and flocculation processes

6.4.2 Jar-tests for sludge recirculation

The implementation of the sludge circle inside the pilot process has been tested in laboratory scale before the pilot test-runs as well. The imitation of recirculation has been done on the basement of jar-tests for chemical optimization, the only difference was that the certain amount of backwash water has been injected to the raw water right before coagulant. The amount of needed BW water has been calculated as it was explained in chapter 6.3. Figure 13 shows how the floc formation differs from the one shown in the previous chapter.



Figure 13. Coagulation and flocculation processes with sludge addition

6.5 Pilot plant

The results obtained from the pilot test-runs are considered as more valid and solid than the ones achieved from laboratory analyses. Based on pilot test-runs and its outputs, much more precise estimations can be done considering large scale design process.

The pilot plant built inside Viikinmäki WWTP intakes the water, which is being the effluent from the plant ($SS_{\text{average}}=4.9$ mg/l and $TP_{\text{average}}=0.221$ mg/l, (HSY, 2016)).

The overall process in the form of scheme is presented in the Figure 14. The water is pumped into the pilot with portable pump (Flygt, DS 3057.181), the flow can be changed in the range from 7,5 to 18 m³/h (1000 Population Equivalent). Since the incoming water has low phosphorus content, extra P (from 3 to 5 mg/l) is added into the stream to simulate the process without chemical or bio-phosphorus removal. Phosphate solution is produced from the powder chemical monopotassium phosphate KH₂PO₄ (Algol Chemicals Oy, MKP-FOOD-SB) by dilution and mixing. Further it is loaded into the flow by membrane pump (GRUNDFOS, DDA 17-7) with maximum flow of 17 l/h. In the next step, the coagulant is loaded by membrane pump (ProMinent, GMXa 1602) with 2,3 l/h as maximum possible flow. Coagulant is mixed with the stream by static mixer inside the main process tube. Further, there are two coagulation and two flocculation basins equipped with mixers, the specifications for them are presented on the Table 6 below.

Table 6. Pilot parameters needed for different estimations

Volume (coagulation basin)	0,178 m ³
Volume (flocculation basin)	0,584 m ³
Coagulation mixer (max, 50 Hz)	930 rpm
Flocculation mixer (max, 50 Hz)	73 rpm

Polymer Make-Up System (Tomal, PolyRex 1.0) uses technical water to make the solution from polymer powder (Kemira, A-100 or C-492 VP). After 45 min mixing it is added into the stream with membrane pump (ProMinent, Sigma/ 2, max. flow 56 l/h) into the first or second coagulator with intense mixing before first flocculator. Floc formation is taking place in the next two flocculators with slow mixing intensities. Ready wastewater with formed precipitate comes to the discfilter. Disc filtration process was described in detail in the Chapter 3.4. Backwash water from the filter was collected in the sludge sump (40 dm³) and later was pumped by submerged pump (Flygt, SXM 2, 0.115-0.42 m³/h) with level switch into the gravity thickener (1,85 m³) where overflow water and thickened sludge are formed. Treated water from the filter leaves the pilot plant as effluent.

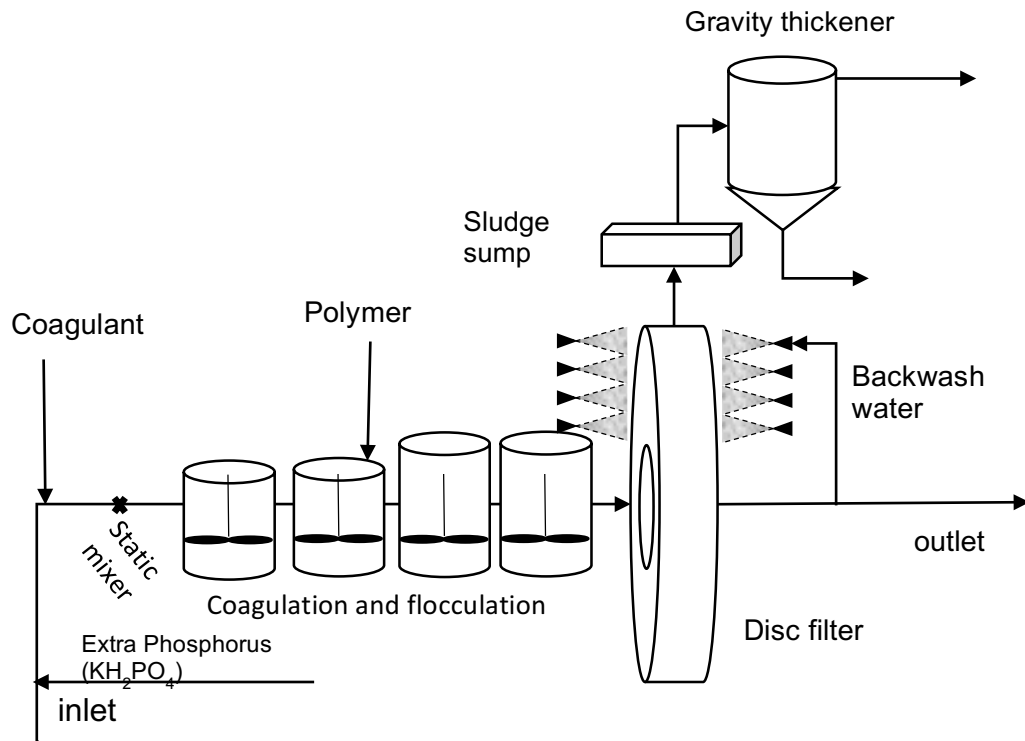


Figure 14. Schematic of Pilot Plant process

In order to conduct test-runs in pilot scale, several steps had to be done. The basement, which is represented by amounts and types of chemicals to use, is taken either from already conducted laboratory tests or straight being tried on site. Major adjustments are done via automated system represented by the Figure 15 below. It is possible to adjust needed inlet flow of wastewater, initial phosphorus concentration in the inlet to the process, final concentrations of the coagulant and polymer and mixing intensities of the first and second coagulators. Mixers of the both flocculation basins are changed manually from the site.

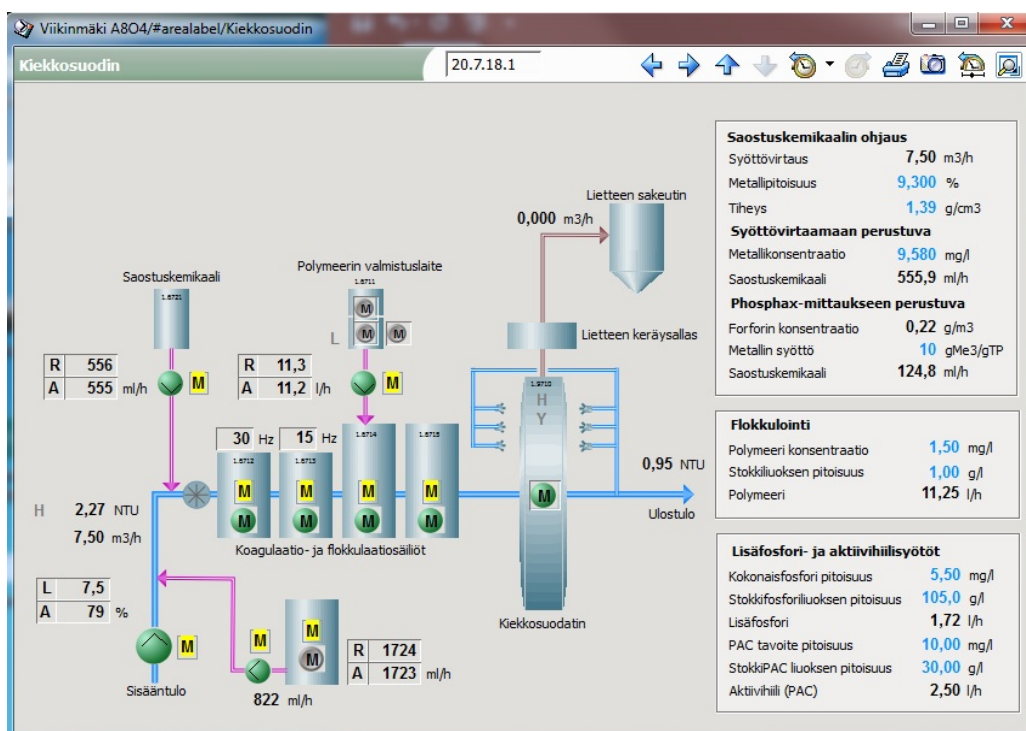


Figure 15. Automated control system of the pilot by Valmet

During the test runs, it is essential to monitor discfilter capacity via parameter BW% described in chapter 6.2.4. Additionally, automated system gives the opportunity to see how different values and readings, including turbidity of influent and effluent are changing within certain period of time as it is shown on the Figure 16 below.

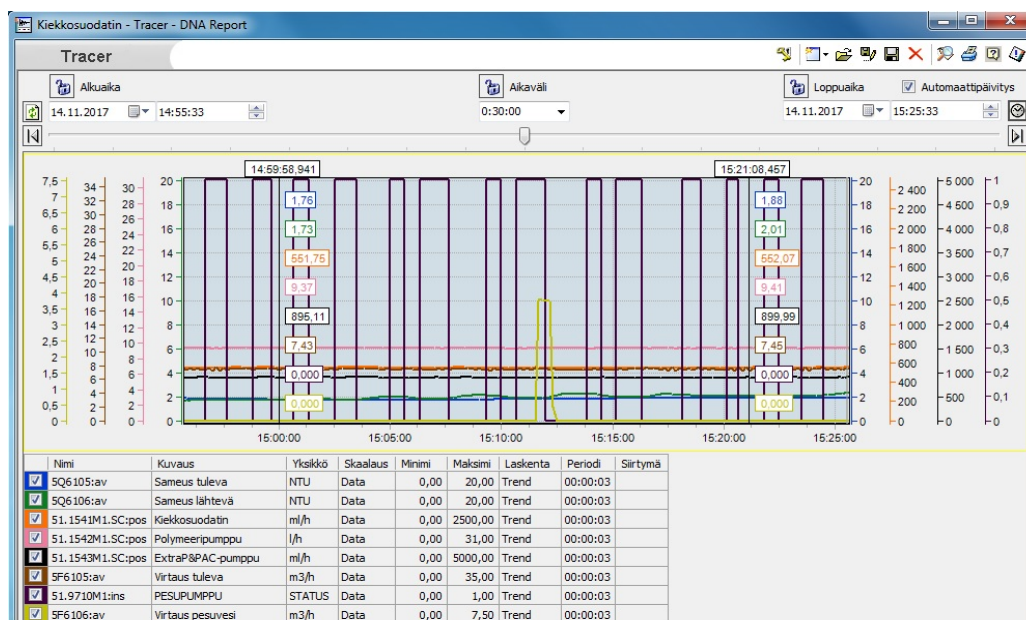


Figure 16. Analysis of the pilot work in Valmet automated system

To finalize the certain test-run, samples are taken manually from different sampling points of the pilot (Figure 17), particularly: influent water (DISC IN), outlet water (DISC OUT), backwash water from the discfilter (DISC BW), thickened sludge (DISC LS) and over-flow water from the thickener (DISC K). Such samples are analyzed either in laboratory in-situ or sent to the external MetropoliLab depending on the type of analyses.

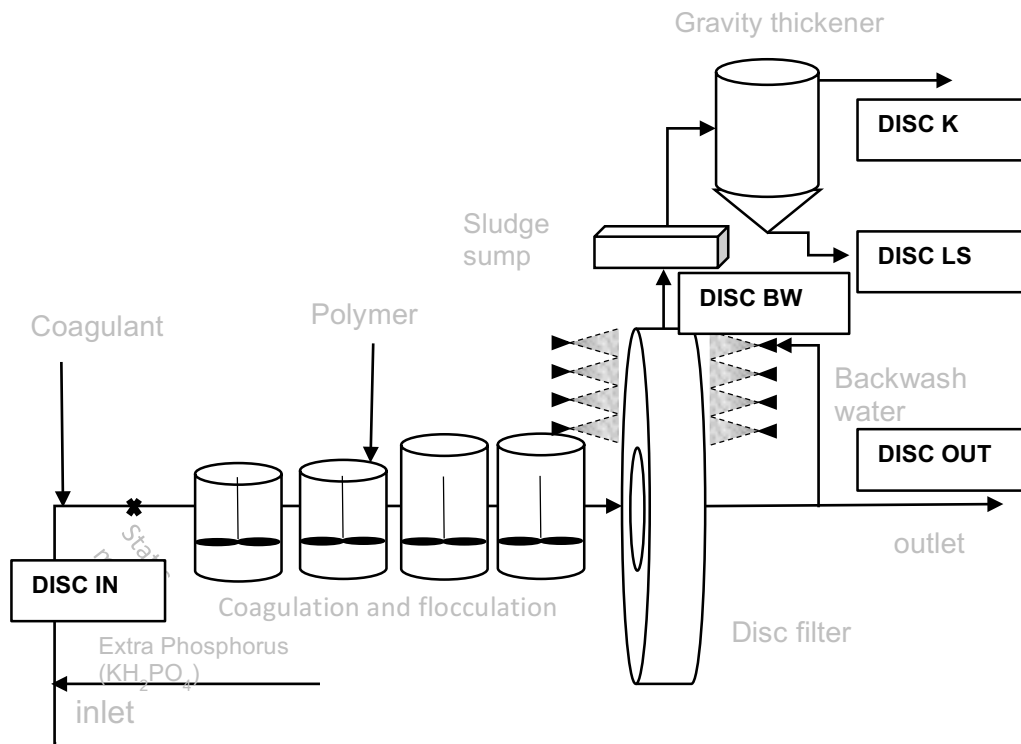


Figure 17. Sampling points of the pilot

6.6 Implementation of the sludge cycle

The sludge recirculation has been implemented in the process with the help of peristaltic pump (Heidolph, Hei-FLOW 06, flow range is 1 – 4056 ml/min) and different tubes of several diameters and thicknesses. As it represented on Figure 18 below, for the first tests, the addition of recirculated sludge was placed to the first coagulator (blue thin arrow). Afterwards, when the effectiveness of such process has been proved, the inlet was designed and installed before coagulant addition (orange thick arrow), so the BW water has more time to be properly mixed with the influent flow of water and precipitates can be attached on the flocs.

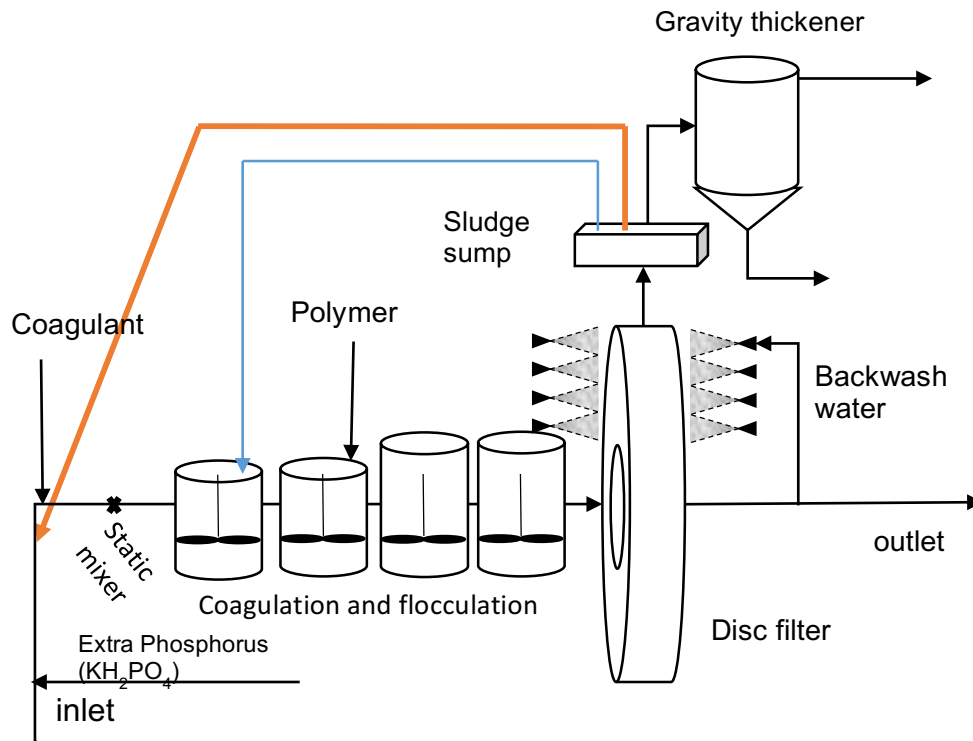


Figure 18. Placement of sludge recirculation inject

6.7 Analytical methods

As it was mentioned previously, the pilot was equipped with online turbidity meters. The measurements of influent and effluent turbidities have been done via nephelometric scattered light technique (Ultraturb system, HachLange). The measurement range was from 0.00001 to 1000 NTU. To control the work of turbidity meters, they have been chemically cleaned once in about 2-3 weeks in addition to parallel measurements of samples' turbidity with portable spectrophotometer (HACH, 2100Q is).

Other analyses that often have been done straight away on site was the TP and phosphates concentrations from inlet and outlet flows (Figure 19). The tests have been conducted with the help of phosphorus and phosphates cuvette tests (Hach Lange, LCK 349). Since the measurement range for this test was between 0.05 and 1.50 mg/l $\text{PO}_4\text{-P}$, the dilution of inlet samples in the rate 1:5 has been done when needed. With the same technology, iron and aluminum content in water samples has been tested several times. (Hach Lange, LCK 321 and LCK 301, respectively).



Figure 19. Kit-tests of phosphates and iron concentrations in samples

Other laboratory analyses have been conducted by external MetropoliLab. All analytical methodologies that have been used while tests are presented by the Table 7 below.

Table 7. Methods used for chemical analyses

Parameter	Laboratory	Measurement uncertainty (%)	On site
Aluminum	SFS-EN ISO 17294-2:2005	25	LCK 301 cuvette test
Ferrous iron	SFS-EN ISO 11885:2009	20	LCK 321 cuvette test
Orthophosphate (PO ₄ -P)	SFS 3025:1986 [invalidated]	15	LCK 349 cuvette test
Suspended solids	SFS-EN 872:2005	10	
Total phosphorus	SFS 3026 mod. DA	15	LCK 349 cuvette test
Turbidity	SFS-EN ISO 7027:2000	15	

7 TRIAL PLANNING

It was planned to firstly estimate the chemical loadings of the pilot, beginning with the selection between cationic and anionic polymer and iron or aluminum coagulant. That is why it was mostly desirable to initially conduct laboratory tests with different selections of coagulant and polymer that would lead to the final decision which substances to use in the pilot scale.

7.1.1 Trials in laboratory scale

Trials in laboratory scale have been conducted using the jar-testing method explained in chapters 6.4.1 and 6.4.2. The results from previous pilot-tests conducted by HSY in 2016 have been taken as a base-line for current research work. After making the decision which polymer to choose, gradual increases and decreases in the molar ratio between Fe/Al and phosphorus content have been tried for the optimum outputs regarding phosphates reduction value and turbidity. The recirculation of formed sludge to enhance the coagulation has been tested with jar-tests as well and adjusted in the same way.

7.1.2 Trials in pilot scale

Usually short trial runs in the pilot scale, related to, for instance, change in the molar ratio between metal and phosphorus or increase in retention time, took around one hour to observe the visual difference in work. Samples have been taken and analyzed both on-site and by the private laboratory. When the promising values had been found, several days' long trial runs were conducted in order to see the stability of settings and check the outlet parameters, such as suspended solids, metal and phosphorus content in different sampling points. All settings and results have been recorded in data base for future needs in development.

8 RESULTS

All the tests and pilot-runs have been conducted in order to achieve values close to formulated goals for each parameter. The first main objective of the research was to minimize TP and SS concentration in effluent water from the pilot (preferably until the level of 0,5 mg/l of TP). Consequently, next aim is to maximize amount of TP and SS in the backwash water from the discfilter. Backwash water is further processed to the thickened sludge, which in ideal situation would be thick enough for easier drying procedures (15-20% of TS is the goal). At the same time discfilter's working capacity, assessed by BW%, should not exceed levels of 50-60%, otherwise the energy consumption and life cycle would be inefficient.

8.1 Chemical optimization

Multiple laboratory tests have been conducted to estimate PIX-105 (Iron-based) or PAX XL100 (Aluminum-based) coagulant to choose and anionic (A-100) or cationic (C-492 VP) polymer to use. It was noted by Janne Väänänen in his doctoral dissertation (2017) that such options vary a lot from one process to another, the quality of influent plays one of the biggest roles here. In some cases, anionic polymer works better with aluminum coagulants, in other plants it is preferred to use the Iron-based ones (Väänänen, 2017.) Sludge produced during the process have been used in lab-scale as coagulant aid as well and further in the project implemented into the pilot plant for research.

8.1.1 Coagulant and polymer optimization

First of all, needed calculations and estimations were done to understand the so-called upper limits of chemical loadings. As the pilot by that time have been loaded with 5 mg/l of phosphate solution, and the molar ratio between added Al coagulant and loaded P should not have exceeded 3, it became possible to calculate maximum preferred amount of coagulant to add using equation (3) as it was described in Chapter 6.2.

It has been theoretically estimated that for the lab tests the amounts from 5 mg/l to 10 mg/l will be used. Approximately the same molar ratio between Iron coagulant and loaded Phosphorus was taken as a basement, the injection dose of Iron coagulant was estimated to be 19,5 mg/l as highest. The amount of polymer was theoretically assessed to be not greater than 2 mg/l and as low as possible since the polymer solution usage in precipitation process is economically feasible only with low enough dosages of injections due to the high price of the product.

8.1.1.1 Laboratory scale tests for coagulant and polymer

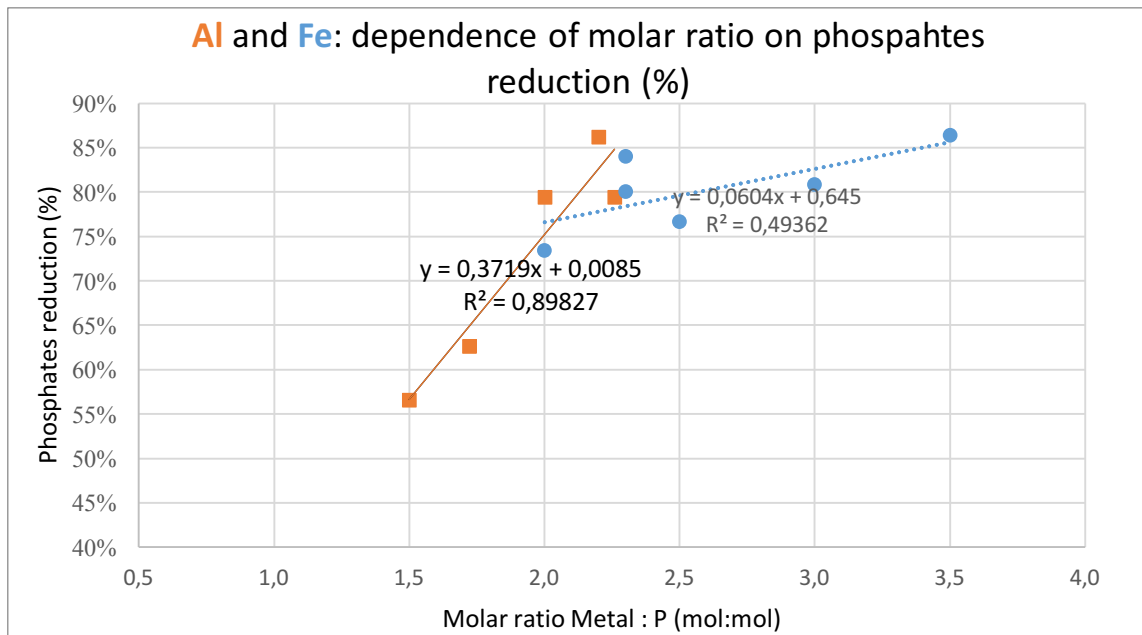
The results from the conducted lab-tests are presented in Appendix 1. It was discovered that anionic polymer showed better results both in turbidity and phosphates reduction in comparison with cationic one. Both PIX-105 and PAX XL100 coagulants showed good and even outputs, the Iron-based coagulant has given reddish color to the water so the turbidity was quite high. Eventually, the results proved the facts (Väänänen, 2017) that coagulant and polymer decision making is done individually for each process and often only practical in-situ tests lead to the final decision making.

With the help of conducted laboratory tests, the decision was to begin with aluminum-based coagulant PAX XL100 and Anionic polymer A100 to continue adjustment of their loadings already both in lab- and pilot-scales simultaneously. Anyway, it was noted that further in the research process it would be advisable to try iron-based coagulant also to see the difference in parameters.

8.1.1.2 Pilot scale tests for coagulant

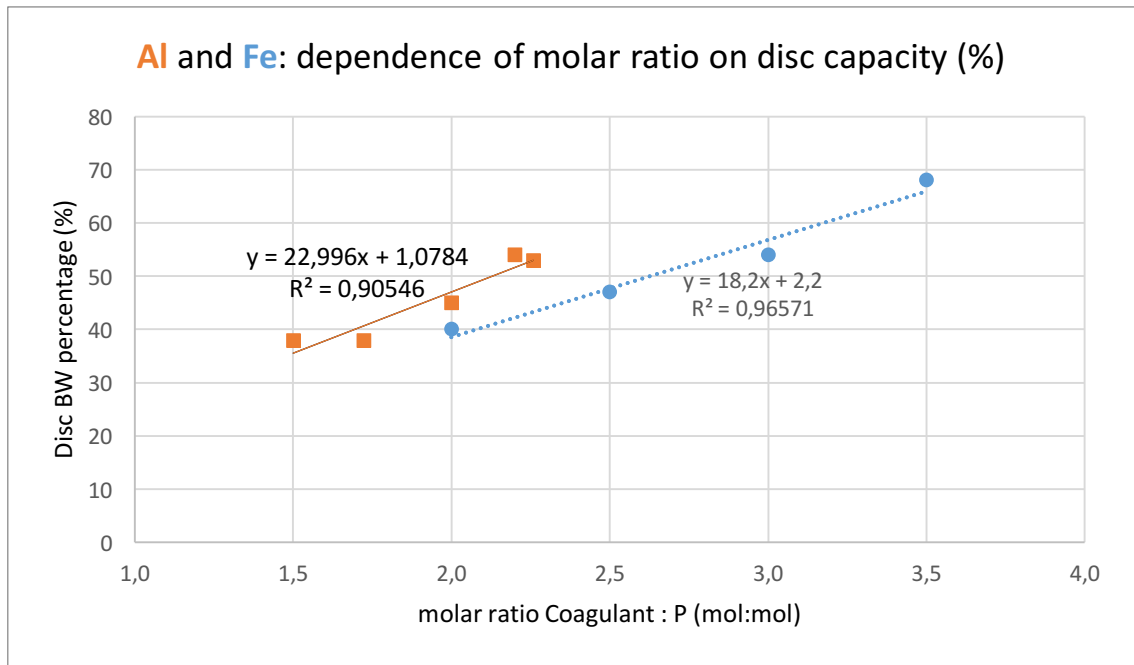
As a base-line for pilot test-runs, following chemicals and concentrations have been chosen: 5 mg/l of initial phosphate solution addition into the influent, 8,71 mg/l of Aluminum-based coagulant and 1,25 mg/l of anionic polymer. During adjustments, initial P concentration of 3 mg/l was also tried, PAX XL100 amounts

were in the range 3,92-9,58 mg/l (mol Al/mol P = 1,5-2,3). PIX-105 coagulant has been tested in the range 10,84-18.97 mg/l so the molar ratio varied from 2 to 3,5. The first two graphs (Graph 1 and Graph 2) represent how loading of the pilot with different dosages of coagulants affects the phosphates reduction percentage and the capacity of discfilter. Increase in molar ratio has made the disc more loaded and more efficient the process of phosphorus removal has been conducted. For clarity of results, both PIX-105 and PAX XL100 coagulants are shown on the graphs. In the case of phosphates reduction tests (Graph 1), increase in molar ratio between Fe and P enhanced the process of phosphorus removal less rapid in comparison with Al-based coagulant, and this leads to the greater amounts and consequently costs for the process.



Graph 1. Al and Fe: dependence of molar ratio on phosphates reduction (%)

Talking about the load of the disc filter (Graph 2), here the trend lines are almost parallel, so the filtration capacity increases with the same potential with both PIX-105 and PAX XL100 coagulants. As for the goals of the research the BW% is good to keep at the level 50-60%. In such range the molar ratio should be no larger than 2,5 for Al and 3,2 for Fe. Both coagulants have given good outputs related to parameters, like phosphates reduction and turbidity of effluent, in such ranges.



Graph 2. Al and Fe: dependence of molar ratio on disc capacity (%)

Figure 20 shows the difference in floc formation and the bonding process of the particles while using Al- and Fe-based coagulants. It was observed that PIX-105 creates dense but not too heavy floc which leads to insignificant but noticeable results: optimum work of the filter and good results of sludge formation and phosphorus removal. The visible drawback is the color; iron gives an intense reddish color during the coagulation steps, and it affects the color of the effluent and equipment used in noticeable matter.

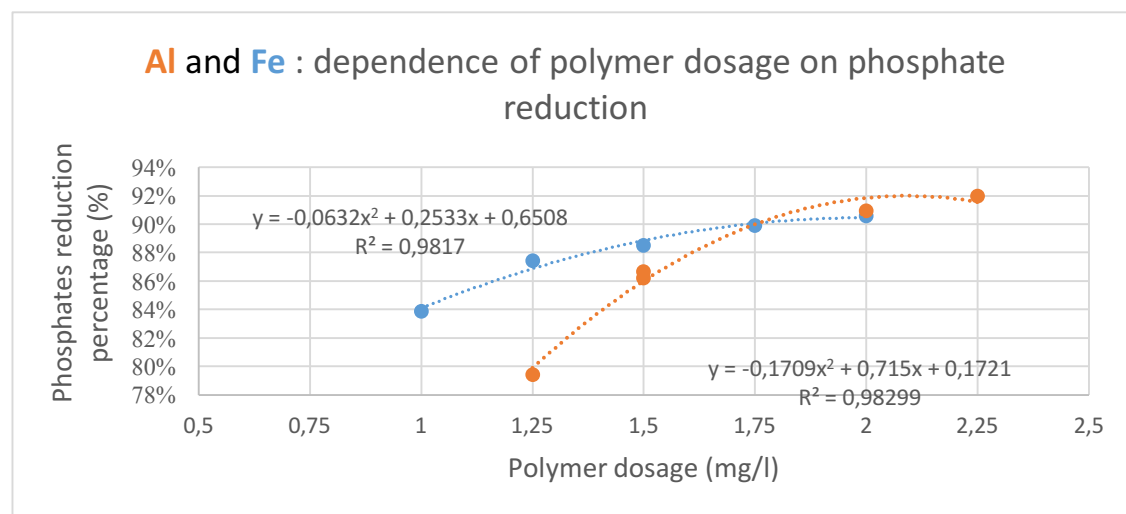


Figure 20. Floc formation with PAX XL100 (on the left) and PIX-105 (on the right)

8.1.1.3 Pilot scale tests for polymer

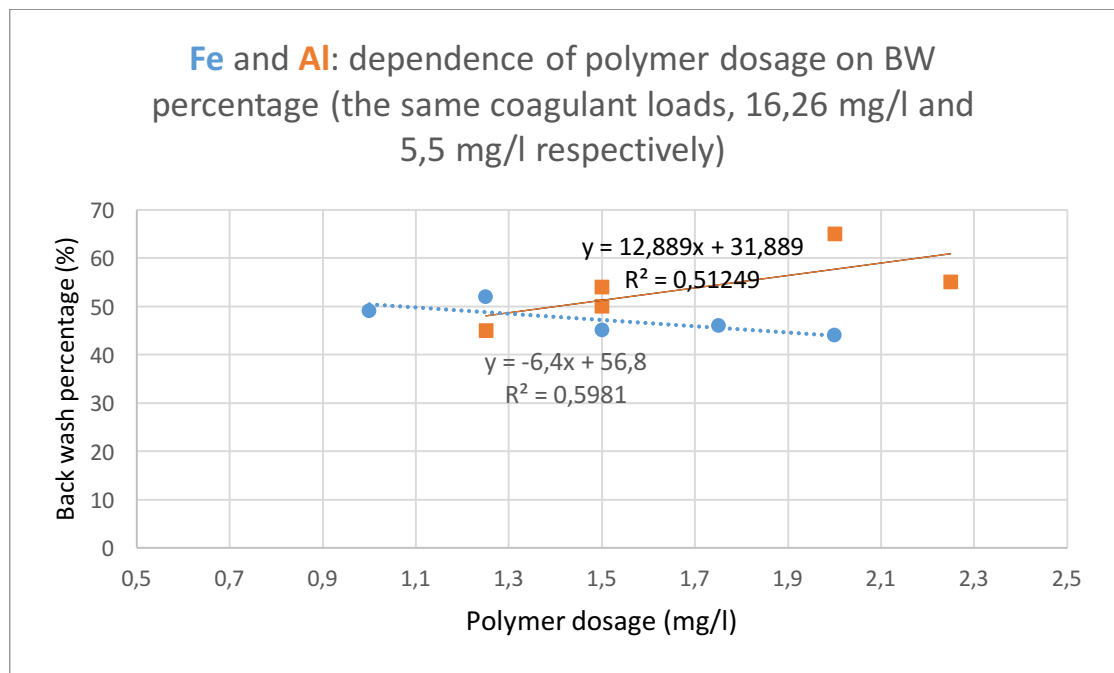
Next pair of graphs shows unpredictable correlations of polymer loading of the pilot and the phosphates reduction percentage in addition to disc capacity, which is represented in BW percentage value. It should be noticed that in both cases the coagulant loading was constant. Molar ratio with Fe coagulant was 3 during these tests and polymer concentrations varied from 1 to 2 mg/l. For PAX XL100 molar ratios were 2 and 2,2 in some cases, the addition of polymer has been tested in the range 1,25-2,25 mg/l.

As it is depicted in the Graph 3, it appears that in the range of polymer loading from 1 to 1,75 mg/l, in most of the cases, the anionic polymer works more efficient in conjunction with ferric coagulant than with aluminum. On the other hand, with greater values the efficiency is appearing to be quite the same with PAX XL100 as well, while considering phosphates reduction within the process. Additionally, when the load of polymer is starting to be greater than 1,75 mg/l, phosphate reduction percentage grows with much less potential than in the range of polymer from 1 to 1,5 mg/l. This could be explained by the fact that the floc formation reaches its maximum point and further increase in polymer addition is unreasonable or too agglomerated flocs are broken down at the filter into smaller particles.



Graph 3. Dependence of polymer dosage on phosphate reduction (molar ratio with Fe coagulant was 3, the values for Al coagulant were 2 and 2,2)

In the Graph 4 it is possible to see an exceptional trend, the increase in polymer dosage during some test runs with Iron-based coagulant has made the BW% gradually decrease. While the same increase with Aluminum coagulant influenced the disc filter capacity in opposite way, the overall working time of the disc filter tended to increase. This phenomenon could appear due to the difference in floc formation between ferric and aluminum salts. The controversy relation has been investigated and explained by Väänänen (2017), where it was explained that in some cases ferric coagulant affected negatively the filtration capacity. The reason could be different quality of influent entering the pilot and another adjustment of chemical loadings.



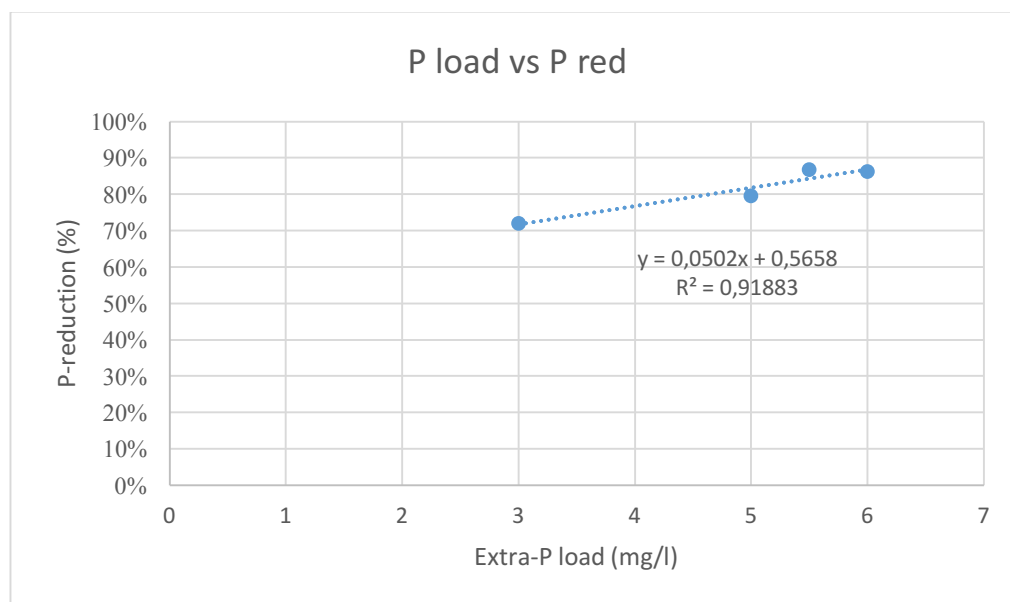
Graph 4. Dependence of polymer dosage on BW% (the same coagulant loads, 16,26 mg/l and 5,5 mg/l respectively)

It is needed to be noticed for further adjustments that additions of A-100 polymer should be in the range between 1 and 2 mg/l. In such cases the disc filtering capacity stays inside the formulated goals. As well as such concentrations help to achieve good value for P-reduction in the pilot plant.

8.1.2 Extra-phosphorus addition

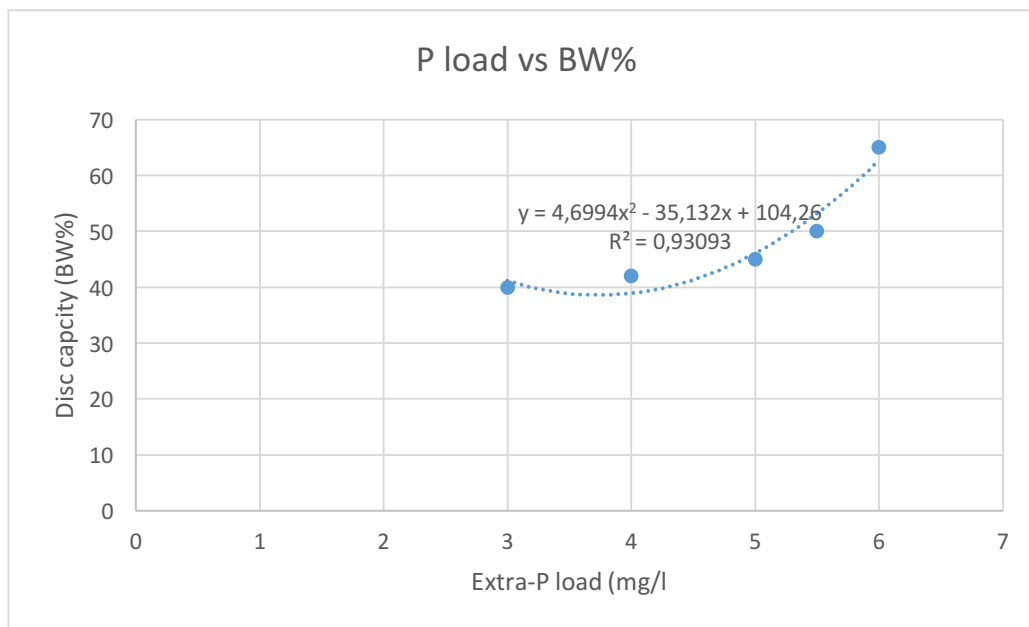
In order to test how the pilot process is affected by different content of P in the influent, different extra-P additions (3 to 6 mg/l) have been tried. The test outcomes have been observed and analyzed. Test-runs were conducted with addition of PAX XL100 (5,23-10,45 mg/l) and molar ratio between Al and P equaled 2.0

As Graph 5 represents, the increase in P loading of the influent consequently enhanced the P reduction in the effluent. Such trend could be explained by the fact that the bigger amount of phosphorus has been loaded into the flow, consequently more floc has been formed, what made the process of capture easier for the disc comparing to the smaller concentrations.



Graph 5. P load vs. P red. (tests have been held with Al coagulant with constant molar ratio - 2)

Such increase consequently affected the filtering capacity of the DF in a negative manner (Graph 6). These outputs are resulting in the decision that discfilter with only one disc installed inside and reasonable loadings of the chemicals can operate normally if the content of P in the influent is in the range between 3 to 5 mg/l. If the phosphorus concentration is higher, then the adjustments are needed to be done in the process: greater additions of chemicals or installation of more discs inside the filter could be the right decisions.



Graph 6. P load vs. BW% (tests have been held with Al coagulant with constant molar ratio - 2)

8.1.3 Sludge implementation

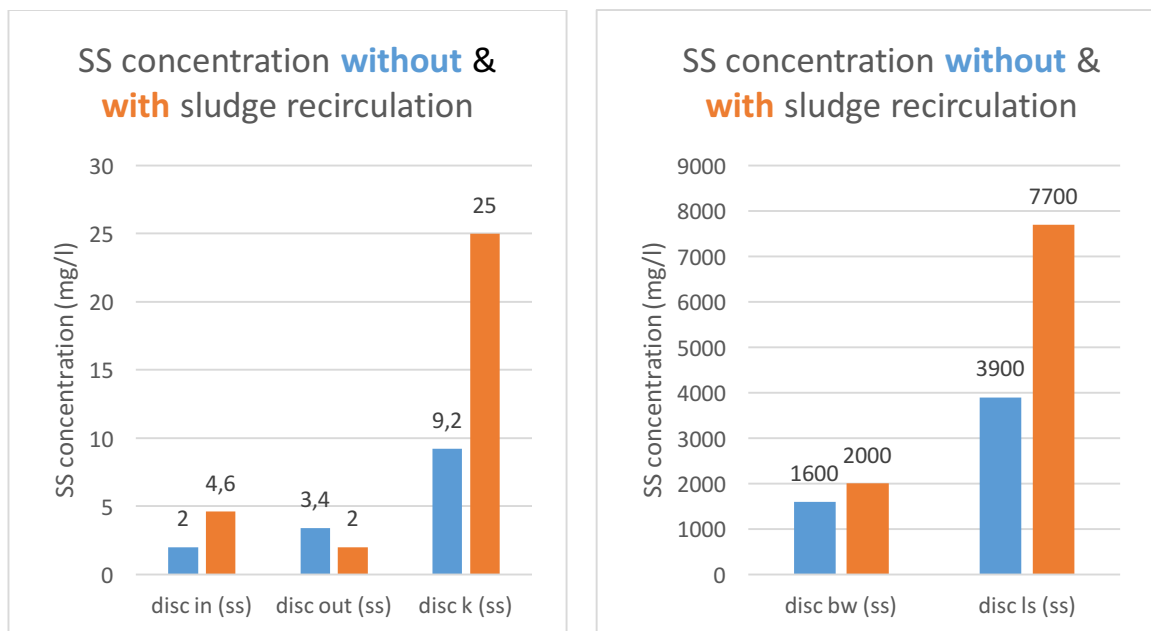
The estimations about using the part of the formed precipitate as coagulant aid have been done theoretically and needed amounts have been discovered with the help of mass balance calculations. The precise information and data have been presented in chapter 6.3.

8.1.3.1 Laboratory scale tests

Laboratory scale tests have been conducted the same way as with chemical optimization estimations using jar-test method. In the Chapter 6.4.2, the actual process has been described, results can be found in Appendix 4. From the outcomes, it was possible to estimate that sludge recirculation implementation into the pilot plant would enhance the precipitation and filtration steps while usage of PAX XL100 and anionic polymer A100. PIX-105 coagulant has been also tried with sludge recycle inside the process.

8.1.3.2 Pilot scale tests

Even though the SS content in the influent flow to the pilot was different while tests without and with sludge addition, the sludge recirculation has helped to decrease such value in the effluent more effectively from 4,6 mg/l till 2 mg/l than standard process where the value of SS in the output water has usually been the same or higher as input. Such factor consequently has slightly increased the amount of SS in the backwash water from the filter by 25% and almost doubled (raised by 97%) the suspended solids content in the thickened sludge and formed over-flow water (Graphs 7 and 8.) One of the reasons for such increase in over-flow could be not enough time for settling or too high load of SS into the thickener.

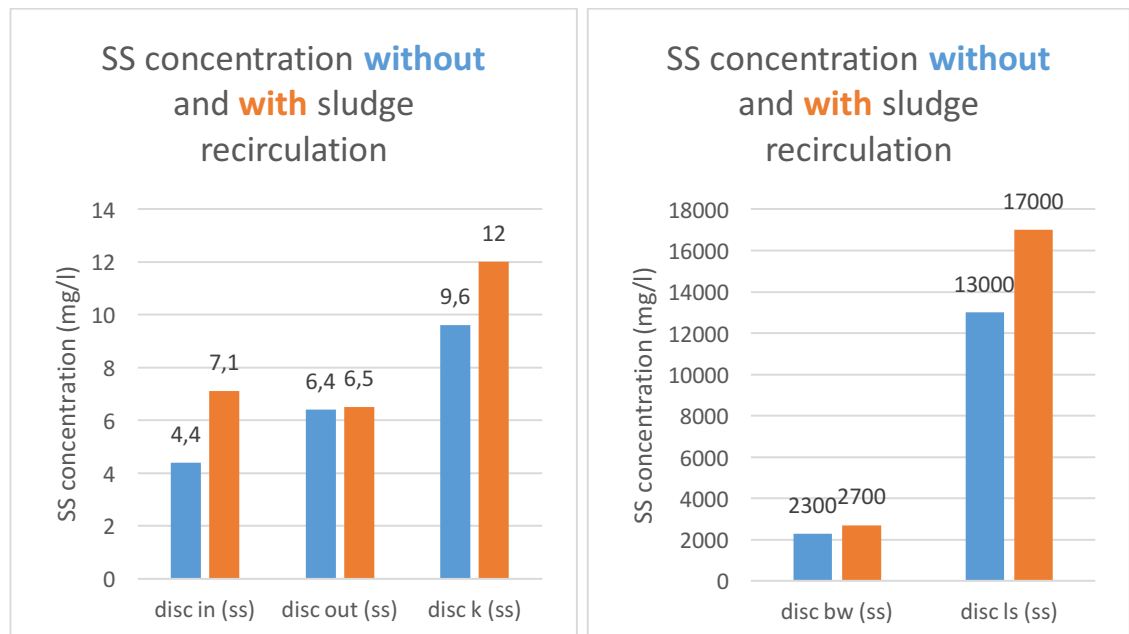


Graph 7 and 8. SS concentration with and without sludge recirculation (PAX XL100)

It has been predicted that the same kind of trends could be observed with Aluminum concentration in different samples and that has been proved practically. Decreased amount of Al in output from the pilot has resulted in rise of Al content in backwash water, thickened sludge and over-flow almost to the same extent as it appeared to be with SS concentrations, results are represented in Appendix 5.

It was also theoretically estimated that sludge recirculation will not enhance the phosphorus reduction in a big scale. Such hypothesis has been observed while several test-runs. The amount of phosphorus has increased the same way as SS and Al have done in backwash water, thickened sludge and over-flow, but it almost has not improved the reduction percentage in effluent comparing to the influent. In the test run without sludge recirculation, the P reduction equaled 79% and after implementation of sludge that value changed to 81%. In other test runs the P reduction sometimes stayed at the same level or even below the value obtained without sludge circle. Results are represented in Appendix 5, Graphs 3 and 4.

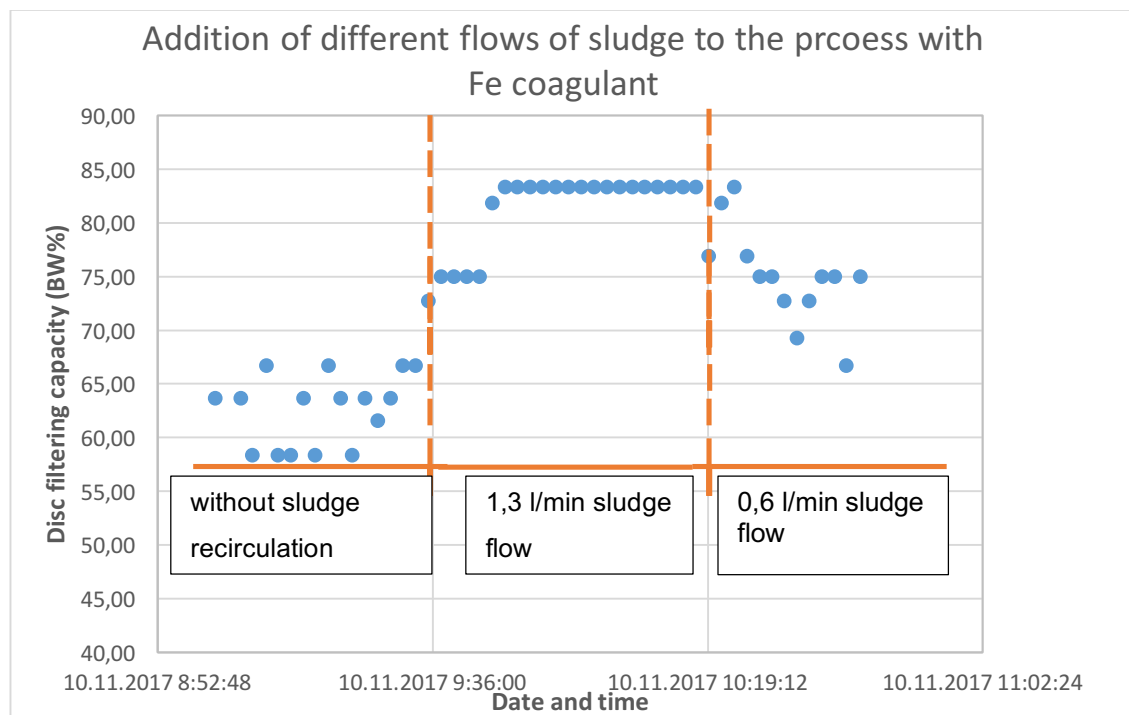
The sludge cycle inside the pilot has been tested also while using PIX-105 and obtained results appeared to be with the same kind of trends as with PAX XL100 tests. The recirculated sludge particles enhanced the coagulation and flocculation steps. Particularly the SS and metal concentrations increased in backwash water and thickened sludge and at the same extent lowered in effluent water. Phosphates reduction parameter was not influenced in big scale. Results with suspended solids content are presented on the Graphs 9 and 10 below. Other outcomes can be found from Appendix 5, Graphs 5,6,7 and 8.



Graph 9 and 10. SS concentration with and without sludge recirculation (PIX-105)

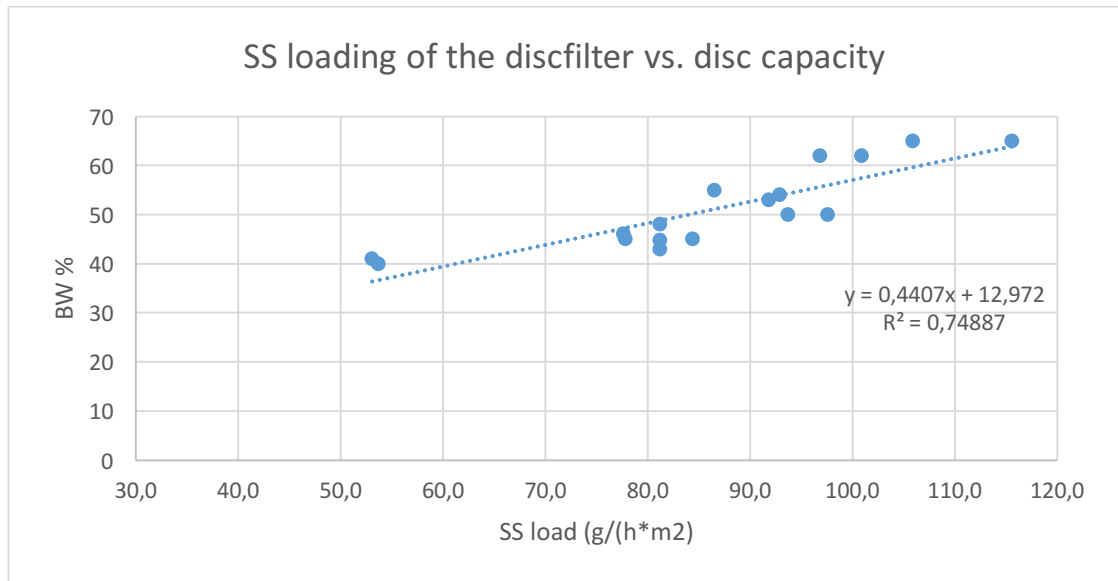
8.1.4 Disc loading with suspended solids

As it can be seen from the Graph 11 different flows of sludge recirculation have been tested and the disc filtering capacity was lowered with addition of too great sludge amount. Lowering the sludge flow helped to get acceptable Disc BW percentage from 80-85% till 65-75%. Later, when the retention time was increased by adjustment of inlet water flow, the BW% got even lower till 40-50%. This change can be explained by the change in SS load of the discfilter while sludge cycle implemented to the process.



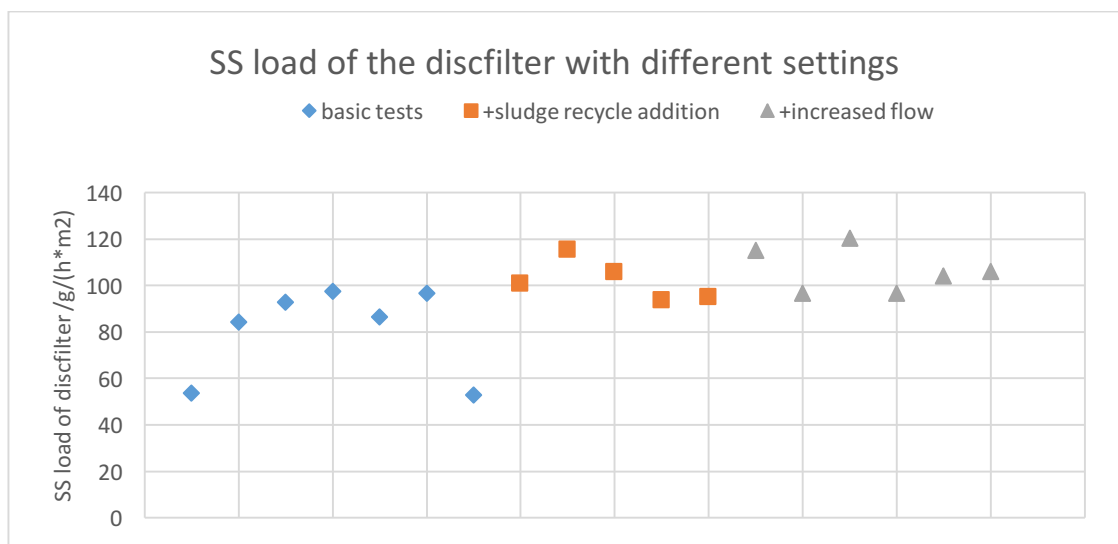
Graph 11. Change of BW% while sludge recirculation implementation into the process with PIX-105

Disc load with SS was calculated from various test-runs and compared to the BW% during some tests with different settings and dependency appeared to be quite linear (Graph 12).



Graph 12. Dependence of SS load of the disc on its capacity

The load of the discfilter by SS is another discovered parameter that has a strong influence on filtering capacity and being dependent on inlet flow, coagulant and phosphorus concentrations and sludge cycle (Graph 13). For instance, while test runs with PAX coagulant, where the initial phosphorus content equaled from 3 to 5 mg/l and the molar ratio between metal and P equaled 2-2,2, the load of the discfilter with suspended solids was in the range 53-97 g/(h*m²). Addition of the sludge circulation into the process increased the range to be between 93 and 115 g/(h*m²). Further the inlet flow of water was increased from 7,5 to 9,5 m³/h and the output of SS load became to be from 97 to 120 g/(h*m²).



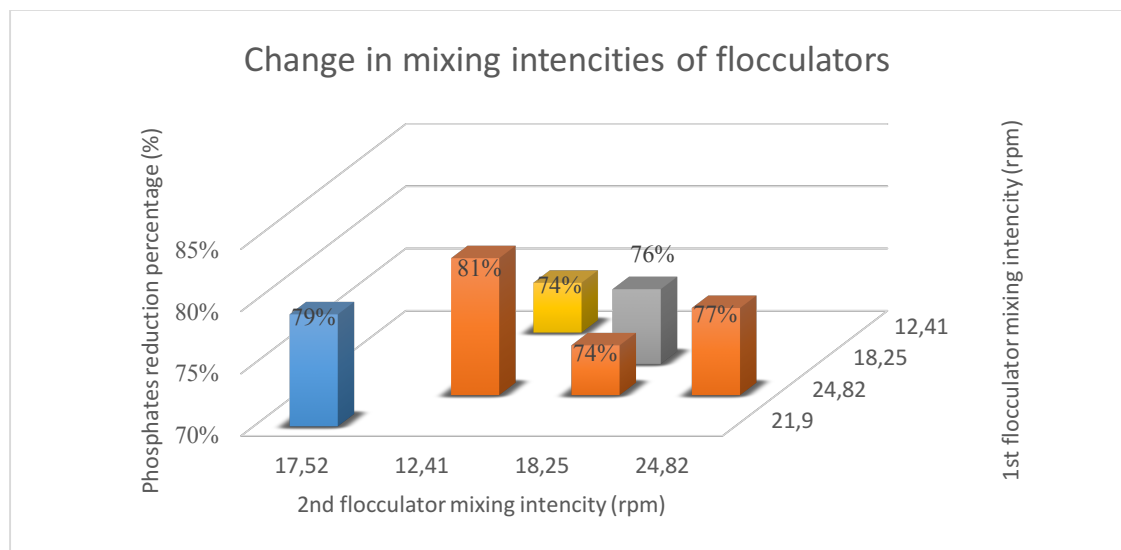
Graph 13. Changing of the SS load of the disc by different parameters

Presented tendency shows clearly how the disc filtration capacity is depended on these variables. This fact helps to estimate and pick up the right settings of the parameters in order not to exceed the acceptable working capacity based on the loading of the disc with suspended solids. According to the correlations presented in this chapter, the load of the current pilot plant with SS should be between 75 and 115 g/(h*m²) in order to get acceptable filtering capacity (BW%=40-60%) named as the goal for the optimization. Based on this values it can be further calculated how much chemicals can be added to the process and which retention time to choose so the operation time of discfilter is under the normal limits.

8.2 Other factors influencing precipitation and separation process

8.2.1 Changes of mixing intensities

The following tests were conducted already with sludge cycle implemented inside the process, to see if any other minor change could improve the efficiency of the pilot plant even more in any scale. Several combinations of mixing intensities for flocculators have been theoretically chosen and tests have been conducted. Test-run for each setting was held for one hour and results were estimated with kit-tests. As it can be seen in Graph 14, the results appeared to be insignificant and the change in phosphates equaled 77±3 %.



Graph 14. Changes in mixing velocities of flocculator

However, the best combination has been chosen to get the most efficient results. Literally it represented the case when mixing intensity of the second flocculator (12,41 rpm) is twice slower than the first one (24,82 rpm). Appeared that during this combination the floc formation is optimal for discfilter, such low mixing in second flocculator does not brake floc and it is then being easily separated from the wastewater stream. In addition, it should be accounted that in current pilot plant the basins are so high compared to the total volume of them, this aspect makes the mixing challenging.

8.2.2 Retention time optimization

HRT was adjusted by changing the inlet flow or basin number. Various tests have been conducted including leaving the same total retention with different set of basins and otherwise adjusting the same flow to see how the change in retention time influenced other parameters. Figure 21 below shows how the classical set of basins looked like: 2 coagulation basins with intense mixing followed by 2 flocculators with slow mixing.



Figure 21. 2 coagulation and 2 flocculation basins

During the first test-runs, the second coagulation basin was taken away and the inlet flow was lowered from 10,5 to 9,5 m³/h, so the retention time stays at the level of 8,5 min. Second set of tests has been conducted with 2+1 basins combinations so that the first flocculator was eliminated from the process. Different

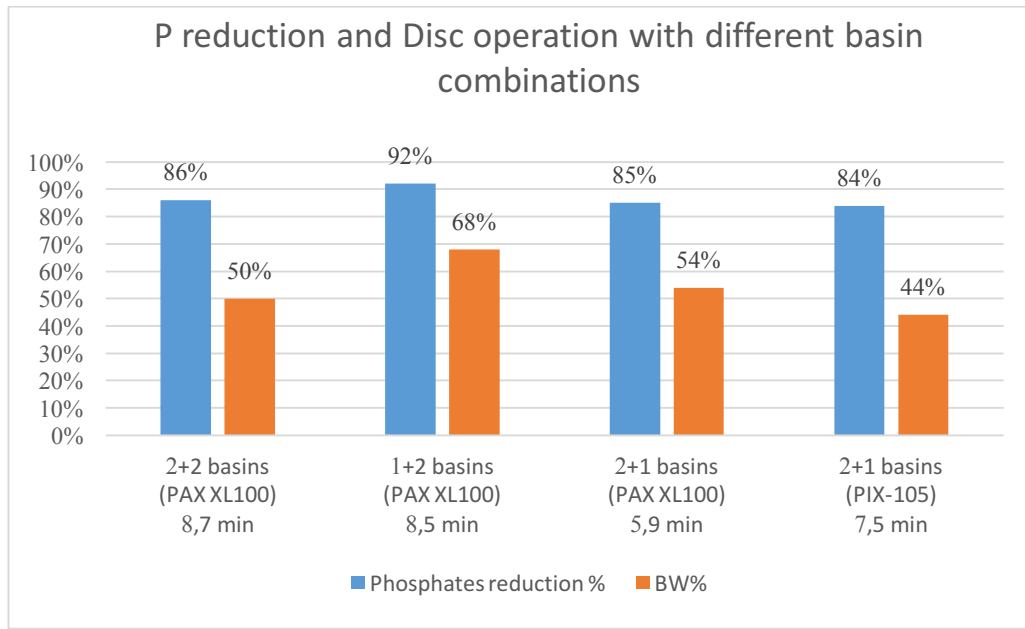
flows have been observed and analyzed. Both combinations are represented below by the Figure 22.



Figure 22. 2 coagulation and 1 flocculation basin (on the left), 1 coag. and 2 flocc. basins on the right

Graph 15 represents how the combination of 1 coagulation and 2 flocculation basins (1+2) showed great phosphate reduction potential, but the filtering capacity raised until 68% which brings it to unnormal total time of discfilter work. The same chemical adjustments (molar ratio 2,3) in combination of all 4 basins (2+2) has given the BW% equaled to 50% even with higher inlet flow of water and consequently higher SS load of the disc.

The combination of 2 coagulation and 1 flocculation basins (2+1) has shown good and stable values for phosphorus reduction remaining in normal limits of discfilter working time. Both Al- and Fe-based coagulants additions have resulted in P removal at the level 85-90% while BW% remained 50% or less. The same outputs could be reached from 2+2 combination but needed to be noticed that 2+1 basins could give such values with less retention time (5,9-7,5 min instead of 8,7 min). This fact proves that 2+1 setting is more efficient: less basins are needed and flow can be higher (less retention time of process) to get good values in comparison with stock 4 mixers and 1+2 combination. This can be explained by the fact that rapid mixing is a more important phase for floc formation rather than a gentle one.



Graph 15. Combinations of the basins

9 ANALYSIS OF THE RESULTS AND DISCUSSION

To sum up all the work conducted for optimization of current process, several main outcomes and strong correlations related to each changeable parameter can be presented and discussed. Talking about the chemical optimization, both PIX-105 and PAX XL100 coagulants showed excellent results regarding phosphorus reduction and disc operation values. Particularly, up to 92% of P removal has been achieved during normal operation of the discfilter (BW% was lower than 60%). It has to be noticed that initial quality of influent has strong dependency on chemical loading of the pilot plant. Lack or over addition of chemicals resulted in either unnormal time of discfilter operation or inadequate P reduction value. Molar ratio between P in influent and added alum coagulant has to be in the range between 2 and 2,3 to obtain satisfying results. Iron based coagulant addition can be even higher, up to molar ratio 3. An addition of 1-2 mg/l of anionic polymer has been applied during majority of tests. It appeared that value range of 1-1,25 mg/l is enough for adequate floc formation and greater addition is not economically feasible, since the floc formation is reaching its maximal point.

The usage of formed BW water from the discfilter as coagulation aid proved itself as possible enhancement of the precipitation and filtration processes. Better results have been achieved with Al-based coagulant rather than with ferric one. As a result, backwash water and thickened sludge had bigger concentrations of suspended solids (raised by 25% and 97% respectively) in normal disc operation limits. P reduction value has not been affected in a great scale.

10 CONCLUSION

To sum up main results of the research, it can be stated that the efficiency of the chemical post-precipitation and separation process has been mainly affected by the dosage of coagulant addition. When optimum molar ratio between initial P and added metal salt has been found, the required amount of polymer enhancing the process has been set. Other adjustments related to the floc formation and its separation have been influencing the process in minor scale but still need an attention for further development. For instance, the usage of 1 flocculation tank instead of 2 and having 2 coagulation tanks at the same time gave promising outcomes regarding all parameters, the results were at the same level as standard 4 basins combination.

The thesis can be used in the future as a basis for further development and enlargement of the pilot plant and RAVITA process overall, since the formed thickened sludge during chemical precipitation has to be treated and it is the attractive source for further nutrient recovery. Moreover, effluent water from the pilot plant has to be polished further to obtain final P content less than 0,3 mg/l. Using the results from this research, it would be possible to estimate the amounts of chemical to be added in chemical post-precipitation procedures while different inlet phosphorus concentrations in wastewater and to adjust the filtering capacity of the discfilter, if such devise has been chosen as optimal separation method.

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Results from laboratory scale tests.

Table 1. Results of laboratory scale tests conducted to choose proper chemicals

test	V of influent	Al ³⁺	PAX XL100	Fe ³⁺	PIX-105	polymer		turbidity	phosphates concentration	PO4 reduction	mol Al:mol P	mol Fe:mol P
#	L	mg/l	μl	mg/l	μl	type	mg/L	FNU	mg/L	%	mol:mol	mol:mol
0								1,25	5,45			
1	1	10	77			C-492VP	1	1,07	0,375	93	2,1	
2	2	10	154			C-492VP	1	1,34	0,305	94	2,1	
3	2	10	154			C-492VP	1,5	0,64	0,457	92	2,1	
4	2	10	154			A100	1,5	0,58	0,354	94	2,1	
5	2	5				A100	1,5	0,669	1,41	74	1,1	
6	2	10	154			A100	2	0,76	0,173	97	2,1	
7	2	10	154			A100	2	0,51			2,1	
8	2	10	154			A100	1,5	0,68	0,331	94	2,1	
9	2			19,5	222	A100	2	1,25	0,345	94		2,0
10	2			19,5	222	C-492VP	2	1,78	0,438	92		2,0

Table 2. Laboratory scale test for sludge recirculation

	filtrate volume (l/10 sec)	turbidity	phosphates (mg/l)	reduction	hydraulic capacity (L/s*m2)	m3/(m2h)
inlet	*	1,79	2,92			
test 0 (without sludge)	0,26	0,41	0,12	96 %	5,91	21,27
test 1 (+20ml)	0,35	0,40	0,10	97 %	7,95	28,64
test 2 (+30ml)	0,30	0,67	0,18	94 %	6,82	24,55
test 3 (+39 ml)	0,34	0,47	*		7,73	27,82

Results from pilot test runs.

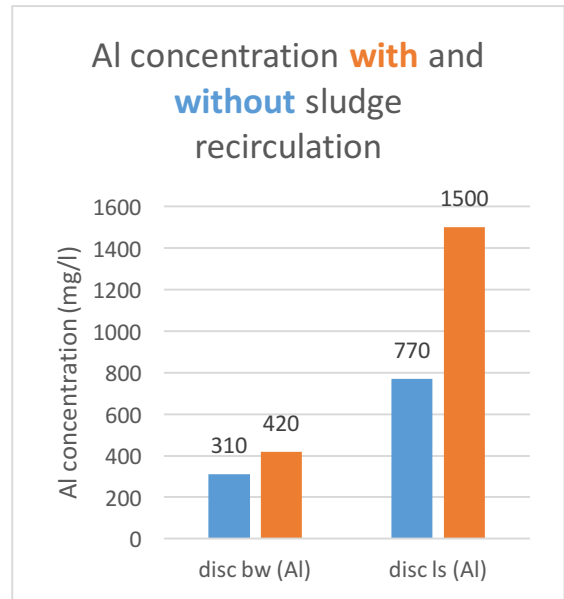
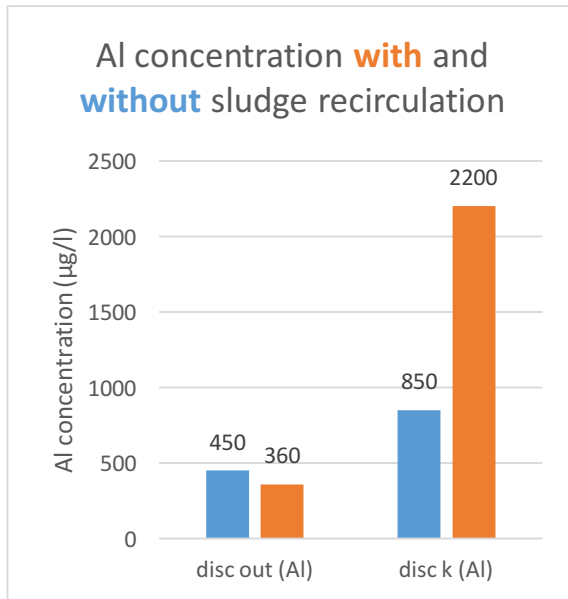
Table 1. Results from different pilot-runs with various chemical loadings

#	loaded P (mg/l)	coagulant PAX (mg/l)	polymer A-100	phosphates in (mg/l)	phosphates out (mg/l)	P reduction	turb in (FNU)	turb out (FNU)	BW%	produced sludge (m3/h)	m3/d	ratio mol Al:P
1 (18.9)	3	5,23	1,25	3,5	0,98	72 %			40	0,0821	1,97	2,0
2 (19.9)	5	8,71	1,25	5,3	1,09	79 %	1,75	0,7	45	0,0987	2,37	2,0
3 (19.9)	5	9,58	1,5	5,3	0,73	86 %	1,75	0,55	54	0,0913	2,19	2,2
4 (19.9)	5,5	9,58	1,5	6	0,8	87 %	1,7	0,47	50	0,0911	2,19	2,0

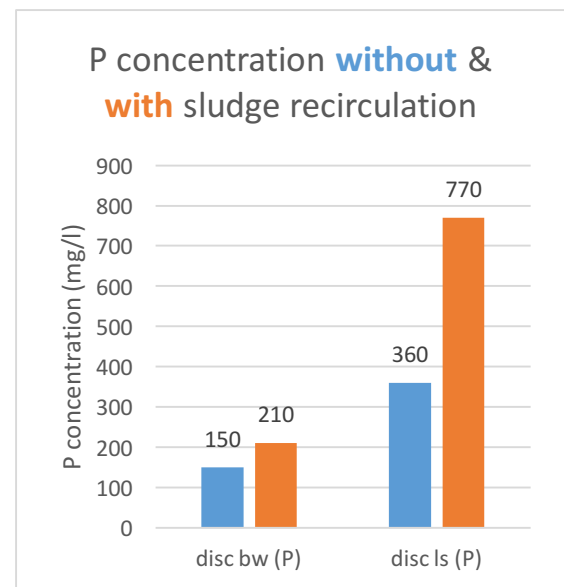
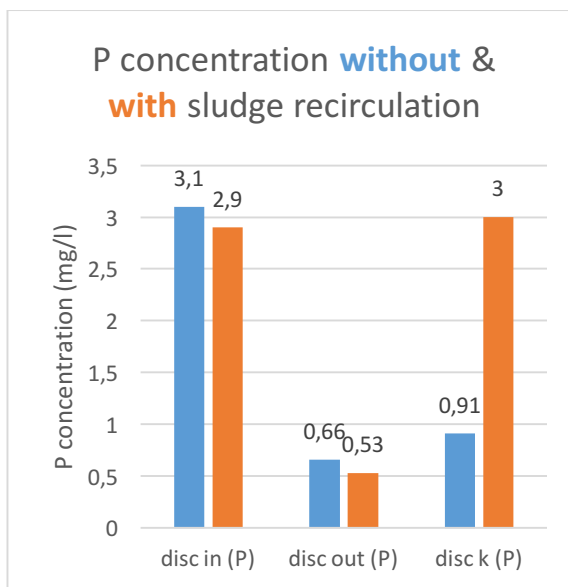
Table 2. Results from different pilot-runs with different combinations of basins

several tests conducted	loaded P (mg/l)	co-agulant PAX (mg/l)	polymer A-100 (mg/l)	phosphates in (mg/l)	phosphates out (mg/l)	P reduction	turb in (FNU)	turb out (FNU)	BW%	produced sludge (m3/h)	m3/d	ratio mol Al:P	flow m3/h	SS load (g/h)	SS load g/(h*m2)
22 (sludge 1 l/min) (23.10) 1+2 basins	3	5,90	1,25	2,8	0,22	92 %	2,23	1,1	68	0,1569	3,77	2,3	9,5	286	102,1
23 (sludge 1 l/min) (24.10) 1+2 basins	3	5,90	1	2,4	0,4	83 %	1,7	0,85	70	0,1809	4,34	2,3	9,5	286	102,1
24 (sludge 1 l/min) (25.10) 1+2 basins	3	5,90	1	2,8	0,6	79 %	1,75	0,95	70	0,1739	4,17	2,3	9,5	286	102,1
25 (sludge 1 l/min) (26.10) 2+2 basins	3	5,90	1	3,5	0,5	86 %	2,1	0,8	50	0,1252	3,00	2,3	10,5	306	109,3

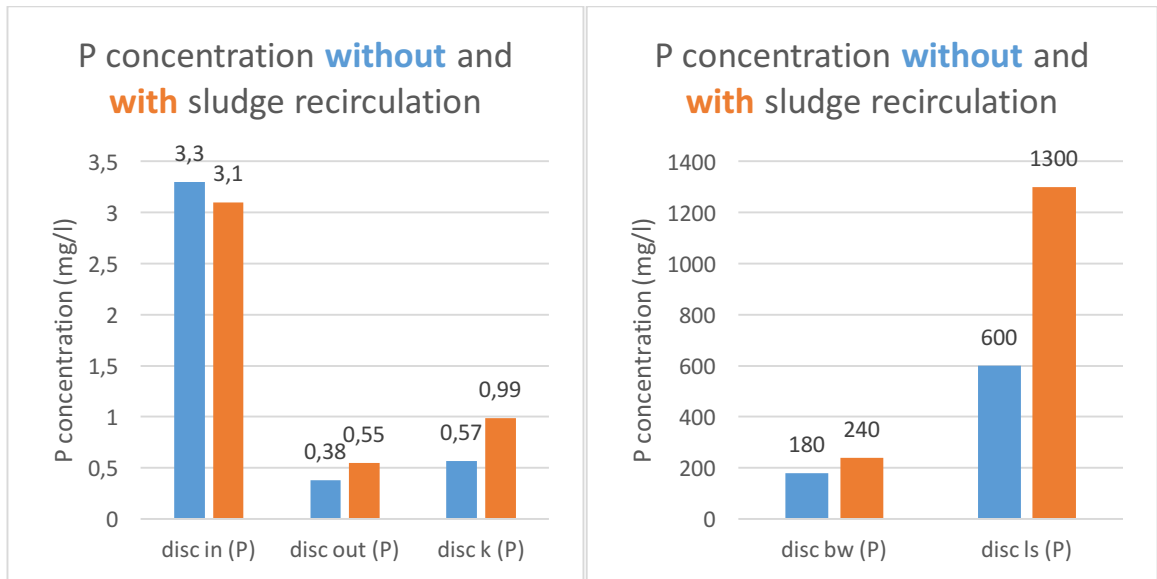
Results from pilot test runs with sludge recycle implemented into the process.



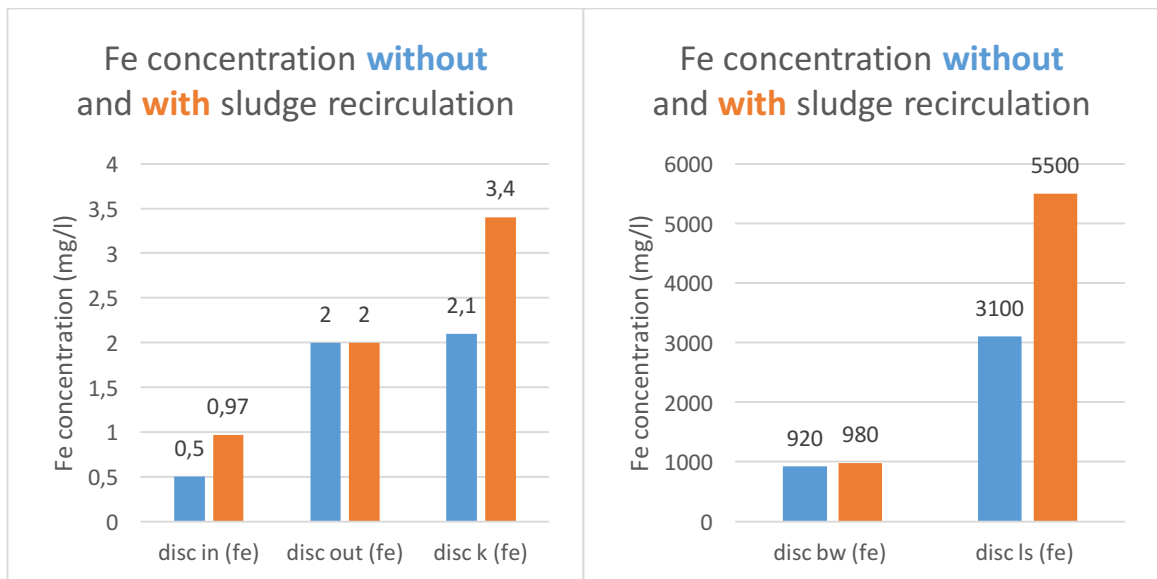
Graph 1 and 2. Al concentration with and without sludge recirculation (inlet concentrations are less than 100 µg/l, PAX XL100)



Graph 3 and 4. P concentration with and without sludge recirculation (PAX XL100)



Graph 5 and 6. P concentration with and without sludge recirculation (PIX-105)



Graph 7 and 8. Fe concentration with and without sludge recirculation (PIX-105)