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Degree Programme of Chemical Technology**

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**ENHANCING PHOSPHORUS REMOVAL BY DISC FILTRATION –
A CASE STUDY FROM VIKINMÄKI WASTEWATER TREATMENT
PLANT**

**Master's thesis for the degree of Master of Science in Technology
submitted for inspection, Espoo, 12.11.2014.**

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Title of thesis Enhancing phosphorus removal by disc filtration- A case study from Viikinmäki wastewater treatment plant

Department Department of Biotechnology and Chemical Technology

Professorship Applied biochemistry**Code of professorship** Kem-30

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Date 12.11.2014**Number of pages**
110+20**Language** English

Abstract

Phosphorus is an essential nutrient for all living organisms. However, high concentrations in a water body accelerates eutrophication. Discharge limits for phosphorus are getting tighter for wastewater treatment plants, thus new tertiary treatments for removal have to be considered. In addition, hygienization of wastewater may become mandatory.

At Viikinmäki wastewater treatment plant, the phosphorus discharge limit can tighten from 0.3 mg/l to 0.1–0.2 mg/l. New limit is not possible to achieve with the current process. The aim of this study was to investigate the feasibility of a discfilter in the removal of phosphorus and suspended solids at the Viikinmäki wastewater treatment plant. The goal was to achieve total phosphorus concentrations below 0.1 mg/l in the effluent. In addition, the ability to treat bypass waters and hygienization was studied. Before pilot scale studies, suitable chemical combinations were determined by jar tests.

Pilot runs proved that mechanical removal is insufficient thus chemical addition is mandatory. Two aluminium based and one iron based coagulant were tested with cationic polymer. Aluminum based coagulants performed better and the optimum dose was 0.5–1.0 mg/l with polymer concentration 1.0 mg/l. However, the quality of the pilot influent affected greatly to the chemical doses. Nevertheless, with the discfilter it was possible to achieve consistently effluent with under 0.1 mg/l total phosphorus concentration.

Furthermore, discfilter was able to reduce the bacteria amount and removal was enhanced by chemical addition and smaller pore size. However, the discfilter is more suitable in removing suspended solids before more efficient hygienization process such as UV-hygienization or ultra- or nanofiltration.

Bypass water tests proved that phosphorus concentrations can be decreased from 1.6 mg/l to 0.51 mg/l.

Based on pilot runs, it can be concluded that the discfilter can be an alternative tertiary treatment step for phosphorus and suspended solid removal at Viikinmäki WWTP

Keywords phosphorus, precipitation, disc filtration

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Päivämäärä 12.11.2014	Sivumäärä 110+20	Kieli englanti

Tiivistelmä

Fosfori on välttämätön ravinne kaikelle kasville, mutta suurina pitoisuuksina vesistöissä se aiheuttaa rehevöitymistä. Jäteveden puhdistamoiden fosforin päästöluparajat tiukkenevat tulevaisuudessa ja erilaisia tertiäärikäsittelyjä täytyy harkita, jotta uudet raja-arvot voidaan saavuttaa. Lisäksi jäteveden hygienisointi voi tulla pakolliseksi.

Viikinmäen jätevedenpuhdistamolla kokonaisfosforin päästöraja on vuosineljänneskeskiarvona 0,3 mg/l, mutta päästöraja voi tiukentua 0,1–0,2 mg/l. Nykyisellä prosessilla ei pystytä saavuttamaan uusia rajoja, koska biologinen typenpoisto vaatii toimiakseen riittävän fosforipitoisuuden.

Tämän tutkimuksen tarkoituksena oli tutkia kiekkosuodattimen soveltuvuutta Viikinmäen jäteveden puhdistamolla sekä fosforin että kiintoaineen poistoon. Tavoitteena oli saavuttaa alle 0,1 mg/l kokonaisfosforikonsentraatio lähtevässä jätevedessä. Ennen pilottikoon koeajoja, sopivat kemikaaliyhdistelmät määritettiin saostuskokeiden avulla. Tavallisen jäteveden lisäksi kiekkosuodattimella testattiin ohitusveden käsittelyä.

Koeajot osoittivat, että kiekkosuodattimen mekaaninen poistokyky oli heikko sekä 10 µm että 20 µm huokoskoilla, joten puhdistusta tehostettiin kemikaaleilla. Saostuskokeiden perusteella testattiin kahta alumiinipohjaista ja yhtä rautapohjaista koagulanttia kationisen polymeerin kanssa. Alumiinipohjaiset koagulantit toimivat paremmin kuin rautapohjainen ja 0,1 mg/l pitoisuuteen päästiin 0,5–1,0 mg Al³⁺/l ja 1,0 mg polymeeri/l annoksilla. Kokeissa huomattiin, että käsiteltävän jäteveden laatu vaikuttaa merkittävästi puhdistustulokseen; korkeat ja matalat kiintoainepitoisuudet vaikeuttavat puhdistusta. Tästä huolimatta kiekkosuodattimella kyettiin tuottamaan tasalaatuista alle 0,1 mg fosfori/l jätevettä.

Fosforin ja kiintoaineen poiston lisäksi tutkittiin laitteiston kykyä hygienisointiin. Bakteerimäärät pienenivät ja puhdistusta voitiin tehostaa kemikaalilisäyksellä sekä pienemmällä huokoskoolla. Hyvin alhaisia bakteerimääriä ei voitu saavuttaa, mutta kiekkosuodatin soveltuu hyvin kiintoaineen ja sameuden poistoon esimerkiksi ennen UV- hygienisointia tai ultrasuodatusta.

Ohitusvesitestissä suorasuostettua esiselkeytetty jätevettä käsiteltiin kiekkosuodattimella. Kokonaisfosforipitoisuus pystyttiin laskemaan 1,6 mg/l:sta 0,5 mg/l:aan kun kemikaaliannostus ennen kiekkosuodatusta oli 3,5 mg Al³⁺/l ja polymeeriannos 2,0 mg/l.

Kokeiden perusteella kiekkosuodatin soveltuu tertiäärikäsittelyvaiheeksi Viikinmäen jäteveden puhdistamolle fosforin ja kiintoaineen poistoon.

Uudenmaan ELY-keskus on mukana Itämeren suojelussa ja tuki kiekkosuodatin projektin rahoitusta.

Avainsanat fosfori, saostus, kiekkosuodatin

Preface

This thesis was completed in Viikinmäki wastewater treatment plant in 2014. The research was funded by The Centre of Economic Development, Transport and the Environment of Uusimaa. In addition, Maa- ja vesitekniikan tuki ry supported my thesis work.

I would like to thank my supervisor, Professor Simo Laakso, for his valuable remarks and helpful comments on my thesis.

I am very thankful for my thesis instructor, Mari Heinonen who gave me the opportunity to carry out this study. Thank you for the time you took to answer my various questions and for your guidance.

I would also like to thank Carles and Janne. Thank you for taking your time in answering my questions and reading my thesis. Your encouragement and feedback gave me lot of confidence.

Furthermore, I want to thank all my co-workers in Viikinmäki. You took me so warmly into your work community. Without your help and support, this thesis would not be in these covers.

Hugs and kisses to all my closest friends. Without all the amazing moments, the whole master's thesis project would have been unbearable.

Finally yet importantly, I want to thank my dearest family. Mom and Dad, you have always supported me and gave me good advice during my studies. Antti, my dearest brother: you actually read my thesis! This means a lot to me.

Espoo, 12.11.2014

Laura Rossi

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NOMENCLATURE

AS	activated sludge
BOD	biological oxygen demand
BW%	backwash percentage
COD	chemical oxygen demand
DAF	dissolved air flotation
EBPR	enhanced biological phosphorus removal
EU	European Union
GAO	glycogen accumulating organisms
HCl	hydrogen chloride
HRT	hydraulic retention time
MBBR	moving bed biofilm reactor
NaOCl	sodium hypochlorite
NaOH	sodium hydroxide
PAA	peracetic acid
PAO	phosphorus accumulating organism
PFA	performic acid
RO	reverse osmosis
SS	Suspended solid
TP	total phosphorus
TPsol	soluble total phosphorus
WWTP	wastewater treatment plant

1 Introduction

Phosphorus is an essential nutritional element for all living organisms and no substitute exists for it (Corell, 1998; Hao *et al.*, 2013). Phosphorus is as well a major compound in fertilizers, detergents and human body wastes. The main phosphorus discharges to water bodies come from agricultural runoffs and from municipal wastewater treatment plant (WWTP) effluents (Laitinen *et al.*, 2014). This leads to an excessive accumulation of phosphorus into a water body and accelerates the growth of algae. This process is called eutrophication and it leads to depletion of water quality of receiving waters. (Bratby, 2006; Smil, 2013) Runoffs from agriculture are hard to limit, but municipal WWTPs have removed nutrients from wastewater for decades.

The knowledge of a nutrient fluxes and concern of the water quality has increased over the years, which has led into different regulation in different countries. In Finland, the European Union Water Framework directive for water (2000/60/EC) and HELCOM commitments of Baltic Sea Action Plan have set targets for nutrient load discharges in order to improve the quality of the Baltic Sea. The traditional phosphorus removal techniques, which include chemical precipitation and biological conversion, are not sufficient for removing phosphorus to extremely low concentrations. Thus, research of different tertiary treatments has increased and for the moment, filtration processes with a possible chemical addition has become more popular.

Although eutrophication is a severe problem, also the depletion of phosphorus reservoirs has become a concern. According to Hao *et al.* (2013), the phosphorus reservoirs are running out in 50 years if the demand of fertilizers keeps rising 3 % per year. Luckily, these two problems are not exclusive. If the phosphorus from the municipal wastewater or sludge is recovered economically, the wastewater could serve as a potential source (Hao *et al.*, 2013).

Another issue that may become mandatory in the future in WWTPs is the hygienization of wastewater. Reason for this is that in some places wastewaters are discharged to water ecosystems that are used as a water resource or as a recreational area but where the flow rate is insufficient for guaranteeing a proper mixing of waters. In many parts of the world, hygienization has already been adopted, but in Finland, the regulations for hygienization are still rare. Hence, different tertiary treatment such as disc filtration for hygienization should be considered.

The main objective of this study was to determine the feasibility of disc filtration in Viikinmäki WWTP to lower phosphorus and suspended solid concentrations, thus improve the effluent quality. The target was to achieve under 0.1 mg/l phosphorus concentrations. Furthermore, feasibility for hygienization and treatment of bypass waters was researched. Results can be exploited in the design of the new WWTP in Blominmäki and in other WWTPs as well.

2 Tertiary treatment

Tertiary treatment, also referred in some cases as effluent polishing, is defined as a process step that follows secondary treatment (Hendricks, 2006). The main object is to reduce effluent nutrient concentrations and thus limit eutrophication in the receiving water bodies. Second object is to reduce pathogen account and secure safe water quality in water bodies that are either highly loaded or used as recreational area. What makes the hygienization challenging, is the diversity of microbes (Gómez *et al.*, 2006). Thus, only one treatment method may not be sufficient to remove all the pathogens. Thirdly, the concern of micropollutants (pharmaceuticals, pesticides and heavy metals) and microplastics has increased in past years (Cole *et al.*, 2011; Luo *et al.*, 2014; Wagner *et al.*, 2014) and this has resulted in many research studies of different removal methods and technologies.

Some tertiary treatment methods are better for nutrient removal and others for hygienization or micropollutant removal. Hence, many treatment methods are available for hygienization and nutrient removal. The main thing is to find the most cost effective and easiest to operate. Furthermore, usually different methods have to be combined to achieve target limits. In Germany, an extensive research was conducted where different filtration processes and UV hygienization were studied to achieve an extremely low phosphorus concentration and removal of pathogens (Langer *et al.*, 2013). In the following Chapters, the most popular methods are discussed.

2.1 Flotation

In flotation, micro scale bubbles are brought into contact with solid particles which will rise on the surface. Bubbles are produced from either air, gas or dispersed water and it is highly energy consuming. A chemical addition is obtained to produce more buoyant particles. Flotation is employed in nutrient removal and it will reduce the bacteria amount (Hendricks, 2006; Kuokkanen, 2013). The removal efficiency depends on particle characteristics and surface charge of the particle (Kaupunkiliitto, 1980).

2.2 Filtration

Filtration methods can be divided into sand, cloth and membrane systems.

In sand filtration, wastewater flows through a bed of sand. Apart from physical separation, adhesion by microbes induces the removal of nutrients and microbes. (Hendricks, 2006) In cloth filtration, wastewater flows through a cloth usually by gravity and particles bigger than the pore size, are retained. (Ljunggren, 2006) In both cases, nutrients and pathogens are removed and the removal can be improved by a chemical addition (see Chapter 0). Furthermore, the removal of microplastics is studied with these methods.

Membrane processes are divided into four classes based on their pore size- microfiltration, ultrafiltration, nanofiltration and reverse osmosis (Figure 1). They can be pressure or vacuum driven or depended on electrical potential gradients, concentration gradients, or other driving forces. (Vesilind, 2003) Water flows through the membrane and contaminants are concentrated on the pressure side. Pathogens and nutrients are removed with these methods. (Gómez *et al.*, 2006). However, suspended solid concentration reduces the efficiency by blocking the pores.

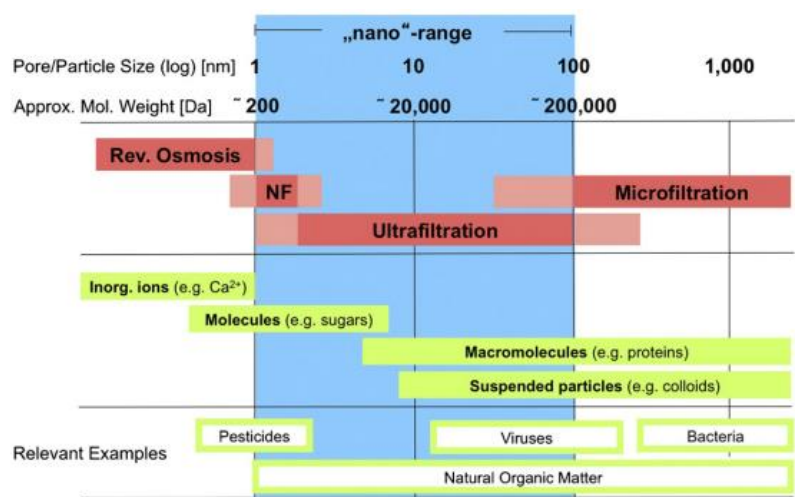


Figure 1. Comparison of the filtration range of the four different filtration methods (Mueller *et al.*, 2012).

2.3 Chemical hygienization

The chemical hygienization of wastewater is traditionally performed by chlorination, ozonization, performic acid and peracetic acid. The main goal is to inactivate pathogens. Because of the diversity of microbes, different techniques have to be obtained.

Chlorination is performed by adding chlorine to the wastewater and it used to be the most widely applied hygienization technique. However, awareness of carcinogenic by-products has decreased the utilization (Gómez *et al.*, 2006; Amin *et al.*, 2010). Ozone is powerful and effective disinfectant that does not produce harmful by-products. Nevertheless, operational costs, work safety issues and maintenance problems make it a less attractive alternative for WWTPs (Gómez *et al.*, 2006). Performic acid (PFA) is prepared by mixing formic acid and hydrogen peroxide and peracetic acid (PAA) is prepared by mixing acetic acid and hydrogen peroxide (Kitis, 2004; Heinonen-Tanski and Miettinen, 2010). Both PFA and PAA have shown high hygienization efficiency and no harmful by-products are generated (Chhetri *et al.*, 2014). Yet, operational costs are high and organic content can increase which may potentially increase the microbial regrowth (Kitis, 2004; Chhetri *et al.*, 2014).

2.4 UV hygienization

UV hygienization is based on inactivating pathogens by UV-light. The process is relatively cheap and easy to operate (Vesilind, 2003). However, it has been claimed that UV can react with aromatic compounds and form products with mutagenic activity (Gómez *et al.*, 2006). In addition, high influent turbidity and fouling can shade the lamps and reduce the effectiveness (Langer *et al.*, 2013), which means that suspended solids have to be removed effectively before UV hygienization.

2.5 Activated carbon

With activated carbon it is possible to remove refractory organic and inorganic compounds such as nitrogen, sulphides, heavy metals and micropollutants (Laitinen *et al.*, 2014). The method is based on adsorption and filtration (Vesilind, 2003). Activated carbon is commonly employed in water treatment but this technique has potential in wastewater treatment as well. However, organic matter may lower the effectiveness. The contact time and regeneration play critical role (Luo *et al.*, 2014).

3 Phosphorus in municipal wastewater

Phosphorus itself is not toxic but the consequences of massive algae growth may cause severe damages and limit the use of water reserves. The living conditions of fish are weakened because of the oxygen depletion and algae can produce toxic substances. In addition, the aesthetic quality of the water is reduced due smell and turbidity which limit the recreational activities (Henze *et al.*, 1997; WEF, 2010).

Eutrophication was first identified as a growing problem in estuaries and coastal areas in the 1950s (Morse *et al.*, 1998; Arnaldos and Pagilla, 2010). The knowledge increased during the 1970s and 80s in the USA, Japan and in some European Union (EU) member countries. This led to a research and development of new phosphorus removal techniques for reducing the discharge loads into the receiving waters. The EU directives' requirements for total phosphorus and total suspended solids discharges from urban wastewater treatment plants are collected in Table 1 (91/271/EEC). Furthermore, the load to the wastewater has been reduced by limiting or forbidding phosphorus amount in detergents (Bratby, 2006).

Table 1. Requirements for discharges from urban waste water treatment plants (91/271/EEC).

Parameters	Population equivalent	Concentration(mg/l)	Minimum reduction (%) [*]
Total phosphorus	10 000–100 000	2	80
	> 100 000	1	80
Total suspended	2 000–10 000	60	70
solids	> 10 000	35 ^{**}	90 ^{**}

^{*}Reduction in relation to the load of the influent

^{**} This requirement is optional

In Finland, phosphorus loads in municipal wastewaters increased since the 1960s because of urbanization when people moved from rural districts to the cities. Point source of pollution increased and washing machines and phosphorus containing detergents became more common. Therefore, phosphorus removal treatment methods were taken into use in the 1970. (Herranen, 2001) The amount of total phosphorus in detergents was decreased in 1990 when it was noticed to be the major nutrient affecting the eutrophication. However, it took over 10 years until EU demanded that the amount of total phosphorus in household detergents has to be limited to 0.5 g per washing. In practice, this means that all phosphorus compounds need to be replaced with other substances. The directive is not obligatory for industrial detergents because equally effective compound does not exist for the moment (259/2012/EU; Teknokemian Yhdistys ry, 2013).

In consequence of the good wastewater treatment, surface waters are in good condition in Finland (Laitinen *et al.*, 2014). The biggest concern at the moment is the Baltic Sea as it is very shallow and water changes slowly (Itämeriportaali, 2014) thus nutrients are concentrated in the coastal area. Since the beginning of the 20th century, the Baltic Sea has changed from clear-water Sea into a highly eutrophic marine environment (HELCOM, 2011). On average, the overall annual phosphorus load to the Baltic Sea from surrounding states is 30 000 tons (Itämeriportaali, 2014). The load has decreased by 20 % from 1994 to 2008 and approximately 50 % from the 1970 to the 2008 (HELCOM, 2011). The discharge of phosphorus from Finland in 2011 was 3 800 tons, hence approximately 12 % of the total. From this, municipal WWTPs produced 4 % (152 tons) whereas the agriculture 68 %. Figure 2 specifies the sources of phosphorus into the Baltic Sea more accurately (Laitinen *et al.*, 2014).

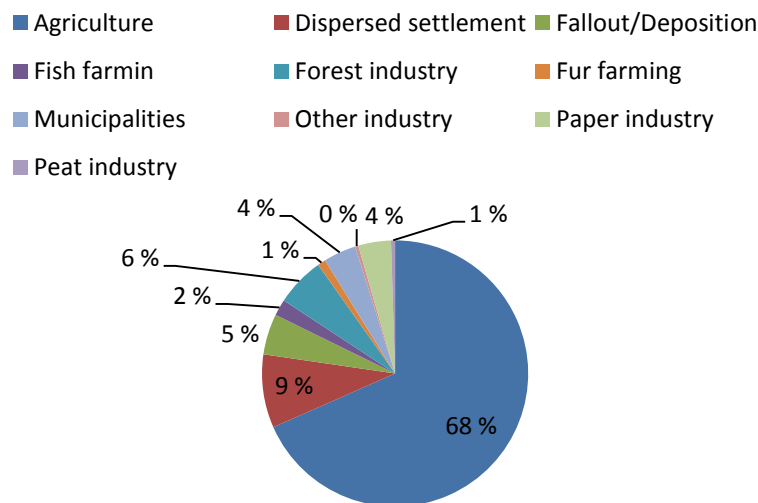


Figure 2. Point and diffuse loads of phosphorus from different sources of release into Baltic Sea from Finland (Laitinen *et al.*, 2014).

Although municipalities and dispersed settlements cause together high phosphorus loads, the biggest concern is agriculture and much research and effort should be focused on how to decrease those loads. In this study, only municipal wastewaters are studied.

3.1 Phosphorus forms in wastewater

In wastewater, phosphorus exists in soluble and particulate fractions. These are analytically separated by filtering a water sample through 0.45 µm filter. The reactive and nonreactive fractions are distinguished according to their ability to react with the test reagent that develops color in the PO_4^{3-} -test (Table 2) (Bratby, 2006).

Table 2. Different phosphorus fractions (modified from Neethling 2013; Henze *et al.*, 1997, Arnaldos and Pagilla, 2010; Valtari and Sahlstedt, 2013).

Total Phosphorus					
Soluble Phosphorus			Particulate Phosphorus = Suspended Phosphorus		
Reactive P	Nonreactive P		Reactive P	Nonreactive Organic P	
Ortho-phosphate	Condensed Phosphates	Organic Phosphorus	Organic-P	Colloidal P	Chemical P

Inorganic orthophosphate is the only form that bacteria can directly use in their metabolism to produce components such as nucleic acids and sugar phosphates (Corell, 1998). Solution pH determines which ionic forms are the most abundant. At pH from 5 to 9, the typical forms are $\text{H}_2\text{PO}_4^{2-}$ and HPO_4^{2-} (Figure 3) (Bratby, 2006).

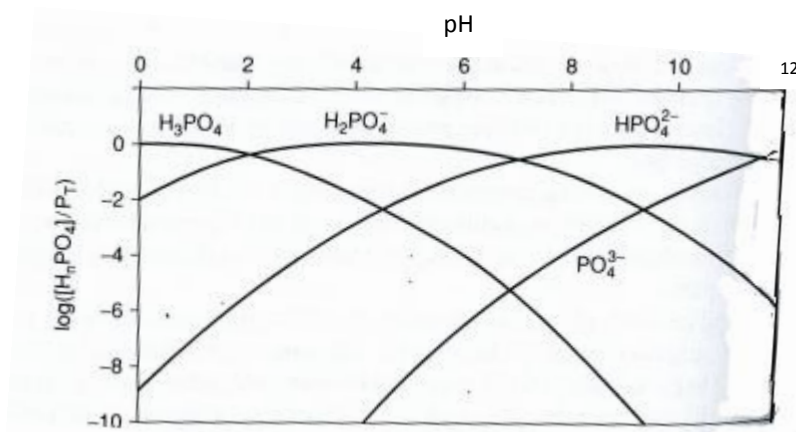


Figure 3. Distribution of phosphorus species with pH (Bratby, 2006).

Condensed inorganic phosphates ($P_2O_6^{2-}$, $P_2O_7^{4-}$, $P_2O_9^{3-}$) are chain- or circular shaped and used in as water softeners in detergents (Laitinen and Toivonen, 1982; Teknokemian Yhdistys Ry, 2013). Soluble organic phosphorus naturally comes from cell protoplasm (Vesilind, 2003). Both polyphosphates and dissolved organic phosphorus are nonreactive so metal coagulants cannot precipitate them. However, these forms are slowly hydrolyzed to the reactive form by biological treatment (Henze *et al.*, 1997; Vesilind 2003; Seo *et al.*, 2013).

Particulate phosphorus covers all the non-filterable fractions: inorganic and organic, particulate and colloidal. These forms are able to deposit in sediment and over the time, release phosphorus into the solution (Corell, 1998) and accordingly the eutrophication may be accelerated. However, settling time of these particles may take years depending on the size, which is why, it is important to remove these particles as well. The removal mechanisms of soluble and particulate fractions differ, which is why the characteristics of colloids are reviewed before the treatment processes for phosphorus removal are covered.

3.2 Colloidal particles

As mentioned, wastewater consists of suspended and dissolved organic and inorganic matter as well as plentiful of biological forms. Particles between size 0.01 and 1 μm are referred to as colloids (Henze *et al.*, 1997; Bratby, 2006). When water molecules collide with colloids, it is referred as Brownian movement. Small size and charge make the colloids to follow Brownian movement and thus the settling is difficult (Henze, 1997; Bratby, 2006).

Colloids are divided into two categories according to their behavior with water molecules (Henze *et al.*, 1997; Bratby 2006). Hydrophilic colloids have a high affinity towards water molecules because they have different functional groups, such as hydroxide and carboxyl groups, on their surface that will dissociate in the solution.

They are often organic by nature such as starches. As against hydrophobic colloids such as nonhydrated metal oxides, are often inorganic and repel water molecules (Henze *et al.*, 1997; Bratby, 2006).

Colloids possess a negative or positive surface charge and the effect is enhanced by the large surface to volume ratio. The surface charge of these colloids may arise from the chemical reactions or dissociation of functional groups (hydrophilic) or from the adsorption of ions from the water phase (hydrophobic) (Henze *et al.*, 1997; Bratby, 2006). In wastewater, the predominant surface charge of colloids is negative (Henze *et al.*, 1997).

Ions that have opposite charge are termed as counter ions and they form a “fixed” layer by enveloping the particle. The fixed layer is surrounded by a “diffuse” layer, where the concentration of counter ions is gradually decreased until the concentration of the bulk liquid is reached. The interface between these two layers is called a plane of shear (Figure 4) (Henze *et al.*, 1997).

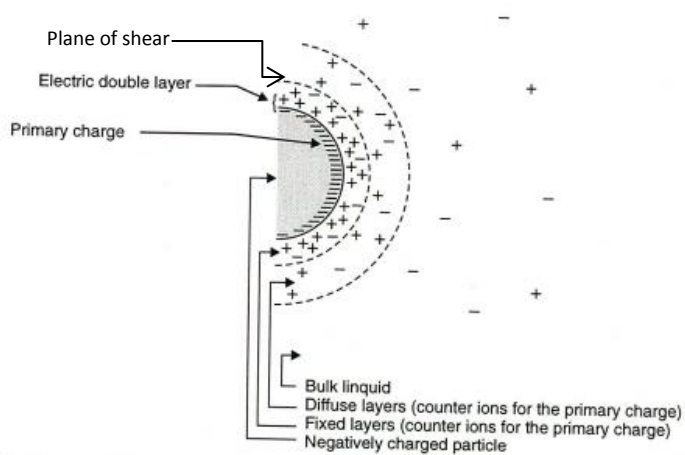


Figure 4. Schematic representation of the double layer of ions around a colloid particle with a negative surface charge (modified from Henze *et al.*, 1997).

Electrostatic potential decreases gradually from the fixed layer to the bulk liquid. The potential at the plane of shear is termed as a Zeta potential. The Zeta potential gives an impression of the extent of the repelling electrostatic forces and determines the stability of colloid. (Henze *et al.*, 1997) However, Henze *et al.* (1997) emphasized that theory is not that simple and in practice, there is not just one single Zeta potential. When the charge of a colloid is neutralized or reduced, the van der Waals force of attraction promotes the formation of microflocs (Ebeling *et al.*, 2005).

Because of the inherent characteristics, colloids are very stable and remain in separate units. Consequently, they are impossible to remove by settlement or filtration. (Henze, 1997; Bratby, 2006) The only way to bring colloids together is to destabilize the surface charge by adding proper amount of chemical coagulant. The coagulation mechanism is explained in more detail in Chapter 0.

3.3 Techniques for phosphorus removal

Unlike some other substances (e.g. nitrogen), phosphorus cannot be altered to a volatile form and removed as a gas (Henze *et al.*, 1997; Vesilind, 2003) Instead, the object is to convert the soluble inorganic phosphorus into particulate form and remove it physically either by settling or filtration. Conversion can be done either chemically or biologically. Phosphorus removal without any specific phosphorus removal steps is very low and according to Dueñas *et al.* (2003), 30 % of the total phosphorus is possible to remove by primary settling. This is mostly well-settleable organic particulate phosphorus. (Dueñas *et al.*, 2003) According to Zuthi *et al.* (2013), natural phosphorus removal by cell synthesis is small (only 1–2 % of the suspended solids mass in the mixed liquor). Altogether, the biological process removes approximately one third of the influent phosphorus because apart from soluble phosphorus intake, colloids will be settled and removed (Saarinen, 2003). For the moment, chemical precipitation is the most popular technique for phosphorus removal but biological removal has also gained attention. What is important is to find a treatment that is

economical and efficient to produce consistently effluent with wanted quality (Tran et al., 2012).

3.3.1 Enhanced biological phosphorus removal

Enhanced biological phosphorus removal (EBPR) was discovered in the late 1950s. Researchers noticed that under particular conditions certain type of microbes (phosphorus accumulating organism, *PAO*) in the activated sludge (AS) process could take up phosphorus in considerable excess to that required for normal biomass growth (Morse *et al.*, 1998).

The phosphorus removal by the EBPR is based on PAOs that are able to grow both in anaerobic and aerobic conditions and are capable of ingesting phosphorus beyond stoichiometric requirements for growth (Vesilind, 2003). The process is divided into two stages, anaerobic and aerobic. First, in the anaerobic zone, microbes utilize easily degradable organic matter like volatile fatty acids and acetic acid. In the absence of oxygen, PAOs store these acids mainly as polyhydroxyalkanoates (Rantanen 1999; Vesilind, 2003). Storing of organic matter consumes energy which is obtained from the cleavage of high-energy bonds in stored inorganic polyphosphates. The energy depot is formed from soluble orthophosphates which are ingested over the required stoichiometric demand at the aerobic zone (Figure 5) (Vesilind, 2003).

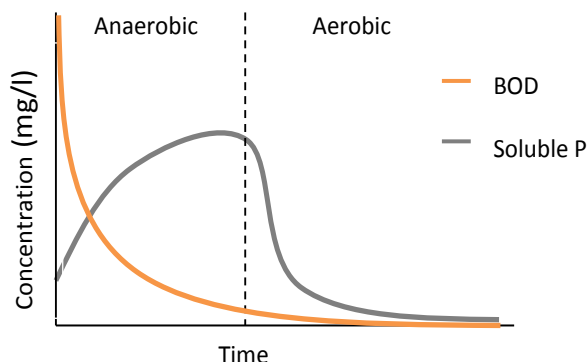


Figure 5. Concentration change of the soluble orthophosphate during enhanced biological phosphorus removal (modified from Neethling, 2013).

The advantages of EBPR are the avoidance of chemical addition and excess chemical sludge production. In addition, if the sludge does not contain organic toxins or metals, it can be used as a fertilizer (Henze *et al.*, 1997). This is because in this type of sludge, the phosphorus is bound to the biomass so that plants can easily utilize it (de-Bashan and Bashan, 2004). Although operational costs are low, (Zhang *et al.*, 2013) the plant configuration and operation is complex (Morse *et al.*, 1998). Even nitrate can inhibit the growth, as most of the organic matter would be consumed to denitrification. Nitrate may also influence the metabolism of PAOs so that polyphosphates are no longer stored. (Henze *et al.*, 1997) Furthermore, factors like sludge retention time, hydraulic retention time, competition with glycogen accumulating organisms (GAOs), alkalinity, pH and temperature affects the efficiency and thus the process becomes unsteady and consistent effluent concentrations are hard to maintain (Rantanen *et al.*, 2001; Zhang *et al.*, 2013; Zuthi *et al.*, 2013). However, in the future it is possible that wastewater treatment plants need to adopt biological phosphorus removal because the reservoirs of phosphorus are becoming scarcer. The phosphorus is easier to utilize

from the biological sludge than from the chemical sludge (de-Bashan and Bashan, 2004).

With the EBPR, it is possible to achieve 1.0–1.5 mg/l total phosphorus concentrations (Sahlstedt, 2008; Vesilind, 2013). The removal efficiency of EBPR is between 80 and 90 % but in general, extremely low effluent phosphorus concentrations are not possible to achieve. These concentrations are possible to achieve by combining EBPR with a chemical addition (El-Hoz and Apperley, 1996, Henze *et al.*, 1997; Morse *et al.*, 1998; Zhang *et al.*, 2013).

3.3.2 Chemical precipitation

Compared with EBPR, chemical precipitation is more common in WWTPs and it has been used for centuries in water and wastewater treatment (Morse *et al.*, 1998; Bratby, 2006). Low equipment and operating costs as well as simple process operation makes it easy for even a small WWTP to reduce phosphorus discharge loads. Also high efficiency makes it a suitable process step. (Liu *et al.*, 2013) With chemical precipitation, it is possible to achieve under 0.1 mg/l total phosphorus concentrations that are nowadays demanded in order to reduce the eutrophication. (US EPA, 2007) Disadvantages of chemical precipitation include the formation of excess chemical sludge that has to be processed and in some cases, expensive chemical costs (Seo *et al.*, 2013). In addition, the metal residues in the effluent as well as salting of the waters by sulphates reduce the quality of the effluent and may cause problems in the receiving waters (Rantanen *et al.*, 2001).

From a technical point of view, chemicals can be added at various points in the process (Figure 6).

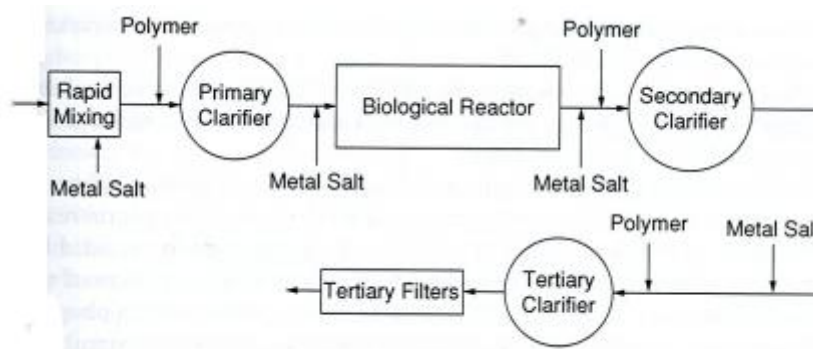


Figure 6. Possible coagulant dosing points (Bratby, 2006).

In pre-precipitation the coagulant is added prior to the primary sedimentation tank. (Bratby, 2006) This increases the removal of organic matter and load to a biological process is reduced (Henze *et al.*, 1997). However, the concentration of polyphosphates in this stage of the process is high because the conversion to orthophosphate by hydrolysis has not started yet. This typically leads to higher chemical doses (Bratby, 2006).

In simultaneous precipitation, biological phosphorus removal is coupled with the chemical addition. Advantages are stability, lower suspended solids, biological oxygen demand (BOD) and chemical oxygen demand (COD) in the effluent and lower sludge volume index. (Bratby, 2006) According to Henze *et al.* (1997), this is the most widespread technique among wastewater treatment plants. The simultaneous addition is also preferred, as the bacteria in the biological process need phosphorus for growth.

In a sequential phosphorus addition scheme, the coagulant is added in two points, after mechanical removal and after an activated sludge process, for example. This will decrease the total chemical amount because at first stage the overall phosphorus removal is accomplished by relatively low metal-to-phosphorus ratios. At the second

stage, the metal-to-phosphorus ratio is high but because the starting concentration is low, the chemical dose is low as well (Figure 7) (Bratby, 2006).

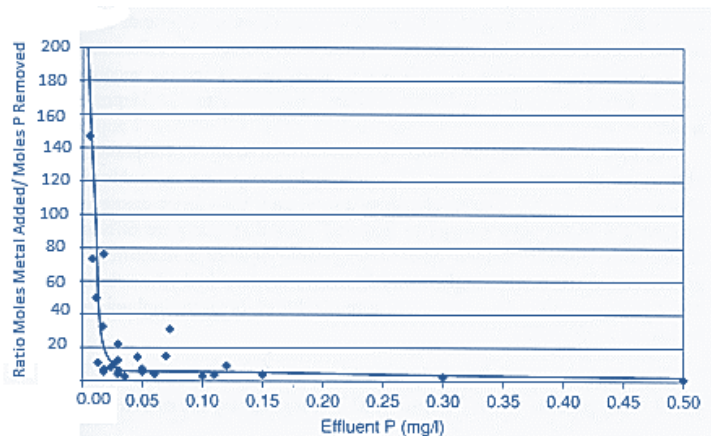


Figure 7. Residual phosphorus and metal to phosphorus ratios (Bratby, 2006).

Because the precipitation reactions occur in seconds, the chemicals have to be dispersed completely and uniformly to the wastewater. This is commonly termed as rapid or flash mixing. According to Ebeling *et al.* (2005), the mixing is dependent upon the amount of energy supplied, the mixing residence time and the related turbulence effect (Ebeling *et al.*, 2005).

Chemicals are purchased either as a solution or as a solid. Transport costs become more inexpensive and a solution with wanted metal concentration is easy to prepare from solid form. In addition, if polymers are used as a flocculants they are as well supplied more frequently as a dry product. The active polymer concentration is approximately 80 to 95 % compared with solution 10 to 50 %. (Bratby, 2006) With solid products, there is also a need for a sufficient tank volume for suspending and aging.

The needed chemical dose can be calculated with different equations but they tend to overestimate the consumption. (Bratby, 2006) A jar test, where wastewater is treated with different chemical doses, is a better option as it takes account the quality of wastewater, which is unique in every wastewater treatment plant (El-Hoz and Apperley, 1996; Langer *et al.*, 2013, Ponou *et al.*, 2014). Both under- and overdosing of metal coagulants reduces the effluent quality. Underdosing results in incomplete removal of particles because the formed flocs are insufficiently strong or big to be removed by the tertiary filter. In addition, the target phosphorus concentration is not achieved.

Overdosing induces residual metal concentration in the effluent because not all of the added metal reacts. Secondly, effluent suspended solid concentration has potential to increase if coagulation continues after the filter (Knapp and Tucker, 2006; Langer *et al.*, 2013). Thirdly, an overdosing of traditional metal coagulants may excessively decrease the pH and reduce the effluent quality. (Langer *et al.*, 2013) Furthermore, overdosing is economically unreasonable.

Because phosphorus concentrations vary diurnally and seasonally, the chemical addition should be linked to tertiary influent phosphorus concentration to avoid under- and overdosing (Langer *et al.*, 2013). The best situation would be that there is phosphorus measurements for orthophosphate and total phosphorus before and after the chemical addition points. However, there should be sampling or online-monitoring at least for effluent.

4 Chemical precipitation steps

The physical-chemical phosphorus removal process is divided into four stages: precipitation, coagulation, flocculation and separation. The first two steps are chemical by nature and occur at the same time in seconds while the following two physical steps

take minutes. In literature, coagulation and flocculation are often considered as synonymous but these two processes should be regarded as separate (Henze *et al.*, 1997).

4.1 Precipitation and coagulation

Precipitation and coagulation are also often mixed together probably because they occur at the same time in seconds and both mechanisms produce a solid particle. Coagulation is described as a process that covers all the mechanisms that destabilize the surface charge of a colloid whilst precipitation is a reaction where a chemical forms a poorly soluble compound (Isoaho and Valve, 1986; Jiang and Graham, 1998).

The main object in the precipitation of phosphorus is to convert the soluble orthophosphate into a non-soluble phosphorus precipitate by adding chemical coagulant. The most popular precipitation chemicals are trivalent metal salts such as aluminum (Al^{3+}) and iron (Fe^{3+}). Divalent atoms like Fe^{2+} and Ca^{2+} are also used but these forms are oxidized to achieve faster precipitation. (Isoaho and Valve, 1998; Vesilind, 2003) In equations (1) and (2) are presented the simplified reactions that take place during precipitation (Henze *et al.*, 1997).



Equation 1 describes the orthophosphate precipitation where the product is a non-soluble metal-phosphate precipitate. In addition, monomeric and complex polymeric species of metals are produced and the amount of these depends on the process conditions such as pH, temperature and wastewater quality (Jiang and Graham, 1998).

Part of the chemical is consumed by the side reaction, which produces a metal hydroxide precipitate (equation 2). As a result, the added chemical amount has to be greater than the stoichiometric need. (Henze *et al.*, 1997) In addition to competing reactions, alkalinity, pH, trace elements and other compounds in the wastewater affect the required chemical dose (Ebeling *et al.*, 2005). As the equation 1 shows, alkalinity is reduced which automatically reduces the pH. (Henze, 1997) Hence, the buffer capacity of water has to be increased so that it does not drop too much, because the lower the pH the more hydroxides are formed and less phosphate is precipitated (Bratby, 2006) In addition, microbes in the biological process prefer neutral pH. If necessary, the buffer capacity can be increased by a lime addition, for example. Even though the formation of hydroxide precipitates consumes the metal coagulant, it does not make the process inefficient. The formation of voluminous particles helps in the flocculation step when the smaller precipitated phosphorus particles agglomerate to form suspended solids. Otherwise, the coagulated metal precipitates would not settle at all (Henze *et al.*, 1997; Zouboulis and Traskas, 2005). Furthermore, phosphate ions can also be adsorbed on to the hydrolysis products (Zouboulis and Traskas, 2005).

Coagulant acts also as a destabilizer for colloidal particles (El-Hoz and Apperley, 1996). Although coagulation has been used for centuries in water and wastewater treatment, the mechanism of destabilization is still relatively unknown because of its complexity. The charge of a colloid is destabilized by adding counter ions into the solution. This will suppress the charge of the diffuse layer and make colloids attract each other. In addition, if the coagulant has polymeric nature it can bridge colloids together. Furthermore, the already formed metal precipitates can further catch colloids (Henze *et al.*, 1997).

The more there are different colloids and particles, more chemical is needed (El-Hoz and Apperley, 1996). However, the coagulant addition should not be exceeded because it will lead to a restabilization of colloids. The restabilization means that destabilized particles start to reject each other again because the overall charge has

altered. (Zouboulis and Traskas, 2005) Colloidal and coagulant characteristics such as the type of the charge and its intensity affect the removal. Including these, precipitation and destabilization are enhanced by controlling alkalinity, pH and temperature. (Isoaho and Valve, 1986; El-Hoz and Apperley, 1996; Bratby, 2006) Table 3 summarizes the mechanisms that are involved in precipitation and coagulation.

Table 3. Summary of mechanism involved in precipitation and coagulation.

Precipitation
Precipitation with metal salt and formation of metal-phosphate precipitate
Phosphate adsorption on the hydrolysis products of coagulant
Adsorption of phosphates onto the suspended solids
Coagulation
Destabilization of a colloidal charge with coagulant
Adsorption of colloidal particle onto the hydrolysis products/metal precipitate
Polymeric bridging

4.2 Flocculation

The main object of flocculation is to agglomerate the already destabilized colloidal particles and metal precipitates into bigger particles either by perikinetic or orthokinetic movement. Perikinetic movement is caused by Brownian movement. This would take too long, which is why flocculation is enhanced by slow mixing. This is termed as orthokinetic movement. (Isoaho and Valve, 1986) The formation of particles is enhanced by adding a flocculation aid (e.g. polymer) during slow mixing. The polymer acts like glue that binds flocs together. Mixing has to be adjusted so that it does not break down the formed particles. (Isoaho and Valve, 1986; Henze *et al.*, 1997, Bratby, 2006) Excessive polymer addition can result in membrane fouling in tertiary

filtration step as flocs become too sticky and are irreversibly attached to the cloth or membrane (Ljunggren *et al.*, 2005).

Treatment step after flocculation determines what kind of flocs are desired. For filtration and sedimentation, the aim is to form particles that are dense, strong and big enough for settling or filtration. On the other hand, for flotation, the particle needs to be light and buoyant (Kaupunkiliitto, 1980).

4.3 Chemicals used in phosphorus removal

Iron and aluminum based coagulants are the most used in phosphorus removal. In literature, various opinions and results about which is the best metal for coagulation can be found. Other studies have proved that iron works better (Liu *et al.*, 2013) as against others have noticed that aluminum coagulant is more effective (Langer *et al.*, 2013).

Coagulant doses vary between different Finnish WWTPs and the amount depends on the wastewater quality and the efficiency of upstream processes. Usually, the coagulant doses are reported by “mg/l” but the best way to report would be by weight or molar basis (g Me³⁺ added/g removed P or mol Me³⁺ added/ mol P removed). According to Bratby (2006) the metal addition varies between 40 and 180 mg/l thus between 0.8 and 1200 g Me³⁺/g P. (Bratby, 2006; US EPA, 2007). In Table 4 are listed coagulant doses in different WWTPs that do not have tertiary treatment after secondary settling.

As from the Table 4 can be seen, polymer doses are much lower than coagulant. Synthetic polymer doses vary from 0.5 to 2 mg/l (Bratby, 2006; US EPA, 2007). The reason for this will be discussed in Chapter 4.3.3.

Table 4. Coagulant and polymer dose in different WWTPs without tertiary treatment.

WWTP	Coagulant			Polymer		Reference
	Type	Dosing point	g/m ³	Dosing point	g/m ³	
Oulu, Taskila	Poly-aluminium chloride	Primary settler	66	Primary settler	0.15	Oulun Vesi, 2012
	Ferric sulphate	Secondary settler	162	Secondary settler	0.73	
Espoo, Suomenoja	Ferrous sulphate	Primary settler	114	-	-	Lehtinen and Urho, 2014
Turku, Kakolanmäki	Ferrous sulphate	Before primary settler	116	Secondary settler	1.6	Leino, 2014
Viinikan-lahti, Tampere	Ferric sulphate	Before primary settler	369	Secondary settler	0.3	Tampereen Vesi, 2013

4.3.1 Traditional metal coagulants

Iron, aluminum and lime based chemicals are the most frequently used coagulants in phosphorus precipitation. These metal coagulants are effective as well as relatively inexpensive. Henze *et al.* (1997) explain that the effectiveness is dependent on the formation of multicharged polynuclear complexes in solution with enhanced adsorption characteristics. Precipitation can be controlled and enhanced by pH adjustment (Henze *et al.*, 1997).

Ferrous iron (Fe^{+2}) is commonly used as precipitant because of its low price and its availability (Henze *et al.*, 1997). The drawback is that the formed precipitate is poorly settleable and floc formation takes about two hours. Precipitation by ferric (Fe^{3+}) takes

a few seconds and the precipitate has better characteristics. Consequently, Fe^{2+} is often oxidized to Fe^{3+} (Isoaho and Valve, 1986) The formed precipitates are FePO_4 and $\text{Fe}(\text{OH})_3$. The optimum pH for phosphorus precipitation with iron is between 4.5 and 5.0, but according to Vesilind (2003) significant phosphorus removal can occur at pH 7 and slightly above. The main iron coagulant products are ferrous sulphate (FeSO_4) and ferric chloride (FeCl_3) (Bratby, 2006).

The most used aluminum based chemical in phosphorus precipitation is aluminum sulfate ($\text{Al}_2(\text{SO}_4)_3$, called alum. Aluminum reacts with phosphorus and produces a well settleable AlPO_4 and $\text{Al}(\text{OH})_3$ precipitates. The most efficient pH for precipitation by aluminum is between 5.5 and 6.5 (Vesilind, 2003; WEF, 2010).

Alum is easy to handle and it produces less sludge than lime (Ebeling *et al.* 2005) Compared with iron, aluminum is slightly more expensive (Kettunen, 2014). In addition, iron is more environmentally friendly than aluminum. These may be the reasons, why iron is more common in primary treatment than alum. Removal efficiency with aluminum and iron are typically on average 95 % (Bratby, 2006).

Calcium is used as a precipitate in phosphorus removal. This is done by adding either $\text{Ca}(\text{OH})_2$ or CaO . This produces hydroxyapatite as primary product and calcium carbonate (CaCO_3) as a by-product. (Henze *et al.*, 1997) Sludge formation is higher compared with alum which may become a problem (Ebeling *et al.*, 2005) Calcium is cheap and easy to handle, but the precipitation process is complicated (de-Bashan and Bashan, 2004). Hydroxyapatite crystallizes at pH 8.0–8.5 and the removal efficiency ranges from 75% to 85%. If optimum pH is not achieved, CaCO_3 starts to inhibit the hydroxyapatite formation because carbonate and phosphate are competing for calcium. (Henze *et al.*, 1997; de-Bashan and Bashan, 2004) In addition, alkalinity plays a critical role (Vesilind, 2003).

4.3.2 Pre-polymerized in-organic coagulants

When metal coagulants are mixed in the wastewater, they tend to hydrolyze into various metal hydrolysis species in an uncontrolled way. Thus, the quality of the water as well as the process conditions like pH, rapid mixing and the coagulant dosage define which hydrolysis products are predominant. This has led to the development and use of pre-polymerized inorganic coagulants. They are prepared by undertaking a partial hydrolysis of acid aluminum chloride or ferric chloride solution. Properties can be altered by substituting different functional groups. For example, they can contain species that are stable and more effective for charge neutralization than the respective monomeric species due to their higher charge density. In Table 5 are listed several advantages of these coagulants (Jiang and Graham, 1998; Zouboulis and Traskas, 2005; Bratby, 2006).

Table 5. Advantages of pre-polymerized in-organic coagulants compared with traditional coagulants (Jiang and Graham, 1998; Bratby, 2006).

-
- Process conditions during treatment do not affect to the hydrolysis species produced
 - Work efficiently in a wide pH range and temperature
 - Less sensitive to low temperatures than conventional coagulants
 - Required dose to achieve the treatment goal is lower than with traditional coagulants
 - Less chemical residuals in the effluent than
 - Lower chlorine and/or sulfate residuals from the coagulant → lower final total dissolved solids concentration
-

Basicity ratio r is the molar ratio of hydroxide ions bound per mole of metal ($[\text{OH}^-]/[\text{Me}^{3+}]$) and is an important parameter in coagulation with pre-polymerized coagulants. Higher the basicity value, less alkalinity is consumed and thus pH will not drop as dramatically. Thus, they have stability towards hydrolysis. On the other hand, phosphorus removal is more efficient if the basicity ratio is small because more metal

molecules are specifically consumed to phosphorus precipitation. (Gillberg *et al.*, 2003; Bratby, 2006; Liu *et al.*, 2013) On the other hand, optimal pH for precipitation may not be achieved without pH adjustment. Formed flocs are bigger, denser and better settleable than the ones produced by traditional metal coagulants (Bratby, 2006; Liu *et al.*, 2013).

4.3.3 Flocculation aids

Usually, coagulants alone are not sufficient for producing dense, strong and big particles thus flocculation aids (polyelectrolytes) are used (Isoaho and Valve, 1986). With them, it is possible to decrease the needed metal salt concentration (Hart *et al.*, 2012; Tran *et al.*, 2012). However, polymers are roughly 10 times more expensive than traditional coagulants, which is why it is preferred to use higher coagulant than polymer doses (Kettunen, 2014).

The structure of a polymer consists of monomer units that are held together by covalent bonds (Figure 8). Polymers are divided into two groups, synthetic ones and biopolymers, according to their origin. Many synthetic polymers are based on polyacrylamide. Biopolymers are processed from several types of starches or tannins, for example. (Bratby, 2006) For the moment, synthetic polymers are more common and the biopolymers are under development.

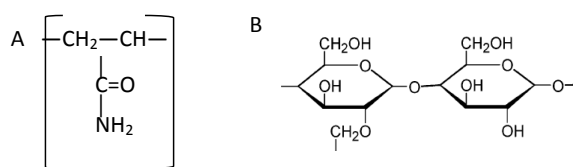


Figure 8. The structure of nonionic polyacrylamide (A) (Bratby, 2006) and structure of a starch polymer (Modified from Crini, 2005).

Polyelectrolytes (polyions) are polymers, which contain ionizable functional groups in their skeleton. In solution, the functional groups dissociate and give the polymer its charge. Cationic polymers possess positive charge and anionic negative. Polyamfolytes have both negatively and positively charged groups in their skeleton. Polymers that do not have charge at all are called nonionic (Bratby, 2006).

Functional groups like -COOH, -OH, -NH₃, form bonds during flocculation and make the polymer water soluble. The flocculation process is the better the more intense the charge. Charge density can be increased by forming longer polymer chains thus increasing the molecular weight. No upper limit exists for molecular weight but the solubility decreases after 10⁷ g/mol. In addition, according to Chuang *et al.*, (2007) fouling of membranes increase if molecular weight and charge density of a polymer increase. Furthermore, the maturation time (i.e. aging) becomes longer because mixing intensity has to be lowered so that it does not break the chains. On the other hand, mixing has to be strong enough so that the polymer is thoroughly wetted. Inefficient mixing can be noticed as insoluble polymer lumps in the solution (“fish eyes”). (Isoaho and Valve, 1986; Bratby, 2006; Tran *et al.*, 2012) The configuration of the polyelectrolytes can be linear, filament-like, branched or meshy (Bratby, 2006; Tran *et al.*, 2012).

Drawbacks with synthetic polymers are that the final polymer product may contain unreacted monomer units that are toxic for aquatic life. Acryl amide, for example is a neurotoxin and a carcinogenic compound that accumulates to aquatic animals. In addition, wastewater contains many different compounds that may react with the polymer and form toxic side products (Bratby, 2006).

Biopolymers are virtually toxic free, biodegradable and raw products are often locally available. The downsides of biopolymers are that they are not as effective as synthetic ones so the needed amount is higher, typically between 2 and 20 mg/l (compare with 0.5–2 mg/l). For example, in a study made by Sørud *et al.* (2013) they used potato-

based flocculant in storm water treatment. The added amount was 10 mg/l, which is high, compared with the commercial polymer (1 mg/l). (Sørud *et al.*, 2013) The shelf life of a biopolymer is shorter compared with a synthetic one because active components will biodegrade with time. For the moment, it is easier to produce tailor-made synthetic polymers than biopolymers and because polymers are expensive, the synthetic ones are often preferred (Bratby, 2006; Lee *et al.*, 2014).

4.4 Separation

After suitable flocs are formed, they can be removed either by settlement, flotation or filtration. The decision is affected by suspended solid load and floc characteristics. If coagulation and flocculation take place at the beginning of a waste water treatment process, settling is preferred because the formed flocs are heavy and well settleable. Flotation and filtration processes are good choices for tertiary treatment (Chapter 2).

In this study, the performance of a discfilter was evaluated. The goal was to achieve under 0.1 mg/l effluent total phosphorus concentrations.

5 Disc filtration

Discfilters are a type of micro screens and have been used as tertiary treatment step in the USA since the 1990 and its popularity is increasing (Gutierrez, 2010). At municipal WWTPs, they are mostly used for effluent polishing and in storm water treatment. Polishing is required to remove suspended solids and phosphorus and achieve greater reliability in achieving lower concentrations (Neethling *et al.*, 2008). Food processing, cooling systems and pulp and paper industries are examples of the industrial applications (Hydrotech, 2014).

5.1 Mechanism

Discfilters can be divided into two categories depending on the direction the water flow through the filter membrane: inside-out or outside-in (Figure 9 and Figure 10). The removal of particles is based on physical blocking and the removal is enhanced by a sludge cake that is formed either inside or outside the membrane (Persson *et al.*, 2006). In both types, the water flows by gravity and no external pumping is demanded so they can be categorized as low pressure membranes (Guo *et al.*, 2012).

In an inside-out system (Figure 9), the water flows to the central cylinder from where it is filtered through discs. Cake formation inside the filter panels leads to water level rise inside the cylinder and when water meets the level sensor, backwash is initiated. Thus, the removal efficiency is at maximum just before the washing (Langer, 2013). Filtration is not interrupted during the backwash. Nozzles spray filtered water with high pressure (8 bars) in order to rinse off the solids. Solids are collected in a trough and discharged into a sludge basin. (Ljunggren, 2006) Filters are only partially submerged in the filtered water (Gutierrez, 2010).

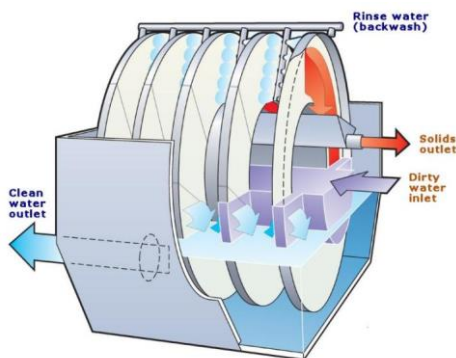


Figure 9. Basic function of Hydrotech inside-out Discfilter (Veolia Water Technologies, 2014).

In an outside-in process (Figure 10), wastewater is filtered through the disc cloth into a center collection pipe where it flows to the effluent chamber (Knapp and Tucker, 2006). Discs are completely submerged in the influent water. (Gutierrez, 2010) Backwash is initiated when the water level meets a specific sensor in the filter tank. A backwash vacuum shoe is mounted on each side of the disc and during disc rotation the solids are vacuumed from the cloth. The vacuum effect is created by a pump. Filtration continues during the cleaning cycle like in an inside-out system (Knapp and Tucker, 2006).

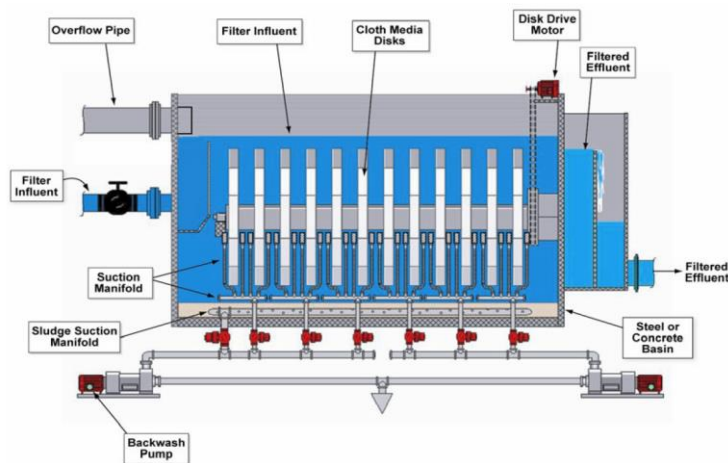


Figure 10. Schematic mechanism of AquaDisc outside-in cloth filter (Knapp and Tucker, 2006).

Different membrane materials are available such as cloth (needle felts, pile fabrics and different kinds of weaves), plastic and stainless steel (Persson *et al.*, 2006; Gutierrez, 2010; Schlebusch, 2012). It is essential that the material possesses sufficient mechanical strength and tolerates chemical washing. Naturally, the geometry and size of the pores affect the separation which is why the pore geometry should be designed so that the pore is not irreversible clogged by small particles. (Schlebusch, 2012) Pore

size can be chosen between 10 and 100 μm . For tertiary treatment, it is recommended to apply the 10 μm pore size as the particle size distribution is small. (Gutierrez, 2010) With it, it is possible to remove even microorganisms and viruses (Ghayeni *et al.*, 1996; Persson *et al.*, 2006). Size distribution studies have shown that conformation (e.g. size and shape) of the particles influences the filtration. Particles that are bigger than the pore size can be transported through the membrane due to their conformation. On the other hand, particles that are smaller than the pore size can be removed because of the cake formation (Persson *et al.*, 2006).

Because the filter panels are arranged in a vertical configuration, it gives large filter area in a small footprint. According to Bourgeois *et al.* (2003), the filtration area is up to 75 % smaller than with conventional sand filtration and compared with a conventional drum filter, the discfilter has 2–3 times more filter area with the same external dimensions (Veolia Water Technologies, 2014).

The energy consumption with discfilter is low because the system is gravity based and discs stay in rest during the filtration and turn only when backwash is initiated. Langer *et al.* (2013) calculated that the average energy consumption was approximately 21 Wh/m^3 and this is about 30–33 $\text{MJ}/(\text{PE}\cdot\text{a})$ (Langer *et al.*, 2013; Remy *et al.*, 2014). According to Persson *et al.* (2006), the energy requirement of a discfilter during maximum loading was 0.009 kW/m^3 . On top of that, no external wash water is needed because the filtered water is used and the volume is only a few percent of the water to be filtered. (Ebeling *et al.*, 2005; Knapp and Tucker, 2006; Schlebusch, 2013; HUBER Technology, 2014). The quality of the produced sludge depends on pore size, frequency of the backwash, and influent suspended solid load on the filter (Ebeling *et al.*, 2005).

Of course, there are drawbacks as well. During the high-pressure cleaning solids can go through the filter cloth to the filter media. Biological matter can grow on the filtrate side of the filtration thus lowering the quality of filtrate (Gutierrez, 2010).

Furthermore, it has been reported that the maintenance of the discfilter takes approximately 1300 man-hours per year from which most of the time (520 hours) is consumed to the nozzle inspection (Nunes *et al.*, 2013). If chemical pre-treatment is required for achieving low phosphorus concentrations, it becomes one of the critical points as discussed in Chapter 4. Furthermore, sludge volume increases and it has to be processed. However, the membrane fouling is the biggest drawback concerning discfilter mechanism.

5.2 Filter cloth fouling

Although the discfilter has many advantages in wastewater treatment, various challenges are met in different treatment plants. The mechanism of the filter is simple and usually the problems are associated with chemical addition and membrane fouling (Hancock, 2014).

Membrane fouling represents one of the major cost concerns in filtration processes as it reduces the capacity and lifetime of a membrane. Thus, much research has been conducted to investigate the fouling mechanisms and its prevention (Mohammadi *et al.*, 2002; Lim and Bai, 2003; Chuang *et al.*, 2007; Chon *et al.*, 2012; Zheng *et al.*, 2012).

Fouling is defined as a reduction of permeate flux through the membrane. A pore blocking, a cake formation and/or a biofouling on the membrane causes fouling (Mohammadi *et al.*, 2002; Lim and Bai, 2003). Pore blocking is caused by small particles which have blocked the pores from the inside and not on the surface of the membrane like in the cake formation (Lim and Bai, 2003). For example, excessive polymer addition can result in sticky flocs that are attached to the membrane (Ljunggren *et al.*, 2005). Biofouling arises from the biofilm formation in the pores or on the surface of the membrane. Bacteria can improve its adhesion on the membrane by secreting extracellular polymeric substances. Biofouling is harmful because bacteria can impair the membrane quality by enzymes (Lim and Bai, 2003). The effect of fouling

mechanisms depends on such membrane characteristics as pore size and material and such process conditions as particle size distribution and microorganism amount (Lim and Bai, 2003; Chon *et al.*, 2012).

These different fouling mechanisms can result in either reversible or irreversible fouling. In reversible fouling, the transmembrane flux is possible to restore by appropriate physical washing protocol such as high-pressure backwashing (Guo *et al.*, 2012). As against, in irreversible fouling, the transmembrane flux cannot be restored chemically or hydrodynamically. Thus, membranes must go through an extensive chemical cleaning or be replaced. (Guo *et al.*, 2012) Chemicals will hydrolyze organic molecules and loosen the particles and biofilm attachment to membrane (Lim and Bai, 2003).

In micro screen filtration, the fouling can be monitored by measuring the backwash frequency. When backwash is initiated frequently, it tells about cake formation on the surface. If the frequency does not decrease with decreasing solids load and keeps growing, it is highly presumable that filter pores are irreversibly clogged. Because backwashing is the main energy consumer, it is recommended to perform chemical cleaning often enough. This enables a lower level of energy demand and a longer membrane lifetime. (Lim and Bai, 2003; Langer, 2013) Cleaning solutions should be chemically stable, safe, cheap and washable with water (Mohammad *et al.*, 2002). Usually, the filter supplier has a recommendation for suitable chemicals but sodium hypochloride and hydrochloric acid are a few examples. Usually the best practice is found by trial and error (Mohammadi *et al.*, 2002).

5.3 Hygienization

Traditional wastewater treatment achieves typically 90–99.9 % reductions of enteric microorganisms. Further 90–99% reductions can be achieved with tertiary treatment. (Koivunen and Heinonen-Tanski, 2005). Few studies have been conducted to

investigate pathogen removal by disc filtration (Gómez *et al.*, 2006; Enerhall and Stenmark, 2012; Abdalla and Gaid, 2013).

Removal by only mechanical sieving is not significant. In Gómez *et al.* (2006) and Enerhall and Stenmark's (2012) studies, only 33 % and 26 % of *E. coli* was removed with the pore sizes of 20 and 15 μm , respectively (Gómez *et al.*, 2006; Enerhall and Stenmark, 2012). However, bigger organisms such as helminth eggs (20–80 μm) are removed completely with 20 μm pore size. (Gómez *et al.*, 2006; Abdalla and Gaid, 2013). The typical sizes of different pathogens are listed Table 6. The size is smaller than the typical pore sizes in tertiary disc filtration (10–20 μm) but microbes are attached to suspended solid particles which helps the removal.

Table 6. Typical size ranges for microbial pathogens (Enerhall and Stenmark, 2012).

Pathogen group	Size
Bacteria	D 0.5–1 μm , L 1–2 μm
Protozoa	> 2 μm
Viruses	0.018–0.5 μm

The pathogen removal often depends on the influent quality such as suspended solid concentration, turbidity, particle size distribution and diversity of microorganisms (Gómez *et al.*, 2006). However, with a combination of coagulation and discfiltration it is possible to enhance the removal as the particle size increases and formed filter-cake layer acts as an extra filter. (Wintgens *et al.*, 2005; Amin *et al.*, 2010) This way, it is possible to guarantee more reliable removal efficiency.

Gómez *et al.* (2006) and Langer *et al.* (2013) concluded from their studies that microfiltration slightly reduces the pathogen concentration but its advantage is more

in removing suspended solids and turbidity. Thus, discfilter works as a pre-treatment for UV hygienization or for other membrane techniques like ultrafiltration or RO.

5.4 Design basis

One should bear in mind that the discfilter has to be able to function under a wide range of operation conditions. The time of the day as well as the organic loading of the influent, affect the suspended solid and phosphorus concentration of the secondary effluent (Amin *et al.*, 2010). Usually, disc filtration alone is not sufficient to achieve wanted phosphorus or suspended solids concentrations. This leads to the application of chemicals prior to filtration (Rytkönen, 2012; Hydrotech, 2014).

In the overall design, adequate chemical storage tanks as well polymer preparation tanks need to be taken into account. Especially polymer preparation tanks have to be designed so that the aging time is sufficient.

Hydraulic retention time (*HRT*, min) is the time that water stays in the basin. It is important that the HRT is long enough to ensure adequate time for coagulation and flocculation. If the time is excessively short, coagulation may occur after the filter. The recommended retention times for coagulation are usually between one to two minutes as the coagulation occurs rapidly. For flocculation, the HRT is higher, normally from four to five minutes (Langer *et al.*, 2013).

As mentioned before in Chapter 4, the coagulant has to be mixed properly with the wastewater so that collisions between colloids and metal ions take place as much as possible. These flocs will serve as a base core in flocculation, where the velocity must not be excessively intense so that the bigger flocs will stay unbroken. (Langer *et al.*, 2013) For design and operation, a mean velocity gradient in a coagulation tank (*G* value, s^{-1}) is determined. It is defined as average energy dissipation rate per unit volume of suspension. Typical *G* values for rapid mixing are between 40 to 1 000 s^{-1} and for flocculation between 20 to 80 s^{-1} (Ebeling *et al.*, 2004; Sheng *et al.*, 2006).

The ability of the filter to treat a certain flow of water in a certain application is very dependent on the solids loading rates. Therefore, for the discfilter design, one has to know the maximum solid to be treated as well as the target quality.

6 Case studies

In America as well as in Europe, disc filtration as a tertiary treatment process has already been used with good results (EPA, 2007; Veolia Water Technologies, 2013). In Finland, full-scale tertiary filtration processes were not very common in the beginning of the 21st century but the amount of tertiary treatment applications has increased and pilot studies have been made in different WWTPs. (Saarinen, 2003; Rytönen 2012) However, there are no full-scale discfilter applications in Finland.

The popularity of pilot scale studies has risen because the best practices for wastewater purification are site specific so it is good to test new processes in a smaller scale before big and expensive investments are made (Persson *et al*, 2006). In this chapter, four different discfilter cases are reviewed.

6.1 Ruhleben WWTP, Berlin

Hydrotech's Discfilter pilot was tested in Ruhleben's WWTP in Germany for effluent polishing. The goal was to achieve good and reliable phosphorus removal with effluent values < 80 µg/l. The overall process scheme of the WWTP is described in Figure 11 and the pilot was installed after a secondary settler. The average daily flow of the WWTP is 247 500 m³/d (Langer *et al.*, 2013).

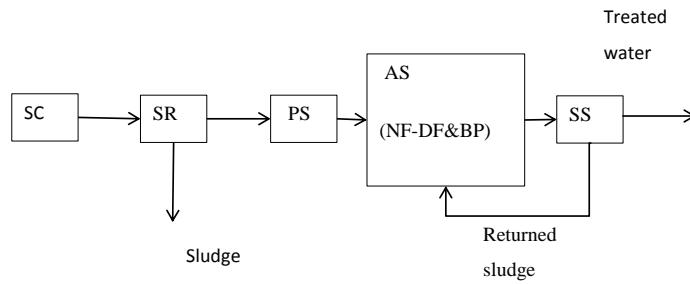


Figure 11. Process scheme of Ruhleben WWTP. SC=screening, SR=sand removal, PS=primary settler, AS=activated sludge, NF-DF=nitrification-denitrification, BP=biological phosphorus removal, SS=secondary settler [modified from Langer 2013].

Iron and aluminum based coagulants with cationic and anionic polymers were tested. The best results were obtained with the aluminum based coagulant and cationic polymer. Total phosphorus concentration of 80 µg/l could be achieved consistently. This amounted to 73% removal of phosphorus by the disc filtration. Chemical consumption could be reduced if the dosing was linked to influent orthophosphate concentration. Concentration of metal residuals was lower with aluminum than iron. UV hygienization was also more efficient with aluminum than iron (Langer *et al.*, 2013).

An interesting remark was that both high and low SS concentrations impaired the discfilter operation. No removal was detected when SS concentration dropped to 4 mg/l in the pilot influent. However, the discfilter was able to recover from high turbidity incidents (Langer *et al.*, 2013).

6.2 Rya WWTP, Gothenburg

Before the discfilter installation at Rya's WWTP of Gothenburg in 2010, the outlet phosphorus concentration was between 0.4–0.6 mg TP/l. The average daily flow is 373 000 m³/d. (Behzadirad, 2010). In June 2010, 32 filter discs were installed in the plant, which makes it the world's largest discfilter installation. The main purpose of the discfilters was to achieve the new standard phosphorus concentration of 0.3 mg/l and to remove the biomass generated and sloughed from the denitrifying moving bed biofilm reactors (MBBR). (Nunes *et al.*, 2013) Figure 12 below illustrates the process configuration.

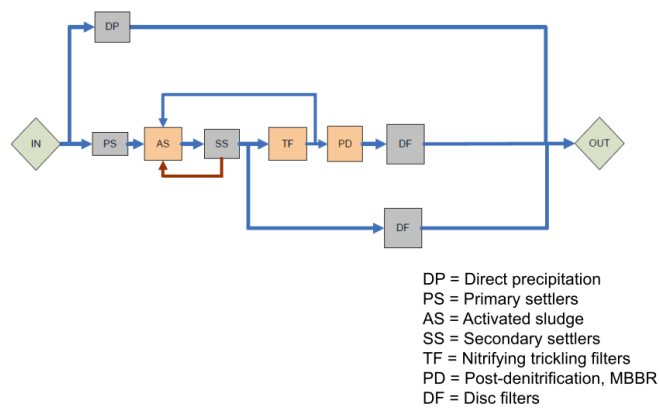


Figure 12. Process configuration of the Rya WWTP (Nunes *et al.*, 2013).

As the Figure 12 shows, part of the secondary settled water was directed to the discfilter and the other part was treated through the MBBR and filtered. Storm waters were treated with direct precipitation without disc filtration.

Discfilters were able to reduce the total phosphorus concentration to 0.2 mg/l and the SS removal was 80 %. Nunes *et al.* (2013) also concluded that the solid removal is higher for the MBBR effluent compared with the effluent from the secondary settler. Reason for this might be that after MBBR the particles are bigger because microbes have formed bioflocs. Nunes *et al.* (2013) also analyzed the different phosphorus forms in the influent water and noticed that most of the phosphorus was in the suspended solids, thus possible to remove by filtration. In Rya WWTP, simultaneous precipitation is used to remove phosphorus with iron sulphate but no chemicals are added prior to the discfilter. Most of the phosphorus is in suspended solids and the particle size is apparently adequate so the new 0.3 mg/l is possible to achieve without a chemical addition. However, if phosphorus limits tighten, it is possible that Rya WWTP has to consider the addition of chemicals.

6.3 Clinton WWTP, Massachusetts

At Clinton WWTP, the average daily flow is 11 356 m³/d (3 MGD) and the effluent total phosphorus and SS concentrations are 0.45–0.83 mg/l and 3–6mg/l, respectively. The discharge limit for phosphorus is 1.0 mg/l but the new regulation demands that after 2014 phosphorus concentration during summer time (April-October) has to be 0.15 mg/l. Two different pilots (supplied by Kruger and WesTech) were tested in order to evaluate discfilters' ability to consistently reduce the phosphorus concentration to the new permit limit of 0.15 mg/l (Hart *et al.*, 2012).

Clinton Treatment Plant Flow Schematic

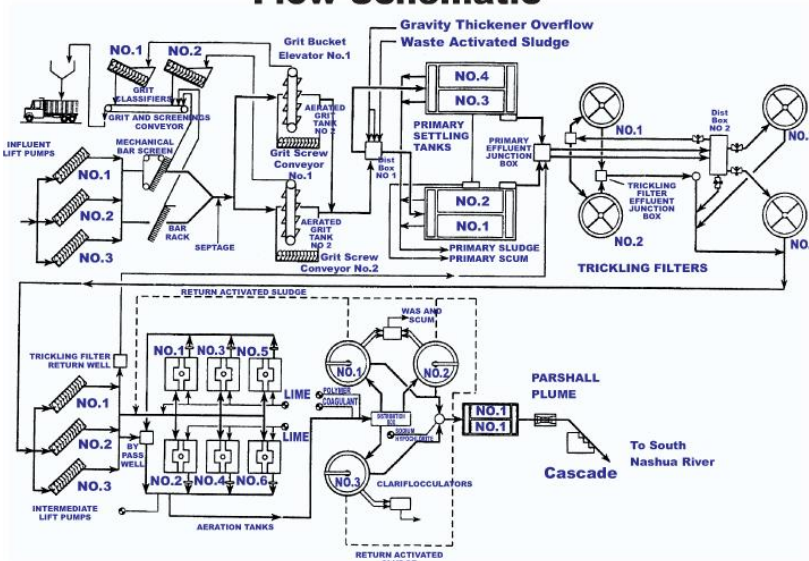


Figure 13. Overview of Clinton WWTP. (MWRA, 2014)

The pilot studies demonstrated that both filter types with the addition of a coagulant and a polymer were able consistently to reduce the total phosphorus concentration under the 0.15 mg TP/l limit. FeCl_3 was chosen over Alum, as the required dose was lower. Plant upsets were performed by adding mixed liquor suspended solids into the filter influent and both filter types were able to produce effluent with total phosphorus concentration of 0.1 mg/l. In addition, they observed that hydraulic loading did not have much of an effect on the phosphorus removal levels. Furthermore, it was proved that two-point chemical addition would decrease the needed total chemical dose and the achieved total phosphorus concentration is also lower (Fay *et al.*, 2012; Hart *et al.*, 2012).

6.4 Sjölanda WWTP, Malmö

The Sjölanda WWTP of Malmö was designed to treat the average daily flow of 142 560 m³/d. Environmental permits are getting tighter which led to the investigation of

resulting SS concentration was under 5 mg/l. In addition, the polymer addition enhanced the phosphorus removal and resulted in phosphorus concentration of 0.12 mg/l. Further enhancement was observed when an aluminum-based coagulant and polymer were dosed together and under 0.1mg TP/l concentrations were achieved (Väänänen *et al.*, 2013).

At high SS concentrations, the suspended solid removal increased with the increasing use of chemicals. Without chemicals, the SS removal was 65 %, with the polymer 90 % and, with the combination of coagulant and polymer 95 % (Gustavsson and Cimbritz, 2012).

6.5 Summary

From these case studies, it can be concluded that disc filtration is a good candidate for a tertiary treatment process concerning suspended solids and phosphorus removal enhancement. Despite different upstream processes, the discfilter was able to remove total phosphorus and suspended solids to the required limit. In Table 7 is summarized the achieved phosphorus and suspended solid levels in the pilot studies presented above.

Table 7. Results from different discfilter pilot tests. Polymer type C stands for cationic.

WWTP	Pore (μm)	Coagulant		Polymer type: dose (mg/l)	Tertiary influent		Effluent	
		type	mg Me^{3+}/l		mg TP/l	mg SS/l	mg TP/l	mg SS/l
Ruhleben	10	PACl	1.9–2.0	C: 0.5–0.7	0.3	5.4	≤ 0.08	~ 2
Rya	15	-	-	-	0.4–0.6	20	~ 0.2	3–4
Clinton	10	FeCl_3	3.0–3.9	C: 0.28–0.36	0.45–0.83	3–6	0.024–0.076	3
Sjölunda	10	PACl	~ 2	C: 0.6	0.38	13	< 0.10	< 5

* calculated from product dose, assuming metal content is 13.8 %

Furthermore, these case studies show the fact that pilot studies should be made in order to know if a chemical pre-treatment is necessary or not. In many cases, chemical additions are compulsory but the needed doses are low because the initial concentrations of suspended solids and total phosphorus in the effluent are already low. It was proved that with a combination of chemical addition and disc filtration, it is possible to achieve consistently under 0.1 mg/l total phosphorus concentrations (Fay *et al.*, 2012; Väänänen, 2013).

In the USA, really low phosphorus removals are demanded in some states but also the removal of suspended solids and turbidity is important. Numerous studies have demonstrated that with a combination of coagulation and disc filtration, it is possible to continuously produce effluent with low turbidity and suspended solids concentrations (Furuya, 2004; US EPA, 2007; Knapp and Tucker, 2006; Lanoue *et al.*, 2010).

7 Research background and prior studies

7.1 Viikinmäki wastewater treatment plant

The Viikinmäki municipal wastewater treatment plant was put into operation in 1994 and it is the biggest WWTP in Finland as well as in the Nordic countries. It treats the waters of about 840 000 inhabitants of Helsinki, Kerava, Tuusula, Järvenpää, Pornainen, Sipoo, the central and eastern districts of Vantaa and the southern district of Mäntsälä as well as the wastewaters of local industries. The plant is located mostly in underground rock caverns.

After treatment, water is discharged to the Baltic Sea via a 16 km long rock tunnel, to the depth of 20 m, 8 km away from the southern shoreline of Helsinki. On average, 85 % of the incoming wastewater is from households and 15 % from industries.

The treatment is based on a conventional activated sludge process including mechanical, chemical and biological polishing treatment steps. Before discharge, the water flows through the tertiary phase i.e post-denitrification filters (Figure 15).

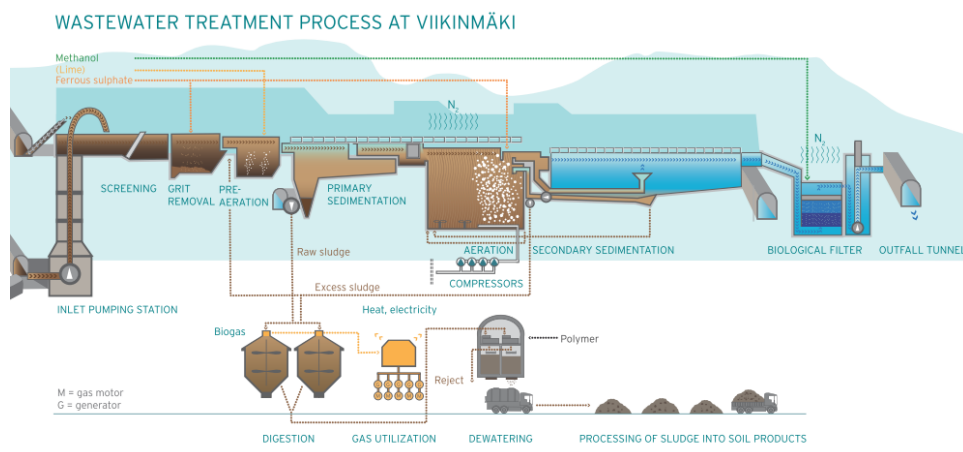


Figure 15. Process scheme from Viikinmäki WWTP.

In Table 8 are presented the environmental permit limits of Viikinmäki WWTP, the EU directive terms as well as the purification results in 2013 (Lehtinen and Urho, 2014; 91/271/ETY).

Table 8. Environmental permit terms and EU directive terms (91/271/ETY) in Viikinmäki WWTP (Lehtinen and Urho, 2014).

	Environmental permit		EU directive terms		Purification results and load in 2013		
	mg/l	Removal %	mg/l	Removal %	mg/l	Removal %	t/a
SS	≤15	-	35	90	6.4	-	661
TP	≤ 0,3*	≥95*	2	80	0.21	96.8	20
BOD₇-ATU	≤ 10 *	≥ 95*	25	40	5.8	97.3	564
COD_{Cr}	≤ 75*	≥ 80*	125	75	42.8	92	-
TN	-	≥ 70**	15	70–80	-	92.4	345

* Quarterly average value

** Yearly average

Permit limits are met easily which may result in tighter discharge limits in the future. In the future, the phosphorus discharge limit maybe reduced to 0.2 mg/l and then possibly to 0.1 mg/l.

7.2 Phosphorus removal at Viikinmäki WWTP

Phosphorus is removed by chemical precipitation in two stages. First, the ferrous sulfate is added to the grit removal chamber where iron (Fe^{2+}) is oxidized to ferric (Fe^{3+}). The second addition is done prior to the secondary settler. The average chemical addition was 96 mg/l, thus annually 9 250 tons. (Lehtinen and Urho, 2013) Approximately 75 % of the iron is added at the first stage and the rest 25 % at the second stage. This two-point addition will decrease the overall coagulant consumption as Bratby (2006) explained.

Because of the biological denitrification filter, the phosphorus concentration has to be adequate to ensure microbes have enough phosphorus for their metabolism. Consequently, the post-denitrifying filter is a bottleneck in the enhancement of

phosphorus removal as it limits the removal of phosphorus in the traditional precipitation step. In Table 9 summarizes the phosphorus removal efficiencies of different treatment steps in Viikinmäki WWTP in 1/2012–6/2014 and Figure 16 depicts the phosphorus concentration in the effluent and removal efficiency.

Table 9. Phosphorus concentrations and removal efficiencies in different process steps (1/2008–6/2014).

Process step	Total phosphorus		Orthophosphate		PO ₄ -P/TP
	mg/l	Removal (%)	mg/l	Removal %	
Influent	6.78	-	2.96	-	0.44
Pre-sedimentation	3.39	50	0.40	86	0.12
Activated sludge	0.46	86	0.17	58	0.37
Effluent	0.22	52	0.06	65	0.29
Overall removal	6.56	97	2.90	98	-

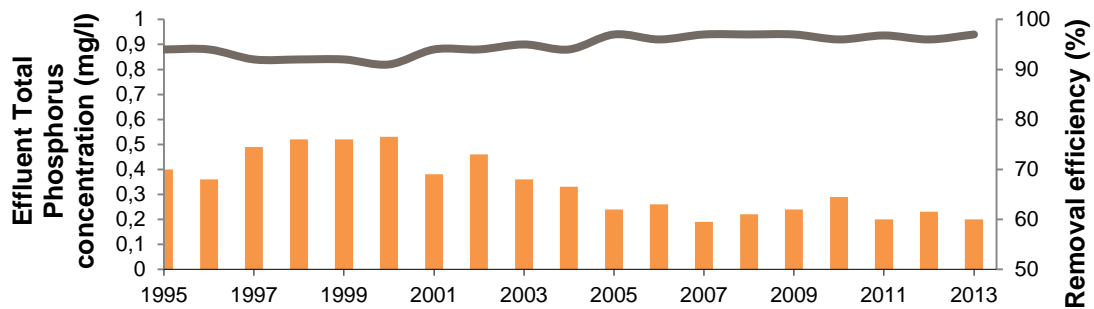


Figure 16. Total phosphorus concentrations in the effluent and removal efficiency during 1995–2013 in Viikinmäki WWTP.

Although phosphorus load to the WWTP has increased approximately 1 % per year as a long time average (1995–2013) the removal efficiency has increased. One reason for the increased removal efficiency is the post-denitrification process that was put into operation in 2004. Microorganisms utilize the orthophosphate in their metabolism, thus decreasing the concentration (Table 9) by 65 %. In addition, microbes form a biofilm on the filter surface, catch particle suspended phosphorus, and decrease the total phosphorus concentration by 52 %. However, the driving force behind the efficiency increase has been the tightening of the discharge limit from 0.5 to 0.3 mg/l since July 2008.

7.3 Challenges in phosphorus and suspended solids removal

Although phosphorus limits are met without complications in normal operation, there are cases that may complicate the achievement of tighter limits. These include the backwashes of post-denitrification filters, plant upsets and bypass water treatment during wet weather conditions.

The phosphorus concentration before post-denitrification filters has to be kept in an adequate level for ensuring sufficient nutrient concentration for denitrifying bacteria. Biofilm formation and suspended solids will block the pores and backwash will be initiated. Backwash events lead to an increase of suspended solids and phosphorus in the effluent (Figure 17).

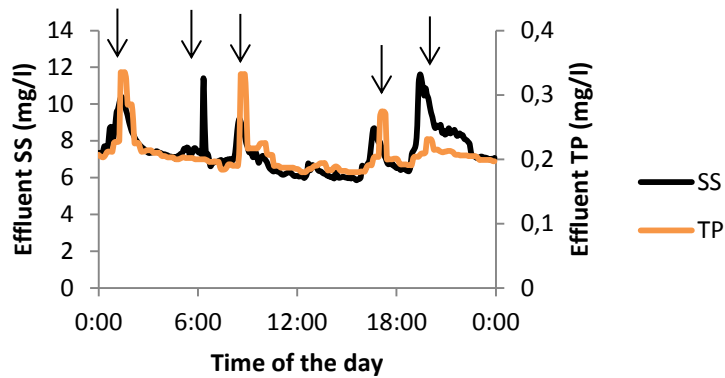


Figure 17. Suspended solid and total phosphorus concentration in the effluent (15.5.2013). Backwash of post-denitrification filters are marked with arrows.

Plant upsets can impair the overall process and reduce purification results. For example during spring 2014, occurred a plant upset, which led to an increase in effluent phosphorus concentration (0.48 mg/l). Low alkalinity, extremely high influent suspended solid concentrations can cause plant upsets. Sometimes these situations can continue for days. With tertiary treatment step, fluctuations in up-stream processes could be eliminated or at least reduced. This would lead to operation that is more reliable. In addition, the suspended solid and phosphorus peaks from post-denitrification filters could also be removed.

One challenge is bypass situations during winter and spring. Fortunately, these occasions are rare in Viikinmäki WWTP. During these peak conditions, water is treated mechanically and chemicals are added before primary sedimentation and discharge (Valtari, 2006; Mattsson *et al.*, 2012). Typically, only one or two pre-sedimentation lines are treated with direct precipitation. Chemical doses are always determined case by case, as the occasions are so rare. In Table 10 are calculated the average results from the samples of bypass situations in 2008, 2010, 2011 and 2012. The bypassed volumes were 0.6, 0.6, 4 and 0.2 Mm³, respectively.

Table 10. An average laboratory results of pre-settled and direct precipitated water during bypass situations in 2008, 2010 and 2012. Sample amount 30.

Analysis	Value (mg/l)
SS	91
TP	2.0
PO ₄ -P	0.6
BOD ₇ -ATU	66

With direct precipitation, it is possible to achieve relatively good reductions in phosphorus and suspended solid concentrations compared with by-passed effluent quality without any additional treatment but the concentrations are still rather high. In the autumn of 2014, ninth treatment line has taken into operation. This will increase the capacity and reduce the need for bypassing. Yet, one goal in this study was to determine the discfilter's ability to treat bypass waters. These results may be applied in the design of Blominmäki WWTP.

7.4 Prior studies in summer 2013

During summer 2013, phosphorus and suspended solids removal was studied with a discfilter pilot (Figure 18). The pilot unit consisted of a coagulation tank (62 dm³) and 2 flocculation tanks, 1.0 and 0.5 m³ respectively. Tanks wear equipped with mixers. From the flocculation tank, water overflowed to the discfilter by gravity. The overall filtration area was 1.8 m².

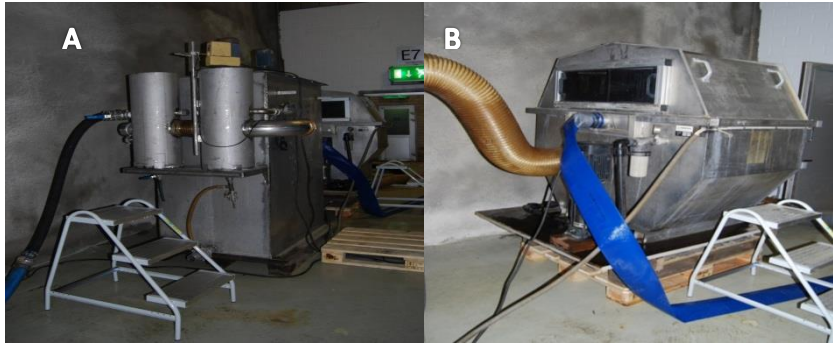


Figure 18. Discfilter pilot unit of summer 2013 prior study. Picture A is from the chemical tanks and picture B from the discfilter.

Trial tests were divided into two stages. At the first stage, mechanical removal capacity without a chemical addition was studied and an appropriate flow for the next stage was determined. At the second stage, purification was enhanced with either coagulant addition (polyaluminium chloride) or with a combination of coagulant and cationic polymer (polyaluminium chloride and Superfloc C492VP).

The results showed that the mechanical removal capacity was insufficient for removing phosphorus and suspended solids to the target limits. The chemical addition improved the removal but precipitation and flocculation did not succeed as wished. The basins were too small to achieve proper coagulation and flocculation times, which led to the formation of a thick precipitate layer on the surface of the basins. Because of the insufficient flocculation time, the chemicals went through the filter and precipitation took place after the filter.

Nevertheless, disc filtration appeared to be a simple and easy technique for removing phosphorus. Therefore, a pilot studies were performed again with a more advanced pilot unit in the study reported in Chapter 8.

8 Materials and methods

The study was divided into two parts, laboratory studies and discfilter pilot scale studies. In the laboratory tests, different chemicals and doses were compared with each other and best ones were chosen for the pilot scale trials.

8.1 Applied chemicals

The following coagulation chemicals and polymers were used in the jar tests. The colored ones were used in the pilot testing (Table 11 and Table 12)

Table 11. The chemicals used in the jar tests. Chemicals used in pilot studies are colored.

Coagulant	C1	C2	C3	C4	C5
Supplier	Kemira Oy	Kemira Oy	Kemira Oy	Kemira Oy	TETRA Chemicals
Concentration (%)	35–45	30–40	35–45	20–30	75–99
Metal content (%)	7.5±0.3 (Al)	9.3 ±0.3 (Al)	11.7±0.5 (Fe)	4.3±0.1 (Al)	(Ca)
Density at 20°C (g/cm ³)	1.30–1.33	1.36–1.42	1.45–1.55	1.32 ±0.02	-
Form	Liquid	Liquid	Liquid	Liquid	Solid

Table 12. The polymers used in jar tests. The one chosen for the pilot test is bolded. All polymers were supplied by Kemira. (A=anionic, C=cationic, N=none, HH=very high, H=high, M= medium, S=solid, L=liquid, E=emulsion). Polymers P10 and P11 were organic and P14 was biopolymer. P16* was used in bypass water jar tests.

polymer type	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16*
Charge	A	C	C	C	C	C	C	C	C	C	C	-	-	-	N	A
Charge density (%)	7	2	5		10	10	20	20	-	-	-	-	-	-	0	27
Relative Molecular weight	H	HH	H	H	HH	H	H	HH		M	M	-	-	-	M	HH
Form	S	S	S	S	S	S	S	S	S	S	L	E	E	-	S	S

8.2 Analytical methods

At the site, the quality of influent and effluent of the pilot wastewater was monitored by online meters and phosphorus cuvette tests. Lab samples were taken approximately twice a week (Table 13).

The pilot plant was equipped with automatic flow meters (Siemens, Sitrans) for pilot influent, effluent and backwash water. Turbidity was measured by a nephelometric scattered light technique (Ultraturb system, HachLange). The measurement range was from 0.00001 to 1000 NTU. There was a possibility for orthophosphate measurement (Phosphax, Hach Lange) but the orthophosphate concentrations were so low in the pilot influent that these results were not taken into account in this study. On site, phosphorus was measured with phosphorus cuvette tests (Hach Lange, LCK 349) (Figure 19)



Figure 19. Phosphorus cuvette tests (Hach Lange, LCK 349).

Twice a week 2 liter grab samples of the pilot influent, effluent and sludge were taken. Both pilot influent and effluent samples were filtered through a 0.45 μm (Whatman) for soluble orthophosphate and metal analysis. All the laboratory assays were done by MetropoliLab. In Table 13 are summarized the used analytical methods. The accuracy of phosphorus cuvette tests was ensured by taking parallel samples with laboratory samples and these results were compared.

Table 13. Methods for wastewater analysis.

Parameter	Laboratory	Measurement uncertainty (%)	On site
Aluminum	SFS-EN ISO 17294-2:2005	25	
Biological oxygen demand (BOD _{ATU-7})	SFS-EN 1899-1 1998	15	
Chemical oxygen demand (COD _{Cr})	ISO 15705:2002	15	
Fecal streptococcus	SFS 3014:1984, [invalidated]	N/A	
Thermotolerant coliform bacteria	SFS 4088:2001	N/A	
Orthophosphate (PO ₄ -P)	SFS 3025:1986 [invalidated]	15	LCK 349 cuvette test
pH	SFS 3021:1979	3	
Suspended solids	SFS-EN 872:2005	10	
Total nitrogen	SFS-EN ISO 11905-1		
Total phosphorus	SFS 3026 mod. DA	15	LCK 349 cuvette test
Turbidity	SFS-EN ISO 7027:2000	15	
Ferrous iron	SFS-EN ISO 11885:2009	20	

8.3 Parameters

8.3.1 Filtration velocity

In order to have pre-knowledge about filtration behavior of the chemically treated wastewater, it is useful to calculate the filtration velocity (V') (equation 3).

$$V' = \frac{V}{t} \quad (3)$$

V' filtration velocity (l/s)

V volume that passes the filter during the test (l)

t time during the test tube disc is submerged

8.3.2 Hydraulic retention time

Hydraulic retention time calculated to ensure adequate flocculation time.

$$HRT = \frac{V_{basin}}{Q'} \quad (4)$$

HRT hydraulic retention time (min)

V_{basin} volume of the flocculation basin (m³)

Q' inflow (m³/h)

8.3.3 Backwash ratio

The backwash percent (BW%) was one of the parameters monitored at the pilot. The BW% describes the capacity of the filter. If BW% is increased, either the load to the filter has increased or the filter is clogged. Under normal conditions, the BW% is 20–50 %. BW% higher than 70 % for sustained periods of time, indicate that the filter cloth is clogged and chemical washing is needed. The BW% was calculated using the equation (5).

$$BW\% = \frac{t_{wash}}{t_{tot}} \cdot 100 \% \quad (5)$$

$BW\%$ backwash percent

t_{wash} wash time (s)

t_{tot} total filtration time, wash+cycle (s)

BW% was manually measured by stopwatch until 5.3.2014. After this, it was possible to collect discfilter operation time from the pilot plant and calculate the BW% from it.

8.4 Influent water quality during trial runs (January-June 2014)

The quality of WWTP effluent water varies between seasons and the variation in the pilot influent quality during pilot trial runs is shown in Figure 20.

During the pilot trials, the average total phosphorus concentration in tertiary treated influent was 0.251 mg/l. The concentration varied between 0.150 and 0.480 mg/l. The $\text{PO}_4\text{-P}$ concentration varied between 0.01 and 0.220 mg/l being on average 0.045 mg/l (the detection limit for phosphate was 0.01 mg/l). The $\text{PO}_4\text{-P:TP}$ ratio in the inflow was on average 0.177. Thus, most of the phosphorus is in the particulate form and possible to remove by mechanical separation. The challenge is to form particles that can be retained by the sieve without overdosing chemicals. Soluble total phosphorus concentrations (TP_{sol}) were measured after 12 May 2014. The average concentration was 0.067 mg/l, varying between 0.046 and 0.100 mg/l. The nonreactive soluble phosphorus concentration was on average 0.022 mg/l, which in theory cannot be brought into particulate form. The average concentrations of SS, $\text{BOD}_7\text{-ATU}$ and COD_{Cr} were 7.4, 6.1 and 47 mg/l, respectively.

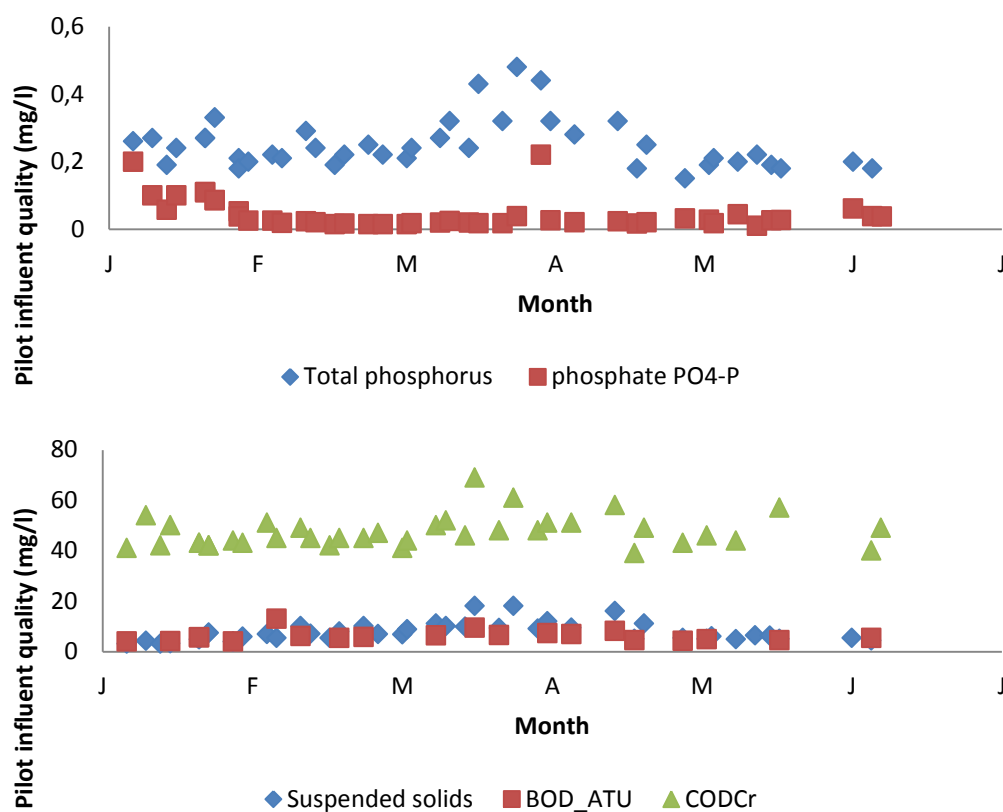


Figure 20. Pilot influent quality variation during trials, from January to June (grab samples, analyzed by Metropolilab).

As Figure 20 shows, there was a plant upset in April that led to increase in phosphorus fractions and in suspended solid concentration. The reason for the plant upset was possibly caused by alkalinity variation in the biological process. Nevertheless, this gave a good opportunity to investigate how the discfilter is able to perform in different conditions.

8.5 Precipitation of phosphorus - jar test and tube test

In all the jar tests, a known amount of chemical product was added to one liter of wastewater and stirred rapidly (400 rpm) for 10 seconds after which the mixture was stirred at 50 rpm for 4 minutes. During fast stirring, the chemical was mixed properly in the water and during slow stirring flocs were formed. If a polymer was employed as a flocculent aid, it was added after the primary precipitation with coagulant. First, the polymer was mixed in the water by stirring at 400 rpm for 10 seconds and then the resulting mixture was slow stirred (50 rpm) for 2 minutes. The formed flocs were visually estimated.

When pH control is performed, the precipitation pH was determined by a converse test. First, a known amount of chemical was added to wastewater after which the pH was adjusted to the wanted level with acid or base. After this in the coagulation tests, the determined amount of acid or base is added before the coagulant.

To get knowledge of the filtration capacity, a tube test was carried out, where coagulated wastewater (1 liter) was filtered through a mini discfilter (Figure 21).



Figure 21. Flocculator, mini discfilters and tube.

In addition, to the filtration velocity total phosphorus and turbidity was measured from water samples and floc formation was observed.

8.5.1 Case 1 – Tertiary treated wastewater from Viikinmäki WWTP

Before pilot trial runs, chemical types and doses were determined by jar tests. The goal was to find and select the right chemicals to achieve total phosphorus concentrations under 0.1 mg/l in the filtered effluent. The wastewater jar tests were done in cooperation with Kemira Oy in Suomenoja.

The previously described jar and tube test procedure was followed. However, the slow stirring time for coagulant was 10 minutes. The water was filtered through 18 µm mini discfilter.

Five different coagulants (Table 11) and 13 different polymers were tested (Table 12). Coagulation conditions such as pH, coagulant and polymer dosages were varied. The pH adjustment was done by either sulfuric acid (H_2SO_4 , 30%) or sodium hydroxide (NaOH, 10 %).

The added coagulant doses were relatively high because it was not known at that time that the recommended maximum chemical addition to the pilot is 4 mg Me^{3+} /l. All the different coagulants, polymers and dose combinations are gathered in Tables 1–6 in Appendix 1.

From wastewater samples, total phosphorous and soluble total phosphorus were analyzed by phosphorus cuvette tests and turbidity. The aluminum content was analyzed, from selected samples by Kemira Oy's laboratory.

8.5.2 Case 2 - Pre-sedimented bypass water

One objective of this study was to find out the feasibility of the discfilter in the treatment of bypass waters. During the jar tests, actual bypass water was not available so mechanically treated and primary settled wastewater was used instead.

These jar tests can be divided into two parts, with and without direct precipitation of pre-settled water. When direct precipitation was employed, the wastewater was treated like in the bypass situation according to Valtari (2006) with C2 and Magnafloc 1011. Before secondary coagulation and flocculation, the biggest flocs were led to settle. After this, coagulation and flocculation and filtration with pore size 18 µm were performed to the resulted mixture.

In the other part, the pre-settled wastewater was treated without direct precipitation. Only coagulation, flocculation and filtration was employed. Chemicals used prior to the filtration were C2 and P6 and pore size of the mini disc was 18 µm. In Table 1 in Appendix 2 are presented the tested chemical doses.

Magnafloc solution (1 g/l) was prepared by mixing 0.1018 g of Magnafloc powder in 100 ml of water. The maturation time was one hour as it is in full-scale. Polymer P6 (0.1 %) was taken from the pilot plant. C2 was used as coagulant.

Total phosphorus and suspended solid concentrations from samples were analyzed by Metropolilab.

8.6 Discfilter pilot unit

The discfilter pilot unit was supplied by Hydrotech and the pilot was installed at the Viikinmäki WWTP in mid-January 2014. Pilot runs lasted until the end of June 2014.

8.6.1 General construction

The pilot was set in two 6.06 x 2.44 x 2.59 m sea containers (Figure 22). The first container contained the chemical dosing unit and the polymer preparation station and the second contained the coagulation and flocculation basins as well as the discfilter unit. The influent for the treatment was pumped from the WWTP's effluent canal after biological de-nitrification filter and the effluent from the discfilter was discharged to the same canal after the feed pump (Figure 1, Appendix 3).



Figure 22. Discfilter pilot in Viikinmäki WWTP.

The chemical solution was pumped by Grundfos DDA membrane pump (Figure 23 A) to the influent flow prior to a static mixer. The volume of the coagulation tank was 580 dm³ and the prepared polymer solution was pumped (Grundfos DME) (Figure 23 A) to this tank before it flowed to the flocculation tank (780 dm³). Both basins were equipped with impellers. HRTs in the basins were 1.7 and 2.3 minutes if the flow was 20 m³/h. The pilot was designed for flows between 10 and 30 m³/h.

The polymer solution was prepared with an automatic polymer preparation unit (TOMAL Polyrex 0.6). The unit contained two 200 dm³ tanks, one for preparation and one for storing. The polymer solution was prepared automatically by mixing adequate amounts of water and polymer powder together. The concentration of the prepared stock solution was 1 g/l and it was matured for 50 minutes before it was transferred to the storage basin. A new polymer batch was automatically made when the level of the solution in the upper preparation basin dropped under 8 cm. (Figure 23). Figure 24 shows the flow chart of the process.



Figure 23. A) The chemical pumps at the pilot plant. On the left is the polymer pump and on the right is the coagulant pump. B) Polymer preparation unit. Upper basin is for preparation and the lower for storing.

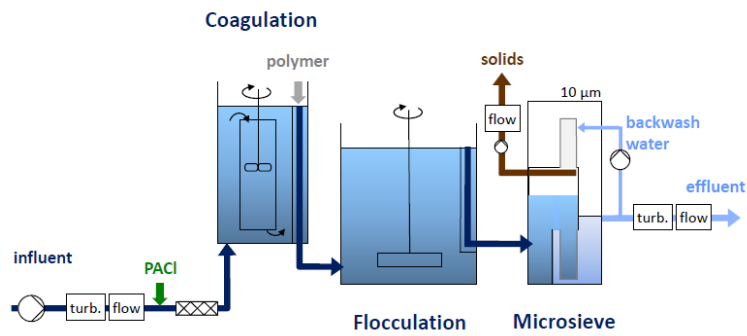


Figure 24. Flow chart of the pilot plant (Hydrotech).

8.6.2 Discfilter unit

The discfilter was a Hydrotech HSF 1702 -1F and consisted of two discs and one disc composed of 24 filter panels (Figure 25). The diameter of one disc was 1.7 m and the overall filtration area 5.76 m². Pore size could be either 10 or 20 μm.



Figure 25. A 20 μm disc panel.

The backwash of the discs was initiated when the water level in the central drum reached a level sensor and discs rotated until the water level stopped touching the sensor. Filtered discfilter effluent was sprayed with high pressure (8 bars) in order to

detach the solids from the filter. The wash water was collected into a sludge container (140 dm³). The basin was emptied when the sludge level met a level sensor and the sludge was pumped back to the effluent canal.

A chemical cleaning of the discs was performed always between different trial runs. The discs were washed with 10 % hydrogen chloride (HCl) and 5 % sodium hypochlorite (NaOCl).

8.7 Trial planning

Different trial runs were conducted with the described pilot unit to get information about the performance of the discfilter (Figure 26). Performance with and without chemicals was tested. In addition, two different pore sizes (10 and 20 µm) were compared. The goal was to achieve 0.1 mg/l total phosphorus concentrations in the pilot effluent.

At the pilot, quality of wastewater was monitored by online turbidity measurement and HachLanges phosphorus cuvette tests. Grab samples were collected for laboratory analysis.

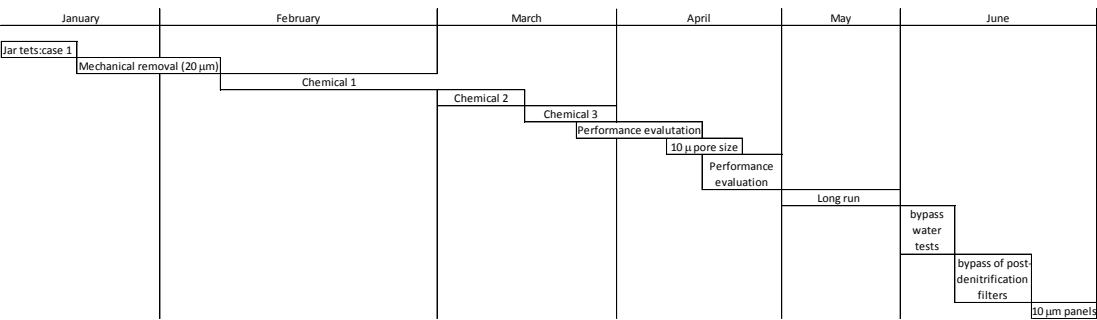


Figure 26. Trial plan from January to June 2014.

8.7.1 Mechanical removal and chemical addition

First, the mechanical removal was tested with two different pore sizes, 10 and 20 μm . Second, three different coagulants with a polymer addition (Table 11 and Table 12) were tested and compared. 10 μm pore size with chemical addition was also tested. The aim was to achieve high removals of phosphorus, suspended solids and turbidity with low and optimized chemical additions.

8.7.2 Performance evaluation

On the site, the performance of the pilot was evaluated by its ability to remove turbidity and phosphorus. In addition, laboratory tests were taken twice a week. BW% and the condition of filter panels were monitored online.

8.7.3 Performance evaluation and long run

After the most suitable chemical combination and doses were determined, the long term performance of the discfilter was monitored during longer filter run with a 20 μm cloth. Constant coagulant and polymer dose concentrations and a daily flow pattern was conducted in order to get knowledge on, how the discfilter perform during longer operation. The daily flow pattern is shown in Figure 27. Coagulant (C2) dosing was 2 mg/l and polymer 1 mg/l.

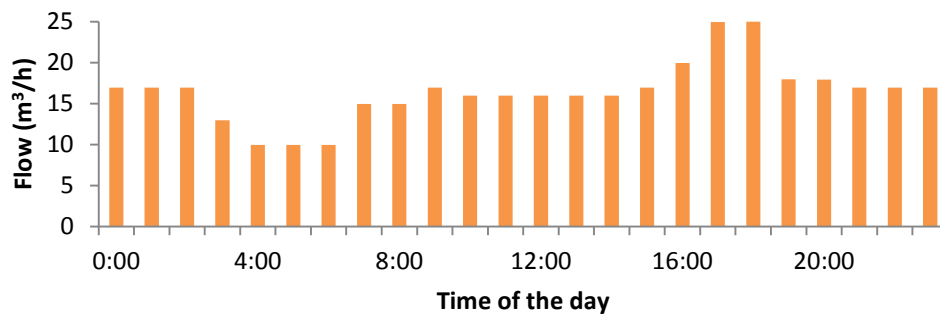


Figure 27. Daily flow pattern of the pilot.

The daily flow pattern depicted more high inflow occasions than a regular day flow at the Viikiniemi WWTP. Filtrate quality, backwash percentage, backwash water pressure and disc panel condition were monitored.

8.7.4 Treatment of secondary settled wastewater

The post-denitrification filters are rather uncommon in WWTPs in Finland. To get information about the discfilter performance for other treatment plants, post-denitrification filters were bypassed for eight hours. One hypothesis was that the mechanical removal would be higher because the suspended solid concentration should be higher as there is no prior filtration process. Both mechanical removal and chemical additions were tested with pore size 20 µm (Table 14).

Table 14. Used chemical additions when bypassing of the biological filter was studied.

Al³⁺ dose	P6 dose
mg/l	mg/l
0	0
0,5	1
2	1
3	1
1	1.5

The goal was to achieve under 0.1 mg /l total phosphorus concentrations in the pilot effluent.

8.7.5 Bypass simulation

Discfilter's ability to treat bypass water was tested. Because there were no actual bypass situations during the spring, one was simulated. Inflow of the mechanically treated wastewater was treated like in a bypass situation by direct precipitation, adding PAX-14 and Magnafloc polymer. Treatment was performed to one Before the pilot start-up, primary water was direct precipitated in one of the pre-sedimentation basins of Viikinmäki WWTP. The goal was to achieve SS under 60 mg/l concentration (Valtari, 2006). PAX 14 addition was approximately 39.9 ml PAX-14/m³. The polymer concentration was increased from 1.0 to 1.5 and to the final concentration of 2 ppm. After approximately six hours of direct precipitation, the pilot was started. The inflow to the discfilter was 10 m³/h and the pore size 20 µm. The tested chemical doses are shown in Table 15.

Table 15. Tested chemical doses during the bypass trial run.

Al³⁺ dose	Polymer
mg/l	mg/l
2.0	1.0
1.0	2.0
2.0	2.0
3.5	2.0

Only a few doses were tested as the pilot scale trial could be carried out only for one day because the volume of bypassed water was large and it would have decreased the purification result.

9 Results and discussion

The goal in this study was to reduce the effluent total phosphorus concentration from the present 0.23 mg/l to 0.1 mg/l with disc filtration. Different chemicals and trial runs were performed. All the removal results considered in the following chapters are from the tertiary treatment.

9.1 Chemical combination comparison

9.1.1 Case 1 - Wastewater

Five different coagulants and 14 different polymers (Table 11 and Table 12) were tested at Kemira Oy laboratory in Suomenoja. Altogether, over 50 combinations were tested and samples were filtered through 20 µm pore size (Tables 1–6, Appendix 1). One of the five coagulants was iron based and the rest were aluminum based. The

tested concentrations were substantially higher than recommended for use at the pilot. For iron, the recommended maximum dose at the pilot was 8 mg Fe³⁺ /l and for aluminum 4 mg Al³⁺/l. Overdosing of the chemicals can potentially lower the capacity of the cloth (Ljunggren *et al.*, 2005). However, a few metal concentrations fitted to this concentration range. During the jar tests, effluent wastewater total phosphorus concentration was 0.23 mg/l on average.

The main objective of these jar tests was to determine the best coagulants for pilot testing. Factors such as total phosphorus, soluble phosphorus, turbidity and filterability were measured. In addition, the formed flocs were visually evaluated (Figure 28). Total phosphorus removal had the biggest importance, as it was the main goal in this study. Turbidity measurement indicates whether the floc formation has been sufficient because if the filtrate turbidity is higher than the influent, it indicates that formed flocs have been too small or fragile and they have passed through the filter.



Figure 28. Flocs formed by C2 (50 mg/l) and P6 (2 mg/l) (Laura Sundell, 2014).

The first thing was to investigate if a polymer addition was needed. Figure 29 shows that the polymer addition enhanced the removal. From Tables 1–5 in Appendix 1 can

be seen that under 0.1 mg TP/l concentrations were not possible to achieve without a polymer addition. However, the polymer concentration did not make a significant difference to the phosphorus removal (Figure 29). In all cases, when only coagulant was used the filtrate turbidity and filtration velocity were high as the floc formation was inadequate and small flocs passed the filter (Tables 1–5, Appendix 1).

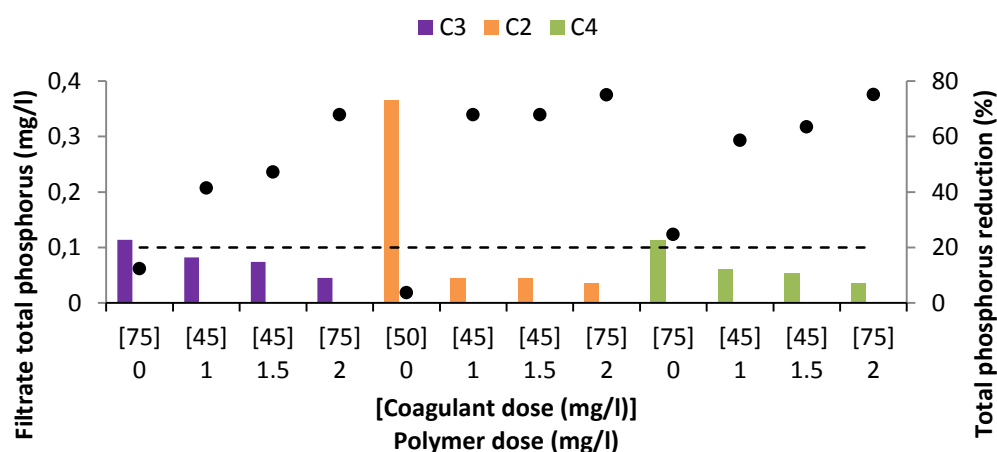


Figure 29. The effect of polymer (P6) concentration on the phosphorus removal in filtrated wastewater. The 0.1 mg/l total phosphorus concentration is marked with dashed line. See also Tables 1–5 in Appendix 1.

The impact of pH was also tested and as can be seen in Figure 30, pH adjustment improved phosphorus removal (Appendix 1, Tables 2–5). The optimum pH for iron and aluminum coagulants was near 5 and 6, respectively. These results were concordant with the coagulation theory (Isoaho and Valve, 1986; Bratby, 2006). pH control in a full-scale application is not reasonable as process costs rise and process operation becomes more complicated. In addition, the results show (Tables 2–6, Appendix 1,)

that target total phosphorus concentrations are possible to achieve without pH control.

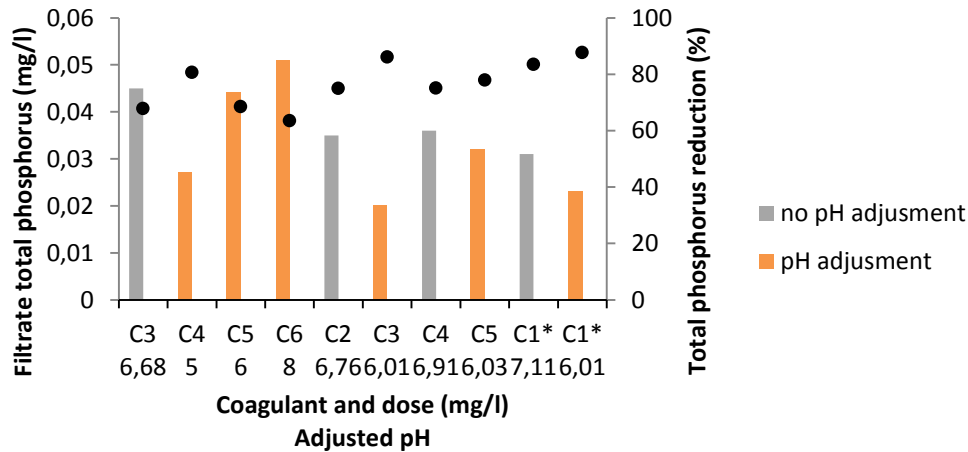


Figure 30. Effect of pH adjustment. Coagulant dose was 75 mg/l and polymer 2.0 mg/l except with C1* where coagulant concentration was 45 mg/l and polymer concentration 1.5 mg/l.

Furthermore, different polymers (Table 12) with C2 were tested. Figure 1 and Table 6 in Appendix 1 show that the best results are obtained with cationic polymers. The reductions varied from 76 % to 89 % (Table 6 and Figure 1 in Appendix 1). Organic, emulsion and nonionic polymers did not perform as well as the cationic ones and phosphorus reductions were between 50 to 58 % (Table 6, Appendix 1). The charge density is higher in the solid polymers, which can be one reason why they performed better than emulsions. There was not that much of a difference between the performances of cationic inorganic polymers. The best removal was achieved with P9. However, P6, which also performed very well, was chosen for pilot tests because it is already used in sludge conditioning at the Viikinmäki WWTP.

Coagulants C1, C2, C3 and C4 were compared based on total phosphorus concentration and removal, filterability and turbidity removal. The results are gathered to Figures 1–4 in Appendix 4 and in Tables 1–5 in Appendix 1. Compared with aluminum based coagulants, C3 performed the poorest, even though, total phosphorus concentrations in the filtrated water were still under 0.1 mg/l with polymer concentrations from 0 to 2 mg/l. However, the added coagulant doses were high and these kinds of additions are not realistic in full-scale applications because of the excess sludge formation and filter capacity reduction. In addition, the process costs may rise too high. The lowest aluminum additions (2.79 and 2.3 mg Al³⁺/l) resulted in 0.04 mg/l total phosphorus concentrations in the filtered effluent. Thus, it could be assumed that with even lower coagulant concentrations under 0.1 mg/l total phosphorus concentrations could be achieved.

From aluminum-based coagulants, C1 and C2 gave the best results almost with every parameter (Figures 1–4 in Appendix 4). Only filterability was better with C4 but as mentioned before, the tube test only gives some insight how the chemical would work in real application. Because aluminum is hazardous for aquatic life, residual aluminum concentrations were also analyzed from certain samples. Results are shown in Table 16.

Table 16. Aluminum concentrations in the filtered water.

Coagulant Type	mg Me ³⁺ /l	Polymer dose mg/l	Al ³⁺ in the filtrate mg/l	pH after precipitation
C1	5.6	0	0.92	7.03
C2	7	0	4.2	6.96
C1	2.3	1.5	0.20	7.15
C2	2.79	1.5	0.24	6.96
C1	5.6	2	<0.1	6.01
C2	7	2	0.91	6.76

Metal concentrations in the filtrate were smaller with C1 compared with C2. C2 product contains aluminum 9.3 % when C1 contains 7.5 % so this is one explanation for the lower metal concentrations with C1. However, as mentioned in the beginning, the tested chemical doses were higher than necessary. Only metal concentrations of 2.3 and 2.79 would be feasible at the pilot conditions. Low pH (4.5) enhances the bad side effects of aluminum. As from Table 16 can be seen the pH of filtrate was in the neutral range.

Calcium based coagulant (C5) was tested and the results were positive. Calcium is cheap and unlike aluminum, it is not toxic to aquatic animals. The drawback is calcium dosage, which is relatively high so the sludge formation might increase too much. C5 and polymer did not remove phosphorus as efficiently as other tested chemicals. In jar tests, wastewater was treated with a combination of C5 and C2 and polymer P6. Results are summarized in Figure 31.

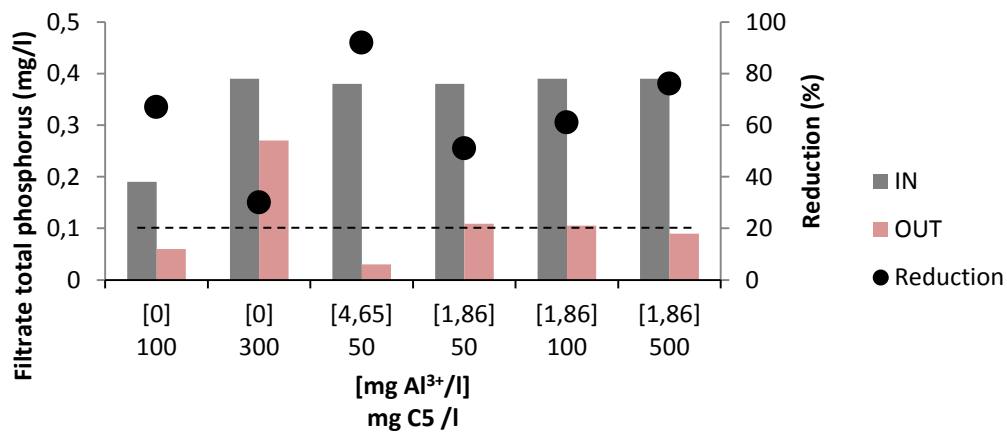


Figure 31. The effect of calcium based coagulant on phosphorus removal. Addition of an aluminum based coagulant (C2) was added to enhance the removal. Cationic polymer (P6) addition was 2 mg/l. 0.1 mg/l total phosphorus limit is marked with dash line.

Results show that increasing C5 concentration did not improve the phosphorus removal. For efficient precipitation with calcium, high pH and alkalinity are preferred. In jar tests, alkalinity was not measured and pH was not controlled. Removals increased when aluminum based coagulant was added. The results were not that much better compared with the ones without calcium. Based on these facts, C5 was not tested at the pilot. In addition, preparation and the addition of calcium to the pilot plant was considered complicated.

From these jar tests, coagulants C1, C2 and C3 were chosen for pilot trial tests. Although C3 did not perform as well as the other two coagulants, it was chosen for the trial runs so that the performance could be investigated in a larger scale.

9.1.2 Case 2 - Bypass water

To get pre-knowledge of the discfilter's ability to treat bypass water, jar tests were performed. In Table 17 are gathered the results from these jar tests with pore size 20 μm . The chemical doses used in these tests are presented in Table 1 in Appendix 2.

Table 17. Results from bypass jar tests. Influent total phosphorus and suspended solid concentrations are analyzed from pre-settled wastewater

Sample code	TP (mg/l)			TSS (mg/l)			Filtrate l/s
	In	out	Red %	In	Out	Red %	
Direct precipitation & secondary precipitation & discfiltration	2.4	0.065	97	94	8.7	91	0.032
Precipitation & discfiltration	2.4	0.43	82	94	19	80	0.020
	2.4	0.79	67	94	47	50	0.021

Compared with the real bypass situations (Table 10) the SS and TP concentrations in the primary settled wastewater are almost the same. Thus, the water to be treated with the discfilter depicts the real situation rather well. However, the particle size distribution can be different in a real event and it can affect the filtration capacity.

Figure 32 shows that floc formation was good. The jar test results indicates that with the combination of direct precipitation in the main stream and pre-coagulation and disc filtration, it is possible to reduce the total phosphorus concentration under 0.1 mg/l and suspended solid concentration under 10 mg/l. Filtration velocity was higher if direct precipitation was performed.



Figure 32. Floc formation during direct precipitation of pre-sedimented water (left) and during secondary precipitation.

Additionally, without direct precipitation, good phosphorus and suspended solid removals were possible to achieve, higher the coagulant dose, the better the removal of phosphorus. However, in order to achieve under 0.3 mg/l total phosphorus concentrations with this combination, the coagulant and flocculant doses should be increased.

Based on these result, it was decided to try bypass simulation at the pilot with direct precipitated wastewater.

9.2 Performance of the discfilter pilot

Filter performance was evaluated by the analysis of total phosphorus, suspended solids and turbidity. Jar test results were taken as an indicator on how much chemicals have to be added to the pilot. In the full-scale piloting, it was soon realized that the needed coagulant dose was much less, than the jar test results indicated.

9.2.1 Mechanical removal capacity tests

The mechanical removal capacity of the discfilter was studied with pore sizes 10 μm and 20 μm . The best optimum situation would be that chemicals are not required to remove phosphorus and suspended solids to the target limit because it would lower operational costs and the sludge formation would be lower. Furthermore, no trace elements are produced. The average total phosphorus, orthophosphate and suspended solid concentrations and removals from these runs are collected in Table 18. The inflow during 20 μm was 25 m^3/h and the test trial lasted 28 days. The 10 μm tests took 2 days and the flow was 20 m^3/h .

Table 18. Laboratory results from mechanical removal tests with 10 and 20 μm pore sizes. Results are average. Sample amount 20 μm =8 pcs and 10 μm =1 pcs.

Pore size μm	Total phosphorus (mg/l)			Orthophosphate (mg/l)			Influent P- PO_4 /TP	Suspended solids (mg/l)		
	In	Out	Red %	In	Out	Red %		In	Out	Red %
20	0.26	0.25	4	0.109	0.111	-2	0.42	4.27	3.08	26
10	0.43	0.26	40	0.018	0.017	6	0.04	18	8	56

As the laboratory results show (Table 18), the influent quality varied much between these test runs. Total phosphorus removal was ten times higher with 10 μm than with 20 μm . However, only one laboratory sample test set was taken from 10 μm pore size tests because it was soon noticed that the mechanical removal is not sufficient in achieving 0.1 mg/l total phosphorus concentration in the pilot effluent. One reason to the more efficient removal by 10 μm is the smaller pore size. Another reason is that during 10 μm tests, most of the phosphorus was in the particulate form (small $\text{PO}_4\text{-P/TP}$ ratio). In both cases, orthophosphate removal was minimal because no chemicals were added. Compared with the study performed in Ryya WWTP, the mechanical removal was not as sufficient in Viikinmäki (Behzadrad, 2010; Nunes *et al.*, 2013).

On-line turbidity measurements of mechanical removal tests showed that turbidity decrease was insignificant (Figure 33) and the pilot influent turbidity influenced the pilot effluent turbidity. High turbidity peaks in the pilot effluent water may be result of turbidity meter cleaning or suspended solids have escaped from the panel. The pilot influent turbidity was on average 2.7 NTU and 10.2 NTU with 20 and 10 μm , respectively. The average removals were 4 % and 32 % with pore sizes 20 and 10 μm , respectively. Visually, it was seen that disc panels turned darker over the time (Figure 34).

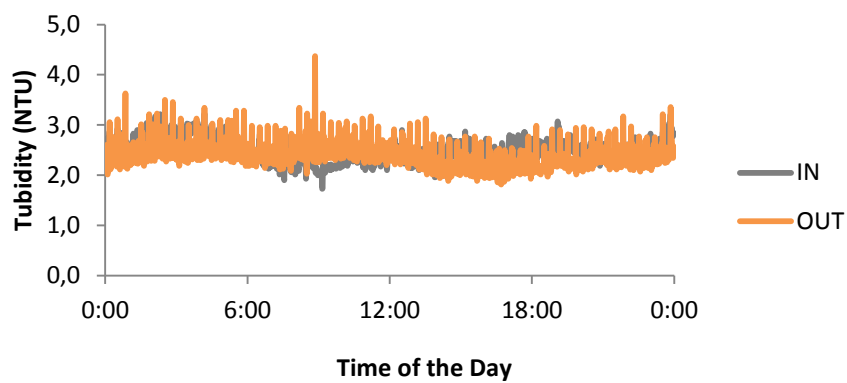


Figure 33. Online turbidity measurement at the pilot from 20 μ m mechanical removal tests. Average from 7 day run (4.2.2014–10.2.2014).



Figure 34. Discfilter discs, 20 μ m (31.1., 4.2, 12.2 and 17.2 (chemically cleaned panel is marked with an arrow))

BW% during 20 μ m tests was on average 6 % and increased from 3 % to 9 % in 28 days. The BW% was 38 % when 10 μ m was tested. The BW% for 20 μ m was measured manually as against with 10 μ m the result is calculated from the data that the pilot plant collected.

Removals with 10 μm were much better than with 20 μm but on the other hand the hydraulic capacity is smaller (ie. higher BW%). What can be concluded, is that mechanical removals are better if influent SS concentration is higher. Then there are bigger particles to be retained by the filter and the formed sludge cake inside the panels can enhance the removal.

Conclusion from these tests was that neither of the pore sizes was able to produce effluent with a phosphorus concentration under 0.1 mg/l. Thus, the chemical addition is mandatory.

9.2.2 Removal capacity tests with chemical addition

Three different coagulants (C1, C2 and C3) together with a cationic polymer (P6) were tested to improve phosphorus, SS and turbidity removals. Dose response tests were carried out to find out the proper doses to meet the total phosphorus limit of under 0.1 mg/l with every chemical. Inflow to the filter was 20 m^3/h during C2 and C3 tests and 25 m^3/h during C1 tests. Pore size was 20 μm and tests took 37 days.

All the tested coagulant and polymer combinations are collected in Tables 1–3 in Appendix 5. In all cases, the needed chemical amount was much less than was determined in the jar tests. Usually, jar tests depict the real situation quite well but in this study, the coagulant concentrations in the jar tests were too high thus the test did not give

As mentioned in Chapter 3.3.2, the higher the influent phosphorus concentration, the lower is the ratio between added metal and removed phosphorus (Bratby, 2006). This was noticed at the pilot tests as well (Figure 35). With iron, the ratio between added metal and removed phosphorus is higher than with aluminum.

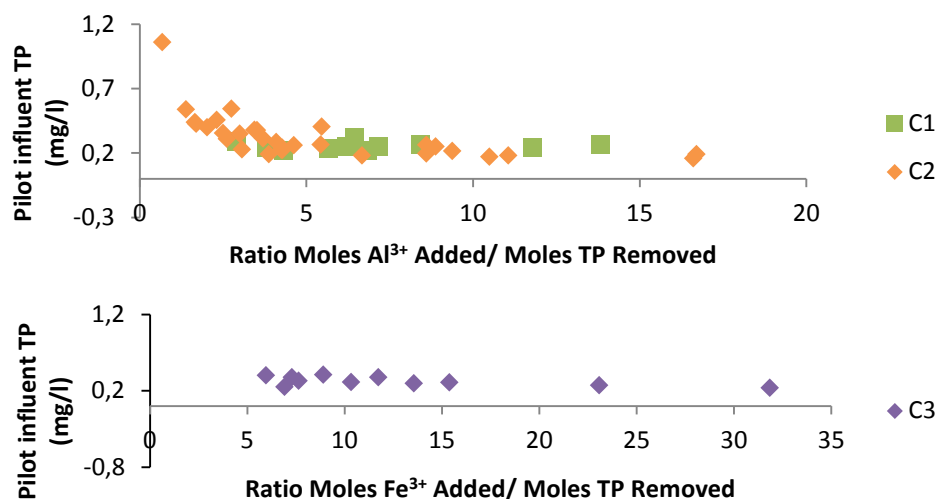


Figure 35. The smaller the influent phosphorus concentration to the pilot, the larger the ratio between added metal and removed phosphorus.

The performance of C1 and C2 was alike (Tables 1 and 2, Appendix 5). However, reductions were slightly better with C1 (Figure 36 and Figure 37). One reason for the better performance with C1 might be that the basicity of the product is 40 % as against with C2 it is 43%. Usually, lower the basicity, better the phosphorus removal as metal is not consumed to produce metal hydroxides (Gillberg *et al.*, 2003; Bratby, 2006; Liu *et al.*, 2013). C3 did not perform as well as the other two (Figure 38 and Table 3 in Appendix 5). The needed metal amount was higher and removals were lower than with aluminum coagulants. Furthermore, iron colored the filter panels but the BW% was lower. Coloring of the panels was noticed with pilot tests in Ruhleben WWTP and this reduced the transmittance of UV lamps in the hygienization step (Langer *et al.*, 2013). The polymer addition had to be higher with iron to produce flocs that could be retained by the filter. In all cases, the response to chemical addition was fast and it could be visually seen that when chemical concentrations were increased the floc size increased.

Results from dose response tests with the three different coagulants are gathered to figures below (Figure 36, Figure 37 and Figure 38).

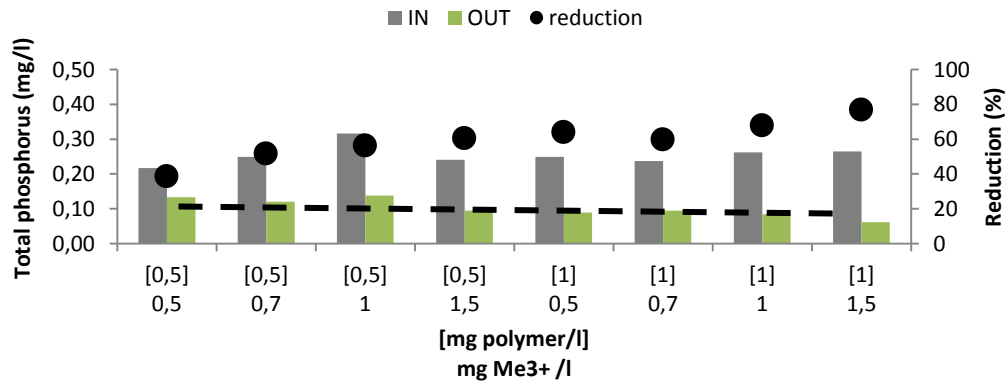


Figure 36. The effect of coagulant (C1) and polymer (P6) concentrations on the phosphorus removal by discfilter. Dash line represents the 0.1 mg/l total phosphorus limit.

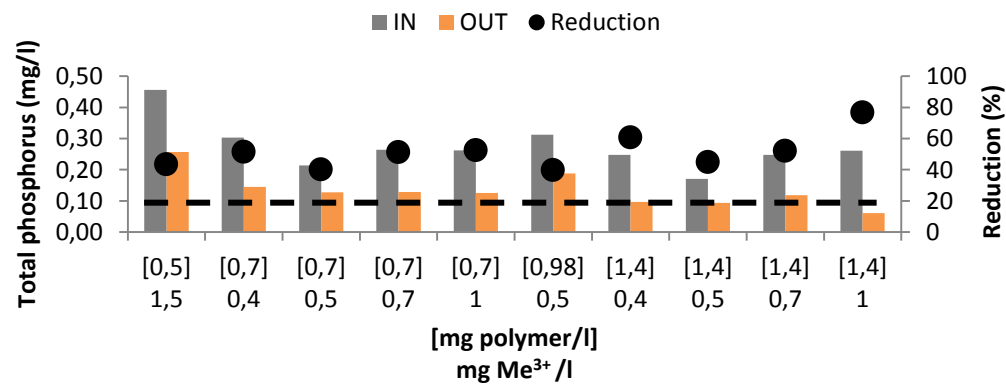


Figure 37. The effect of coagulant (C2) and polymer (P6) on the phosphorus removal by discfilter. Dash line represents the 0.1 mg/l total phosphorus limit.

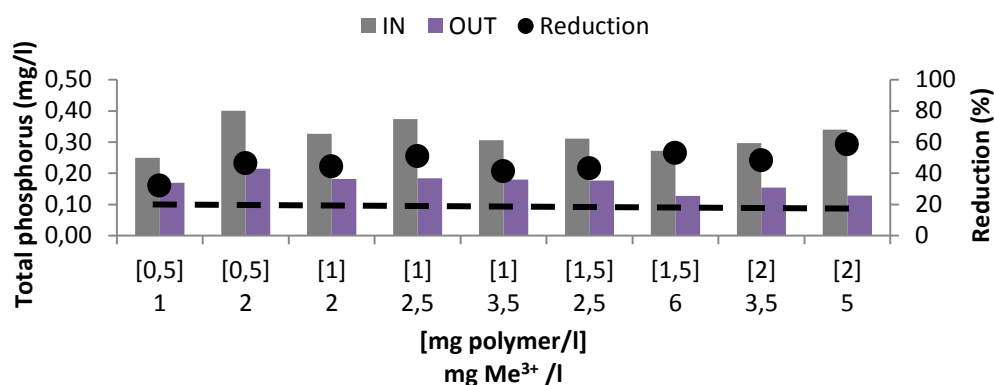


Figure 38. The effect of coagulant (C3) and polymer (P6) on the phosphorus removal by discfilter. Dash line represents the 0.1 mg/l total phosphorus limit.

The chemical addition improved phosphorus removal. These results confirm the same as the jar tests. The best phosphorus removals were achieved with C1 and C2 and the poorest with C3. The difference between C1 and C2 was not significant. In both cases, the optimum aluminum dose was 0.5–1 mg/l and polymer dose 1 mg/l. This is slightly lower than determined in discfilter pilot studies in Ruhleben WWTP and Sjölanda WWTP (Table 7). C3 dose should be 5 mg/l with the polymer (P6) concentration of 2 mg/l. Compared with Clinton WWTP, the dose is higher. However, in their study the cloth pore size was 10 μm which may have enhanced the removal. In this study, the average suspended solids removal was 52 %. The metal concentration of product C2 is higher which is why the product addition is smaller and chemical costs become lower. In addition, the turbidity removal was slightly better with C2. From these results, it was decided that aluminum based coagulant C2 was used in the following tests.

9.3 Performance

Performed chemical runs proved that the discfilter is able to produce consistently a low turbidity effluent. As Figure 39 shows, turbidity peaks caused by the backwash of

the biological filter cells were removed. Compared with mechanical removal, the influent turbidity did not affect significantly to the pilot effluent turbidity. Based on the laboratory tests, the suspended solids removal was on average 52 % if the coagulant and polymer doses were 0.5–1.0 mg Al^{3+} /l and 1.0 mg/l, respectively.

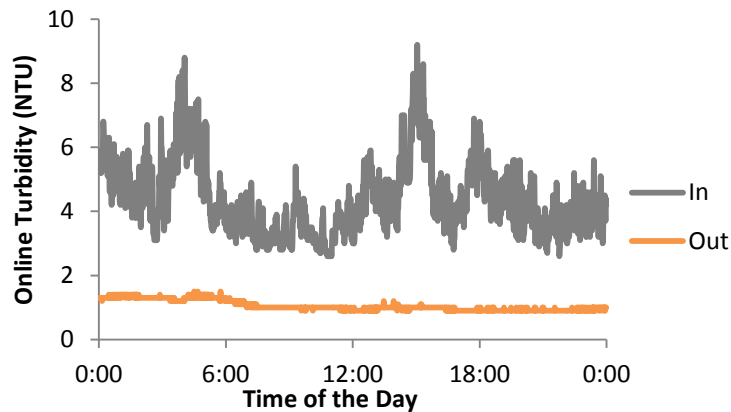


Figure 39. Online turbidity measurement of the pilot influent and effluent. Al^{3+} =0.5 mg/l (C2) and polymer (P6) 1.0 mg/l (1.3.2014).

The pore size of 10 μm was tested with C2 and P6 and removals were compared with pore size 20 μm (Figures 1–4, Appendix 6). In theory, the removal should have been better with smaller pore size but on the other hand, hydraulic capacity is lower. As the Figure 1 in Appendix 6 show, 20 μm pore size removed phosphorus slightly better. Thus, it was decided that rest of the tests are performed with 20 μm pore size.

Inflow did not have significant effect on phosphorus removal (Figure 40) which was also concluded by Hart *et al.* (2012). Thus, the HRT for flocculation was adequate.

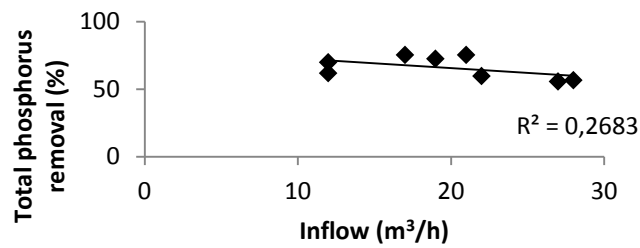


Figure 40. The effect of inflow (m³/h) to the phosphorus removal. Coagulant C2 addition was 2.0 mg Al³⁺/l and polymer addition (P6) 1.0 mg/l.

Overall, the filter was able to produce effluent of wanted quality with relatively low chemical consumptions and the response to chemical dose adjustment was fast.

9.4 Long run

In order to get better knowledge of the discfilter performance, a longer trial run was carried out with pore size 20 µm. The trial lasted 24 days and parameters such as BW% and removal efficiencies of turbidity, phosphorus were monitored. The coagulant and flocculant concentrations were kept constant. C2 addition was 2 mg/l and polymer (P6) addition 1 mg/l. Coagulant dose had to be increased to 2 mg Me³⁺/l because the inflow quality had changed and bigger doses were demanded for achieving the 0.1 mg/l total phosphorus concentration in the pilot effluent. In Table 19 shows the influent quality during long run.

Table 19. Pilot influent quality during long run (laboratory results).

Parameter	Concentration		
	Average	Max	Min
Total phosphorus (mg/l)	0.214	0.320	0.150
Total soluble phosphorus (mg/l)	0.060	0.064	0.047
Orthophosphate (PO ₄ -P) (mg/l)	0.026	0.044	0.017
Suspended solids (mg/l)	7.59	16	4.8
Turbidity (FNU)	3.93	6.8	2.1

The online turbidity measurements showed that the average influent turbidity at the pilot was 6.7 NTU varying between 3.3 NTU and 12.2 NTU. The pilot effluent turbidity was on average 2.1 NTU varying between 1.2 NTU and 3.7 NTU, resulting in 63 % average turbidity removal. Thus, the filter was able to remove the high turbidity peaks that resulted from the flow pattern and washing of the post-denitrification filters (Figure 41).

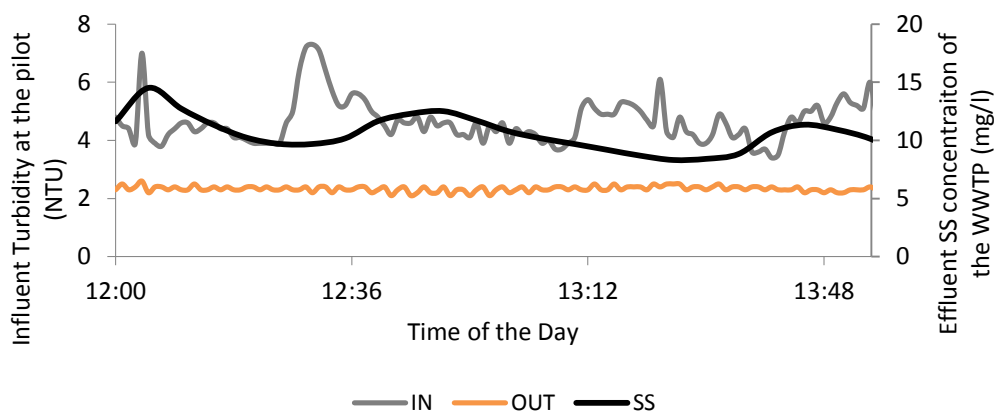


Figure 41. Example of online turbidity measurement from influent and effluent of the pilot plant and online suspended solid measurement of the WWTP effluent during the long run (20.5.2014).

After 13 days of long run, the quality of influent water turned better as the SS concentration decreased (Table 1 in Appendix 7). This resulted in an overdosing of chemicals, which could be seen as suspended solid increase in the pilot effluent. The total phosphorus concentration in the pilot effluent varied between 0.06 and 0.09 mg/l, being on average 0.08 mg/l. Pilot effluent orthophosphate concentration varied between 0.004 and 0.007 mg/l, resulting in 78 % removal. During the first two weeks of long trial run when chemical addition was adequate, the suspended solids removal was on average 34 % and the pilot effluent varied between 9.8 mg/l and 4.3 mg/l. All the results from the long run are collected in Tables 1 and 2 in Appendix 7.

Figure 42 shows that the BW% correlates well with the inflow. The same was observed at Ruhleben (Langer *et al.*, 2013). They concluded that the dynamic of the backwash changed with advancing operation time and progressing fouling (Langer *et al.*, 2013). However, unlike in Ruhleben, the BW% decreased during the trial run as the inflow water quality got better. This indicated that the discfilter was able to recover from plant upsets without irreversible clogging. The average BW% was 45 % varying between 33% and 59 %.

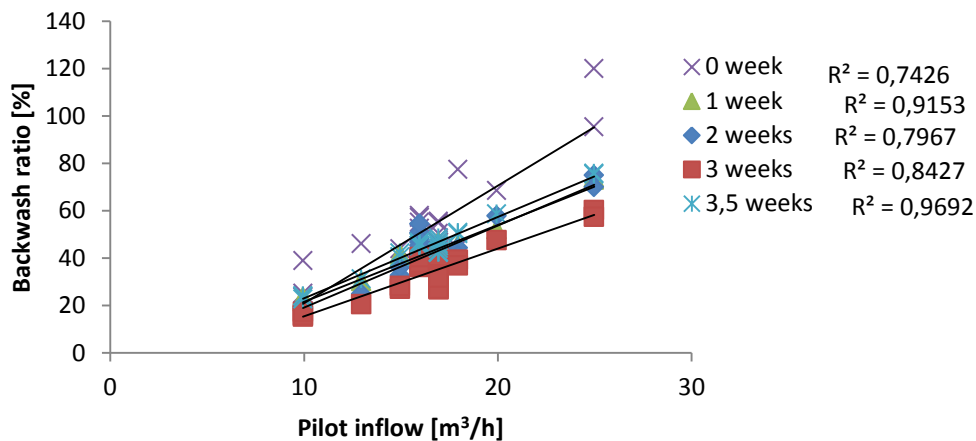


Figure 42. Back wash times as a function of inflow and the operating time. The chemical addition was 2.0 mg Al³⁺/l and 1.0 mg polymer/l.

In addition, it was observed that influent turbidity ie. the suspended solid concentration affected on BW%. The higher the load to the filter, higher the BW%.

During the long trial run, panels turned to brown and the backwash water strainer was slightly clogged (Figure 43). This was noticed as the backwash water pressure had dropped from 8 bars to 7.4 bars. Langer *et al.* (2013) had noticed the same effect. Backwash strainer should be checked once in two weeks. Furthermore, the backwash nozzles were somewhat dirty after 24 days, which means that they should be checked occasionally, once a month, for example (Figure 43). However, no uneven spraying was noticed. Because the long run lasted only 24 days, it is hard to determine how long it would take pores to be irreversibly clogged.

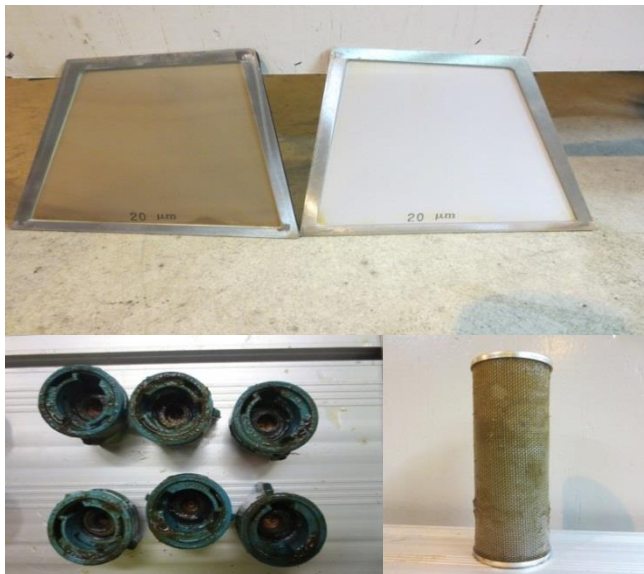


Figure 43. Panels after 24 days trial (up&left) and after cleaning (up&right). Backwash nozzles (down&left) and backwash water strainer (down&right) after trial run.

Because of the influent water quality and limited time, it was not possible to conduct a long run, which would have resulted in a BW% of 80 %. Thus, only an assumption on, how often the chemical cleaning should be performed can be made.

9.5 Treatment of secondary settled wastewater

Biological post-denitrification filters are not that common in WWTPs in Finland. Therefore, the biological post-denitrification filters were bypassed for 6 hours to get information on the discfilter operation with typical WWTP effluent. One interesting object was to find out, if the suspended solids removal percentage is better when the biological filters are bypassed. The analysis results are collected in Tables 1, 2 and 3 in Appendix 8. The pilot inflow was 25 m³/h and the doses of coagulant and polymer were varied to find suitable doses for the phosphorus reduction. From Table 1 in Appendix 8, it can be noticed that the chemical additions were mandatory for adequate phosphorus removal. As was suspected, the mechanical removal of suspended solids was higher compared with typical situation where biological filters are in operation. The PO₄-P and soluble total phosphorus concentrations were three times higher compared with typical situation but the total phosphorus concentration was in typical range. The lowest effluent total phosphorus concentration (0.12 mg/l) was achieved with the coagulant dose of 3 mg Al³⁺/l and polymer dose of 1 mg/l. However, the coagulant and polymer doses should have been slightly higher to achieve under 0.1 mg/l total phosphorus concentrations in the pilot effluent. From Figure 35, it can be estimated, that metal addition of 3.5 mg Al³⁺/l could have yielded to under 0.1 mg/l total phosphorus concentration in the pilot effluent. From previous tests, it can be assumed that even higher removals could have been achieved if polymer concentration was increased.

The suspended solid removal was negative in two cases (Table 1 in Appendix 8). One reason could be that flocs were too small and thus passed the filter. Nitrogen and BOD removals were not significant (Table 2 in Appendix 8).

9.6 Treatment of bypass water

The discfilter's ability to treat bypassed water was tested during the test trials. Bypass water was made from the primary settled water because real bypass situations were not occurring during the spring 2014. The direct precipitation was conducted to the mechanically treated water in one of the eight primary sedimentation tank.

The progress of the direct precipitation was monitored by online suspended solids concentration measurement. The goal was to achieve 30–40 mg/l suspended solids concentration but it was quickly noticed that this target was not possible to achieve. The discfilter pilot was started when the concentration of SS was approximately 50 mg/l. The inflow to the filter was 10 m³/h and the pore size 20 µm. The test lasted approximately 4 hours.

Laboratory results from the trial run are listed in Appendix 9. The average influent parameters are listed in Table 20.

Table 20. Average influent concentrations of the discfilter pilot in the bypass simulation.

Parameter	Concentration		
	Average	Max	Min
Total phosphorus (mg/l)	1.37	1.6	0.96
Total soluble phosphorus (mg/l)	0.05	0.054	0.046
Orthophosphate (PO ₄ -P) (mg/l)	0.02	0.03	0.015
Suspended solids (mg/l)	66	78	54
Turbidity (FNU)	51	59	39

Most of the phosphorus was in particulate form thus the mechanical removal can already reduce the total phosphorus concentration if particles size and form is adequate. The effect of different coagulant doses on the phosphorus fractions (total, soluble and orthophosphate) and SS are given in Figure 44.

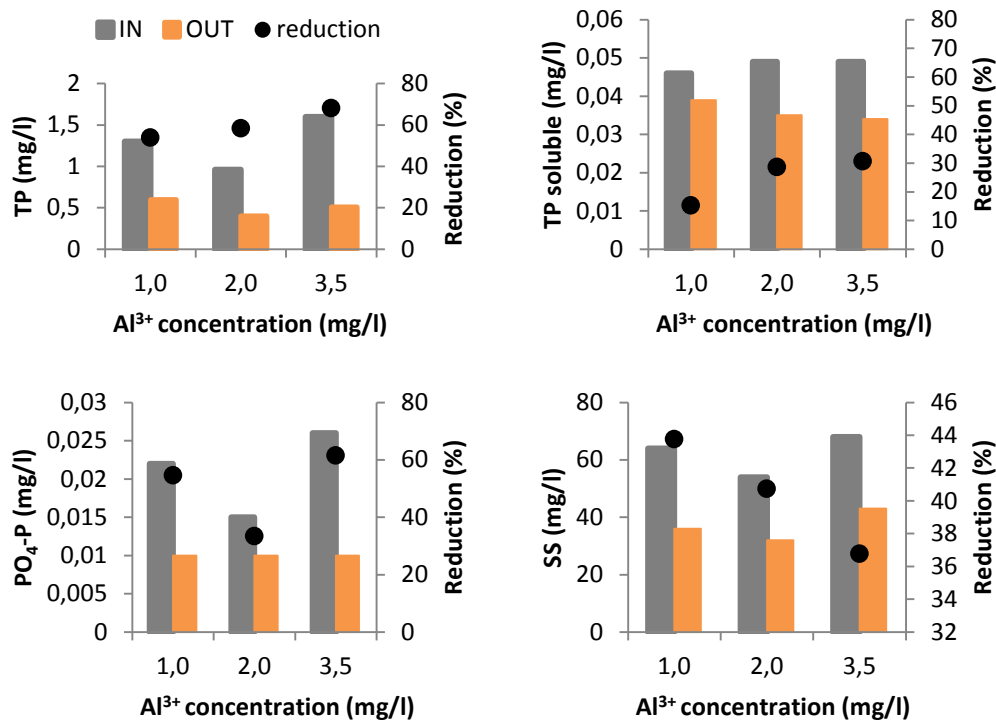


Figure 44. The effect of coagulant (C2) concentration to the removal of total phosphorus, total soluble phosphorus, orthophosphate and suspended solids during bypass trial run. The polymer (P6) dose was 2 mg/l.

The best total phosphorus and total soluble phosphorus removals were achieved when the metal addition was 3.5 mg/l and polymer addition was 2 mg/l. The best removal of suspended solids was with coagulant dosing 1 mg/l and polymer 2 mg/l. Unlike in jar tests, under 0.3 mg/l total phosphorus concentrations could not be achieved. The

formed flocs from the direct precipitation may have broken down because of the pumping prior to the filter (Persson *et al.*, 2006). However, the total phosphorus concentrations in the pilot effluent were at the same range with jar tests where direct precipitation was not employed. Furthermore, the direct precipitation of the primary settled water did not succeed as well as it did in the study performed by Valtari (2006). The SS concentration did not decrease to the wanted level and visually it could be seen that the effluent water from the primary settler was not as clear as it has been in the real bypass situation during wet weather conditions. The coagulant used in direct precipitation may have expired, which might be one reason why the coagulation did not succeed. As in jar tests, also in pilot scale tests the increase of coagulant concentration increased the total phosphorus removal.

9.7 Potential for wastewater hygienization

Already in some countries such as in the USA, wastewater hygienization is demanded especially if the treated water is used for reuse or discharged to a sensitive recreation area. In Finland in some WWTPs hygienization has become mandatory. However, the demanded removal percentages could be achieved with traditional process steps.

In this study, thermotolerant coliforms (TC) and fecal streptococci (FC) were measured from some samples in order to get information about the hygienization ability of the filter. The mechanical removal by discfilter (without a chemical addition) with pore openings 20 μm and 10 μm was insignificant but the removal was enhanced by using smaller pore size. The increase for TC was from 25 % (20 μm) to 66% (10 μm) and FC from 14 (20 μm) to 34 % (10 μm) (Figure 45).

Removal was enhanced with chemicals which can be expected as bacteria are attached to solid particles and during coagulation and flocculation particles are attached together. Thus, the removal is in some scale proportional to the coagulant and flocculant doses and can be further enhanced with smaller pore size (Figure 45).

Although reduction percentages were rather good, the bacteria count should be further decreased if the water is reused. Hygienization could be enhanced either by ultra- or nanofiltration or by UV hygienization. Disc filtration improves the performance of these techniques by lowering suspended solids and the microorganism concentration.

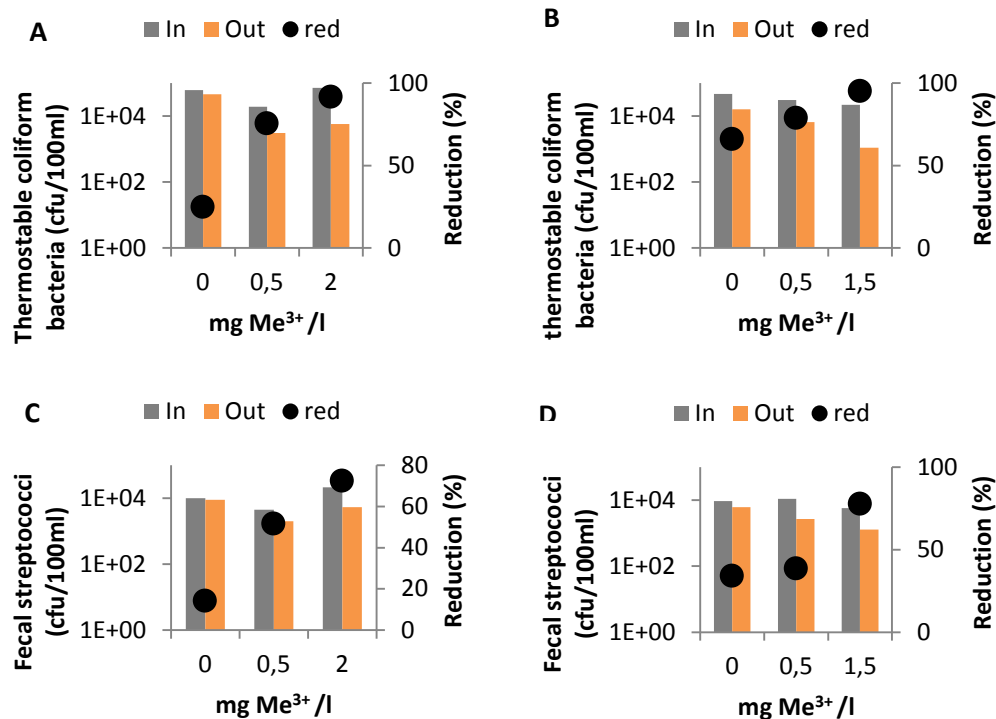


Figure 45. Microorganism removal by disc filtration. Figures A&C are from 20 µm tests and Figures B&D from 10 µm tests. (coagulant (C2), polymer 1.0 mg/l)

10 Result analysis

10.1 Laboratory tests on the site

All the samples for laboratory analysis were grab samples. Thus, the results were highly dependent on the up-stream post-denitrification process. Total phosphorus and suspended solids concentrations in the pilot influent vary depending on the process cycles so that during the post-denitrification filter wash, more phosphorus and suspended solids were released.

At the beginning of trial runs, only orthophosphate cuvette tests were possible to perform on the site because there was no water bath for heating the samples for total phosphorus measurements. Thus, total phosphorus concentrations from C2 dose response tests are calculated from the orthophosphate concentrations using the laboratory results as a reference.

Samples that were taken for total phosphorus cuvette tests between 26 February and 19 March were heated at 95 degrees in a water bath for an hour. After 19 March, the heating was done at 99.9 degrees for an hour. The instructions of the cuvette test tells that the samples should be heated for one hour at 100 degrees. However, samples were taken at the same time with the laboratory samples and the results were in the same range.

10.2 Pilot unit

In mid-March, it was noticed that the inflow had decreased to 20 m³/h although inlet pump was adjusted to 25 m³/h. The first suspicions were that there was a clog in the inlet pump or that the pump was worn out. The reason for the decrease was that the snow melting had stopped which had resulted in a water level drop in the effluent canal of the plant. This led to a decrease of a hydraulic pressure. The problem was

solved by installing a new pump. However, due to the limitation of the pump's frequency converter it was possible to achieve maximum inflow of 29 m³/h.

During long run when chemical dosing concentrations were kept constant, the influent total phosphorus and SS concentrations decreased (Appendix 6, table1). This resulted in overdosing of the coagulant. Figure 46 shows that when the inflow SS meets a certain value (in this case 6.7) the removal is negative. In Ruhleben WWTP, no suspended solids removal was observed when concentration was 4 mg/l and in Clinton WWTP the influent concentration of approximately 2.5 mg/l resulted in higher effluent suspended solids concentration (Hart *et al.*, 2012; Langer *et al.*, 2013). In addition, the aluminum concentration in the pilot effluent was increased which indicates that the addition of coagulant had been too high. Higher suspended solids concentrations in the pilot effluent were hard to notice because the total phosphorus and turbidity reductions were positive.

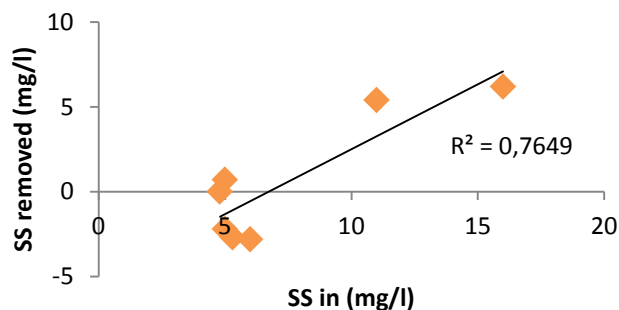


Figure 46. Overdosing of chemicals results in negative suspended solid removal. Long run: C2= 2 mg/l and P6 1 mg/l.

This shows, how important it is to optimize the chemical dosing according to influent quality in order to get the best purification result as well as to minimize the chemical

consumption. For example, the coagulant concentration could be linked to the orthophosphate or total phosphorus concentrations and the polymer concentration to the coagulant concentration. This was done in Ruhleben WWTP and it reduced operational costs (Langer *et al.*, 2013).

11 Conclusions

The main object of this study was to investigate, if phosphorus concentrations under 0.1 mg/l can be achieved with disc filtration at Viikinmäki WWTP. The technique was tested with and without chemical addition. Trial runs confirmed that the process worked well in the treatment of Viikinmäki WWTP effluent if chemicals were added because the suspended solid concentration was low in the effluent. Furthermore, the discfilter functioned under a wide range of operational conditions such as high and low phosphorus and suspended solids concentrations. The technique of the discfilter is simple and the needed space relatively small, which makes this technology very interesting. However, chemical dosing was found to be mandatory in achieving total phosphorus concentration under 0.1 mg/l. The chemical dosing is also the biggest challenge due to fact that both the overdosing and underdosing resulted in an inadequate phosphorus removal.

Both aluminum and iron based coagulants were tested. Aluminum based coagulants had better purification results than iron. The optimum aluminum concentration to treat Viikinmäki WWTP effluent and to achieve under 0.1 mg TP/l level was 0.5–1 mg Al^{3+} /l with polymer concentration of 1.0 mg/l. This resulted in 57 % and 53 % total phosphorus and suspended solids removal, respectively. However, the chemical addition is highly dependent on the influent phosphorus concentration.

During the trial runs, effluent quality of the wastewater varied which gave an excellent opportunity to study the flexibility of the discfilter. Inflow did not have significant effect to the reduction but it did affect to the discfilter backwash time. Two different pore sizes were tested, 10 μm and 20 μm . The removal of phosphorus and suspended solids were not considerably better with 10 μm . Thus, the 20 μm pore size was chosen for longer trial run due to higher hydraulic capacity. It was noticed that chemical dosing is the most critical point and extra attention should be paid to that. Because influent total phosphorus concentration affects greatly to the coagulant dosing, in a

full-scale application the coagulant addition should be linked to the inflow phosphorus concentration and the polymer addition to the coagulant dose. Furthermore, there should be suspended solid measurement for the discfilter effluent so that overdosing of the chemical could be noticed. This would also minimize the risk of overdosing and thus control the operational costs.

During the trial runs, treatment of bypass water and secondary settled wastewater were studied. Bypass water results showed that the filter was able to reduce the total phosphorus concentration from 1.6 mg/l to 0.51 mg/l. The removal was enhanced by higher coagulant and flocculant concentrations. However, with one-step filtration under 0.5 mg/l total phosphorus concentrations were not possible to achieve. Anyhow, the discfilter can be a good alternative for bypass water treatment as a multi-step application or if the bypassed water is mixed with the effluent prior to the disc filtration. Secondary settled wastewater trial runs showed that the phosphorus concentrations could be reduced from 0.33 mg/l to 0.12 mg/l. Based on previous tests, it can be concluded that with higher chemical or polymer concentrations the removal would be higher.

Hygienization and removal of microplastics and micropollutants may become mandatory in the future. Microorganisms are removed fairly well by tested discfilter and the removal was enhanced by chemical additions. In some cases, this is enough for achieving the limits. If higher removals are demanded, disc filtration is a good pre-treatment for other hygienization methods. Recent studies have proved that microplastics can be removed by the discfilter and some studies have been made for micropollutant removal by combining activated carbon and discfilter. However, these applications need more research.

Discfilter was able to produce consistently effluent water with phosphorus concentration under 0.1 mg/l. The operation was robust. However, chemical dosage plays a critical role in achieving extreme low phosphorus concentrations. Overall, the

results showed that discfilter can be an alternative tertiary treatment step for phosphorus and suspended solid removal at Viikinmäki WWTP.

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Results from jar tests (wastewater)

Table 1. Phosphorus removal by iron based coagulant (C3).

Coagulant			pH _{end}	Phosphorus (mg/l)				Turbidity (NTU)			Filterability l/s
mg/l	mg Me ³⁺ /l	mmol Me ³⁺ /l		TP _{in}	TP _{Out}	Red %	P _{sol}	In	Out	Red %	
50	5.90	0.105	6.92	0.13	0.12	12	0.100	1.97	4.14	-110	0.092
75	8.80	0.157	6.84	0.13	0.11	12	0.120	1.97	6.72	-241	0.083
100	11.70	0.209	6.58	0.13	0.11	14	0.130	1.97	7.3	-271	0.023
125	14.60	0.262	6.48	0.13	0.09	32	0.100	1.97	7.12	-261	0.027
50	5.90	0.105	6.71	0.13	0.12	11	0.110	1.97	3.8	-93	0.084
75	8.80	0.157	6.64	0.13	0.11	19	0.100	1.97	6.43	-226	0.078
100	11.70	0.209	6.54	0.13	0.11	18	0.110	1.97	7	-255	0.039

Table 2. Phosphorus removal by iron based (C3) coagulant and cationic polymer (P6). The numbers in italic are under detection limit.

Coagulant			P6 mg/l	pH adjustment (ml)		pH _{end}	Phosphorus (mg/l)				Turbidity (NTU)			Filterability l/s
mg/l	mg Me ³⁺ /l	mmol Me ³⁺ /l		H ₂ SO ₄ (30%)	NaOH (10%)		TP _{in}	TP _{Out}	Red %	P _{sol}	In	Out	Red %	
45	5.3	0.094	1	-	-	6.87	0.14	0.08	41	0.03	1.75	3.01	-72	0.006
30	3.5	0.063	1.5	-	-	6.95	0.14	0.08	41	0.04	1.75	2.73	-56	0.025
45	5.3	0.094	1.5	-	-	6.81	0.14	0.07	47	0.03	1.75	3.11	-78	0.015
60	7	0.126	1.5	-	-	6.78	0.14	0.07	52	0.03	1.75	3.61	-106	0.008
75	8.8	0.157	2	0.134	-	5	0.14	0.03	81	0.02	1.75	1.86	-6	0.020
75	8.8	0.157	2	-	-	6.68	0.14	0.05	68	0.03	1.75	2.37	-35	0.017
75	8.8	0.157	2	0.07	-	6	0.14	0.04	69	0.03	1.75	2.93	-67	0.023
75	8.8	0.157	2	-	0.283	8	0.14	0.05	64	0.03	1.75	2.22	-27	0.010

Table 3. Phosphorus removal by aluminum based coagulant (C2) and cationic polymer (P6). The numbers in italic are under detection limit.

Coagulant				pH adjustment (ml)	pH _{end}	Phosphorus (mg/l)				Turbidity			Filterability
P6						H ₂ SO ₄ (30%)	TP _{in}	TP _{Out}	Red %	P _{sol}	In	Out	
mg/l	mg Me ³⁺ /l	mmol Me ³⁺ /l	mg/l										
50	4.65	0.172	0	-	-	0.38	0.37	4	0.05	3.34	5.78	-73	0.072
45	4.19	0.155	1	-	6.91	0.14	0.05	68	0.03	1.75	2.14	-22	0.003
50	4.65	0.172	1	-	-	0.39	0.07	82	0.05	2.58	2.41	7	0.011
30	2.79	0.103	1.5	-	6.96	0.14	0.04	73	0.02	1.75	1.78	-2	0.005
45	4.19	0.155	1.5	-	6.98	0.14	0.05	68	0.02	1.75	2.16	-23	0.003
60	5.58	0.207	1.5	-	6.86	0.14	0.04	70	0.03	1.75	2.25	-29	0.002
75	6.98	0.258	2	-	6.76	0.14	0.04	75	0.03	1.75	3.16	-81	0.002
50	4.65	0.172	2	-	-	0.38	0.05	86	0.03	3.34	1.28	62	0.024
75	7	0.258	2	0.09	6.01	0.15	0.02	86	0.02	2.13	0.48	77	0.013

Table 4. Phosphorus removal with aluminum based coagulant (C1) and cationic polymer (P6). The numbers in italic are under detection limit.

Coagulant			P6 mg/l	pH adjustment (ml) H ₂ SO ₄ (30%)	pH _{end}	Phosphorus (mg/l)				Turbidity (NTU)			Filterability l/s
mg/l	mg Me ³⁺ /l	mmol Me ³⁺ /l				TP _{in}	TP _{Out}	Red %	P _{sol}	In	Out	Red %	
75	5.6	0.2	0	-	7.03	0.19	0.14	24	<i>0.02</i>	2.47	3.42	-38	0.047
30	2.3	0.1	1.5	-	7.15	0.19	<i>0.04</i>	80	<i>0.03</i>	2.47	1.23	50	0.038
45	3.4	0.1	1.5	-	7.11	0.19	<i>0.03</i>	84	<i>0.02</i>	2.47	0.96	61	0.033
75	5.6	0.2	2	0.095	6.01	0.19	<i>0.02</i>	88	<i>0.02</i>	2.47	0.796	68	0.015

Table 5. Phosphorus removal with aluminum based coagulant (C4) and cationic polymer P6. The numbers in italic are under detection limit.

Coagulant			P6 mg/l	pH adjustment (ml) H ₂ SO ₄ (30%)	pH _{end}	Phosphorus (mg/l)				Turbidity			Filterability l/s
mg/l	mg Me ³⁺ /l	mmol Me ³⁺ /l				TP _{in}	TP _{Out}	Red %	P _{sol}	In	Out	Red%	
75	3.2	0.119	0	-	6.86	0.15	0.11	25	<i>0.03</i>	2.13	2.86	-34	0.057
45	1.9	0.072	1	-	7.02	0.15	0.06	60	<i>0.04</i>	2.13	1.53	28	0.036
30	1.3	0.048	1.5	-	7.03	0.15	0.06	61	<i>0.03</i>	2.13	1.32	38	0.057
45	1.9	0.072	1.5	-	7.02	0.15	0.05	65	<i>0.03</i>	2.13	1.03	52	0.042
60	2.6	0.096	1.5	-	6.95	0.15	0.05	67	<i>0.03</i>	2.13	1.1	48	0.039
75	3.2	0.119	2	-	6.91	0.15	<i>0.04</i>	76	<i>0.03</i>	2.13	0.823	61	0.028
75	3.2	0.119	2	0.1	6.03	0.15	<i>0.03</i>	79	<i>0.02</i>	2.13	1.3	39	0.017

Table 6. Comparison of different polymers. Coagulant (C2) dose was 50 mg/l except with polymer P14 the coagulant (C4) dose was 30 mg/l. The numbers in italic are under detection limit.

Polymer		Phosphorus (mg/l)				Turbidity (NTU)			Filterability
Type	mg/l	TP _{in}	TP _{Out}	Red %	P _{sol}	In	Out	(%)	l/ s
P1	2	0.39	0.08	79	0.04	3.34	2.32	31	0.004
P2	2	0.38	0.09	76	0.03	3.34	1.77	47	0.008
P3	2	0.38	0.06	84	0.03	3.34	N/A	N/A	0.018
P4	2	0.39	0.07	82	0.05	2.58	2.37	8	0.018
P5	2	0.39	0.06	85	0.04	2.58	1.27	51	0.021
P6	2	0.38	0.05	87	0.03	3.34	1.28	62	0.024
P7	2	0.39	0.07	82	0.04	2.58	1.52	41	0.020
P8	2	0.39	0.06	85	0.04	2.58	1.28	50	0.025
P9	2	0.38	0.04	89	0.03	3.34	1.72	49	0.032
P10	10	0.38	0.17	55	0.02	3.34	5.21	-56	0.013
P11	10	0.38	0.17	55	0.12	3.34	1.65	51	0.006
P12	2	0.38	0.16	58	0.10	3.34	2.33	30	0.013
P13	2	0.38	0.19	50	0.12	3.34	3.43	-3	0.014
P14	5	0.15	0.11	26	0.02	2.13	4.73	-122	0.064
P15	2	0.38	0.18	53	0.07	3.34	2.05	39	0.007

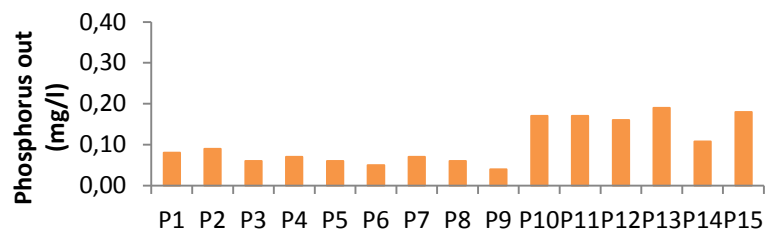


Figure 47. Comparison of different polymers. Data collected from Table 6 in Appendix 1.

Jar tests: Pre-sedimented bypass water

Table 1. Chemical doses used in the treatment of simulated bypass water jar tests.

Sample code	Direct precipitation		Precipitation prior discfilter	
	mg C2/l	Magnafloc (mg/l)	mg Al ³⁺ /l	P6 (mg/l)
Primary settled water	0	0	0	0
Direct precipitation & secondary precipitation & discfiltration	75	1	2.6	2
Precipitation & discfiltration	0	0	4.0	2
	0	0	2.6	2

Discfilter position at Viikinmäki WWTP.

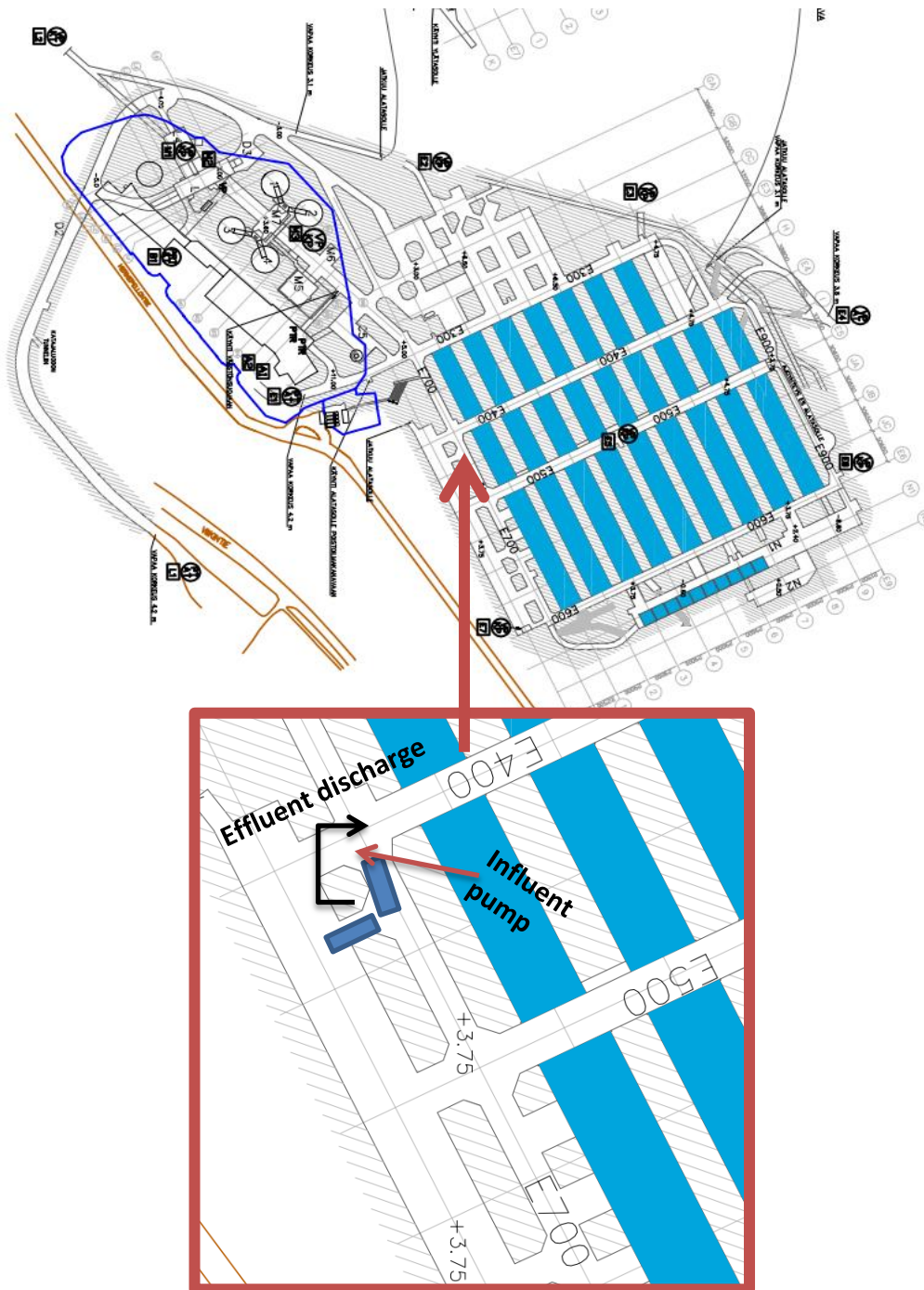


Figure 48. Position of the pump and discfilter pilot unit at Viikinmäki WWTP.

Jar test results: comparing four different coagulant

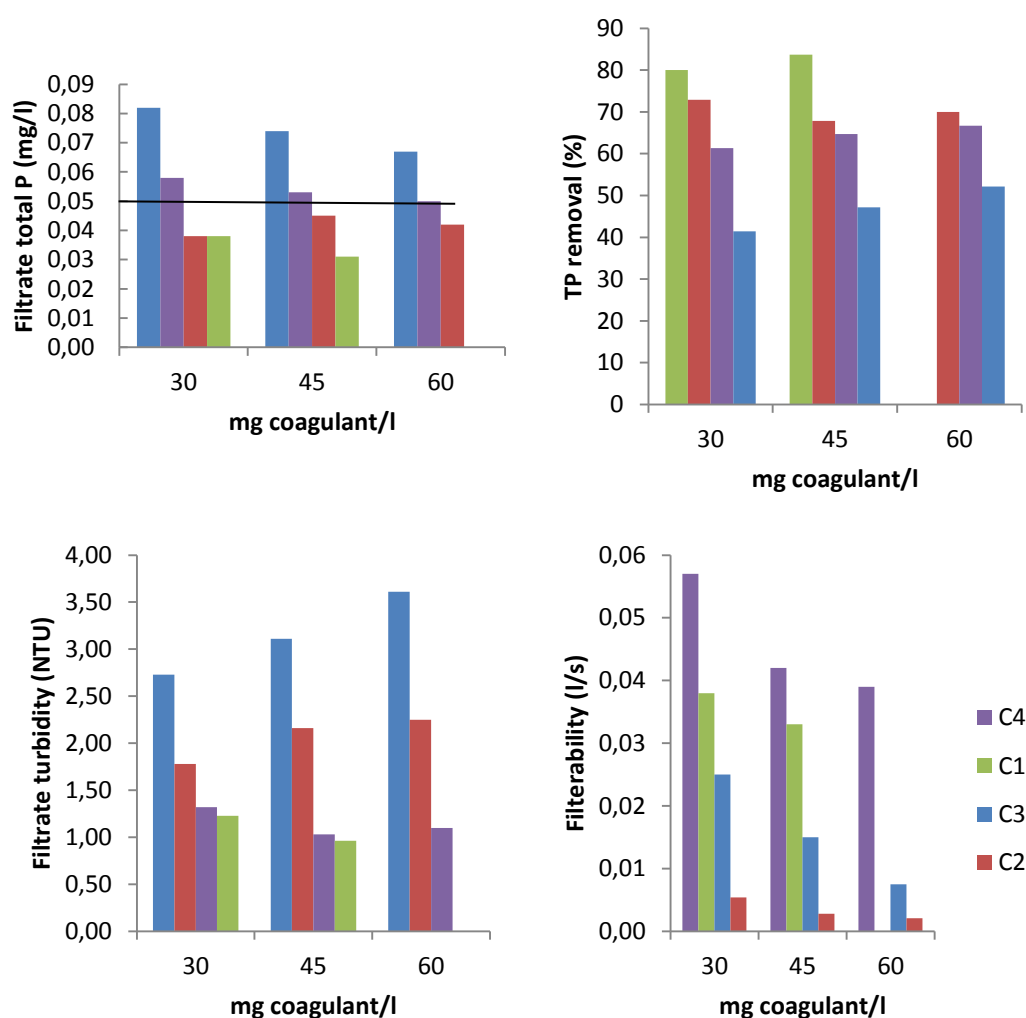


Figure 1. Effect of coagulant dose on phosphorus removal, turbidity and filterability. The polymer dose was 1.5 mg/l. The Detection limit of total phosphorus (0.05 mg/l) is marked with black line.

Dose response tests with different chemicals at the pilot unit

Table 1. Coagulant C2 and polymer P6. Total phosphorus calculated from phosphate measurements using laboratory results as a coefficient. Underlined TP results indicate that the orthophosphate result was under detection limit. Inflow 20 m³/h and pore size 20 µm.

$\frac{\text{g Me}^{3+}}{\text{m}^3}$	Coagulant		Polymer $\frac{\text{g}}{\text{m}^3}$	Turbidity (NTU)			TP (mg/l)		
	mmol Me^{3+}/l	$\frac{\text{g product}}{\text{m}^3}$		in	out	Red. %	in	out	Red. %
1.5	0.056	16.13	0.50	3.8	1.89	50	0.19	0.087	54
0	0.000	0.00	0.70	3.23	2.59	20	<u>0.294</u>	<u>0.423</u>	-44
0.4	0.015	4.30	0.70	3.59	1.88	48	<u>0.456</u>	<u>0.257</u>	44
0.5	0.019	5.38	0.70	5.81	2.73	53	0.258	0.134	48
0.5	0.019	5.38	0.70	6.73	3.68	45	0.348	0.157	55
0.7	0.026	7.53	0.70	5.06	3.09	39	<u>0.213</u>	<u>0.127</u>	40
1	0.037	10.75	0.70	4.19	2.44	42	<u>0.264</u>	<u>0.129</u>	51
0.5	0.019	5.38	0.98	4.62	1.94	58	0.24	0.106	56
0.5	0.019	5.38	0.98	9.94	3.55	64	0.29	0.145	49
0.4	0.015	4.30	1.4	4.39	1.61	63	<u>0.312</u>	<u>0.188</u>	40
0.5	0.019	5.38	1.4	4.75	2.27	52	<u>0.290</u>	<u>0.154</u>	47
0.5	0.019	5.38	1.4	5.66	2.36	58	0.317	0.123	61
0.5	0.019	5.38	1.4	7.1	2.08	71	0.31	0.091	71
0.5	0.019	5.38	1.4	5.32	1.69	68	0.222	0.088	60
0.5	0.019	5.38	1.4	4	1.5	63	0.189	<u>0.041</u>	78
0.5	0.019	5.38	1.4	3.5	2.2	37	<u>0.180</u>	<u>0.094</u>	48
0.5	0.019	5.38	1.4	3.4	1.4	59	0.224	0.089	60
0.7	0.026	7.53	1.4	4.26	1.78	58	<u>0.171</u>	<u>0.094</u>	45
1	0.037	10.75	1.4	4.2	2.2	48	<u>0.248</u>	<u>0.119</u>	52
1.5	0.056	16.13	1.4	3.94	2.48	37	<u>0.261</u>	<u>0.060</u>	77
0.5	0.019	5.38	2.1	3.4	1.91	44	<u>0.228</u>	<u>0.040</u>	82
0.5	0.019	5.38	2.1	4.16	1.72	59	<u>0.194</u>	<u>0.127</u>	34
0.7	0.026	7.53	2.1	3.57	1.54	57	<u>0.180</u>	<u>0.107</u>	40

Table 2. Dose response test results of coagulant C1 and polymer P6. The pore size was 20 μm and inflow 25 m^3/h .

$\text{g Me}^{3+}/\text{m}^3$	Coagulant		Polymer g/m^3	Turbidity (NTU)			TP (mg/l)		
	mmol Me^{3+}/l	g product/ m^3		in	out	Red. %	in	out	Red %
2	0.074	26.67	0.4	5.42	4.17	23	0.263	0.097	63
0.5	0.019	6.67	0.5	4.19	2.87	32	0.217	0.133	39
0.7	0.026	9.33	0.5	4.92	3.94	20	0.249	0.12	52
1	0.037	13.33	0.5	6.36	4.1	36	0.316	0.138	56
1.5	0.056	20.00	0.5	4.78	3.54	26	0.241	0.095	61
0.5	0.019	6.67	1	5.02	2.5	50	0.24	0.089	63
0.5	0.019	6.67	1	5.1	2.74	46	0.216	0.083	62
0.5	0.019	6.67	1	4.65	2.88	38	0.292	0.094	68
0.7	0.026	9.33	1	5.3	2.59	51	0.237	0.095	60
1	0.037	13.33	1	5.81	2.42	58	0.262	0.084	68
1.5	0.056	20.00	1	5.68	1.87	67	0.265	0.061	77

Table 3. Dose response test results of coagulant C3 and polymer P6 with pore size 20 μm .

Inflow m^3/h	Coagulant			Polymer g/m^3	Turbidity (NTU)			TP (mg/l)		
	g $\text{Me}^{3+}/\text{m}^3$	mmol Me^{3+}/l	g product/ m^3		in	out	Red %	in	out	Red %
23	1	0.018	8.55	0.5	7.04	5.1	28	0.25	0.17	32
23	2	0.036	17.09	0.5	8.29	4.34	48	0.401	0.215	46
23	2	0.036	17.09	1	10.8	6.1	44	0.327	0.182	44
23	2.5	0.045	21.37	1	13.9	6.41	54	0.374	0.184	51
23	3.5	0.063	29.91	1	12.4	6.92	44	0.306	0.180	41
23	2.5	0.045	21.37	1.5	13.8	5.08	63	0.311	0.177	43
22	6	0.107	51.28	1.5	12.1	4.7	61	0.272	0.128	53
23	3.5	0.063	29.91	2	11.9	4.98	58	0.297	0.154	48
23	5	0.089	42.74	2	8.63	3.92	55	0.41	0.099	76
22	5	0.089	42.74	2	3.66	4.09	-12	0.375	0.139	63
22	5	0.089	42.74	2	5.5	5.03	9	0.236	0.149	37

The effect of pore size: 10 μm vs 20 μm

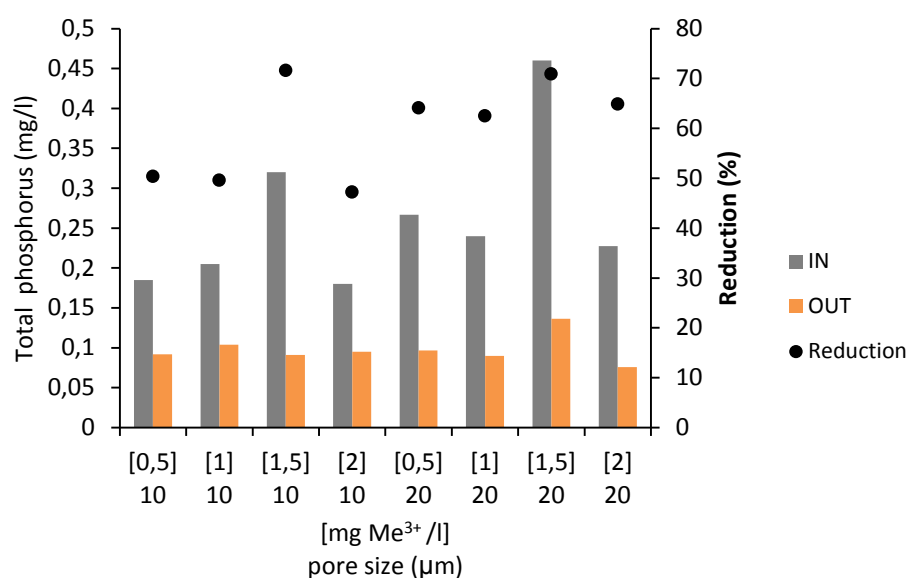


Figure 1. Effect of pore size and metal dose on total phosphorus removal (polymer P6 addition 1 mg/l).

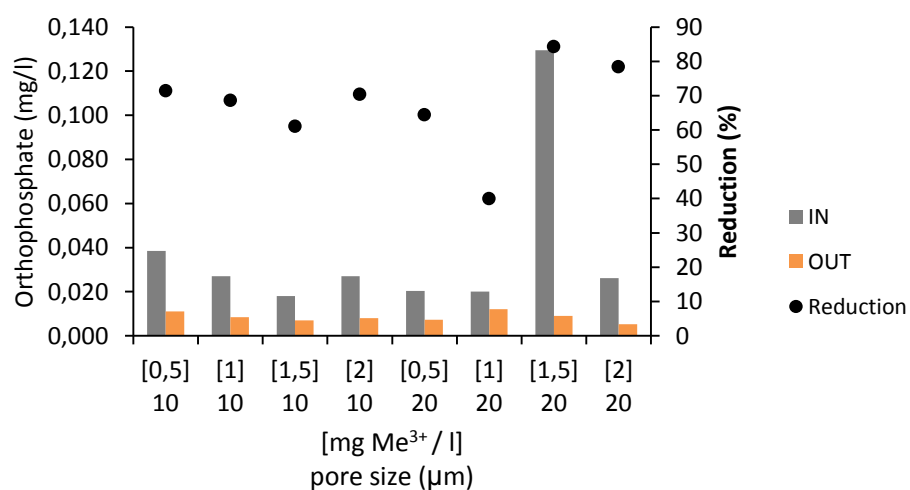


Figure 2. Effect of pore size and metal dose on orthophosphate removal (polymer P6 addition 1 mg/l)

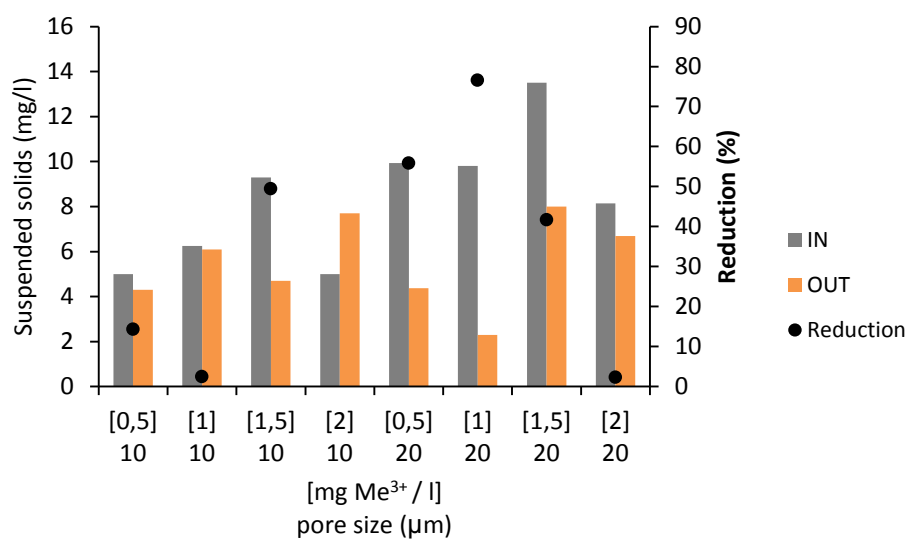


Figure 3. Effect of pore size and metal dose on suspended solids removal (polymer P6 addition 1 mg/l)

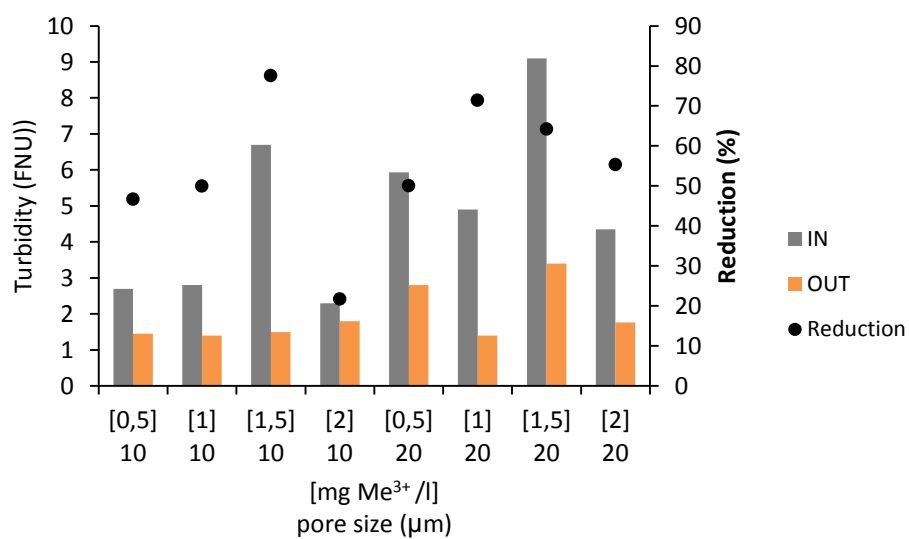


Figure 4. Effect of pore size and coagulant dose on turbidity (polymer addition P6 1 mg/l)

Long trial run

Table 1. Laboratory results from long trial run. Coagulant dose was 2 mg/l (C2) and polymer (P6) 1.0 mg/l.

Date	PO ₄ -P (mg/l)			TP (mg/l)			Soluble TP (mg/l)			Suspended solid (mg/l)			Turbidity (FNU)			Alkalinity (mmol/l)		
	IN	OUT	Red %	IN	OUT	Red %	in	out	Red %	IN	OUT	Red %	IN	OUT	Red %	IN	OUT	Red %
8.5	0.023	0.005	78	0.320	0.094	71	-	-	-	16	9.8	39	6.8	2.4	65	2.4	2.4	0
12.5	0.017	0.004	76	0.180	0.056	69	0.047	0.028	40	5	4.3	14	4	1.5	63	2.2	2.1	5
14.5	0.021	0.004	81	0.250	0.067	73	-	-	-	11	5.6	49	5.1	1.5	71	-	-	-
22.5	0.032	0.006	81	0.150	0.071	53				5.3	8	-51	2.1	1.3	38	2.0	2.0	0
27.5	0.028	0.006	79	0.190	0.086	55	0.064	0.026	59	5	7.2	-44	3.2	1.8	44	2.3	2.2	4
28.5	0.018	0.007	61	0.210	0.094	55	0.063	0.029	54	6	8.8	-47	3.6	2.3	36	-	-	-
2.6.	0.044	0.006	86	0.200	0.069	66	0.064	0.024	63	4.8	4.8	0	2.7	1.2	56			

Table 2. Laboratory results from long trial run. Coagulant dose was 2 mg/l (C2) and polymer (P6) 1.0 mg/l.

[illegible]

Table 3. Laboratory results from sludge samples of long trial run. Coagulant dose was 2 mg/l (C2) and polymer (P6) 1.0 mg/l.

Date	Coagulant.	Polymer.	TP	SS	pH	Alkalinity	BOD ₇ -ATU	COD _{cr}	TN
	g Me ³⁺ /m ³	g/m ³	mg/l	mg/l		mmol/l	mg/l	mg/l	mg/l
8.5.2014	2.00	1.00	9.1	590	6.9	4.6	340	840	36
12.5.2014	2.00	1.00	5.3	540	6.9	4	100	670	29
14.5.2014	2.00	1.00	10	790		-	-	790	-
22.5.2014	2.00	1.00	6.8	800	6.8	3.6	88	720	31
27.5.2014	2.00	1.00	6.2	630	7	3.5	250	760	27
28.5.2014	2.00	1.00	6.6	790	6.8	-	-	-	-
2.6.2014	2.00	1.00	-	630	-	-	-	-	-

Laboratory results from the treatment of secondary settled wastewater

Table 1. Total phosphorus results from the treatment of secondary settled wastewater with discfilter. Different C2 doses and P6 doses were tested.

Al³⁺ mg/l	Polymer mg/l	BW %	SS (mg/l)			PO₄-P (mg/l)			Soluble TP (mg/l)			TP (mg/l)			Soluble TP_{influent}/TP_{influent}
			IN	OUT	Red. %	IN	OUT	Red. %	IN	OUT	Red. %	IN	OUT	Red %	
0	0	17	6.3	3.7	41	0.14	0.14	0	0.17	0.16	6	0.33	0.26	21	0.42
0,5	1	25	5.3	4	25	0.15	0.054	64	0.33	0.087	74	0.34	0.20	41	0.44
2	1	30	5.7	8.6	-51	0.15	<0.01	93	0.17	0.030	82	0.33	0.16	52	0.45
3	1	44	6.3	6.7	-6	0.14	<0.01	93	0.17	0.030	82	0.32	0.12	63	0.44
1	1.5	30	5.7	4	30	0.14	0.013	91	0.32	0.14	56	0.33	0.14	58	0.42

Table 2. Results from the treatment of secondary settled wastewater . Different C2 doses and P6 doses were tested.

Inflow m ³ /h	Al ³⁺ mg/l	Polymer mg/l	Turbidity (FNU)			pH		N _{tot} (mg/l)			BOD ₇ (mg/l)		
			IN	OUT	Red %	IN	OUT	IN	OUT	Red%	IN	OUT	Red %
20	0	0	4.6	2.5	46	6.5	6.6	18	18	0	4.2	3.3	21
25	0.5	1	3.7	1.9	49	6.5	6.6	18	18	0	3.9	2.6	33
25	2	1	3.6	2.3	36	6.6	6.6	17	17	0	4.1	2.4	41
25	3	1	3.9	2.2	44	6.6	6.6	18	16	11	3.9	2.2	44
25	1	1.5	3.5	1.6	54	6.6	6.6	18	17	6	3.9	2.2	44

Table 3. Sludge sample results from the treatment of secondary settled wastewater

Inflow m ³ /h	Al ³⁺ dose mg/l	polymer mg/l	SS mg/l	TP mg/l	BOD7 mg/l
20	0	0	690	12	230
25	0.5	1	580	8.5	100
25	2	1	820	11	78
25	3	1	640	9.3	47
25	1	1.5	770	13	100

Laboratory results from pilot scale bypass simulation

Table 1. Laboratory results from bypass simulation. Numbers in italic are under detection limit.

Inflow	BW	Al ³⁺ dose	Pol.	SS (mg/l)			Turbidity (FNU)			PO ₄ -P (mg/l)			TP soluble (mg/l)			TP (mg/l)		
m ³ /h	%	mg/l	mg/l	IN	OUT	Red %	IN	OUT	Red %	IN	OUT	Red %	IN	OUT	Red %	IN	OUT	Red %
10	25	2.0	1.0	78	52	33	56	28	50	0.030	<i>0.01</i>	67	0.054	0.039	28	1.6	0.83	48
10	15	1.0	2.0	64	36	44	48	20	58	0.022	<i>0.01</i>	55	0.046	0.039	15	1.3	0.6	54
10	19	2.0	2.0	54	32	41	39	14	64	0.015	<i>0.01</i>	33	0.049	0.035	29	0.96	0.4	58
10	32	3.5	2.0	68	43	37	59	18	69	0.026	<i>0.01</i>	62	0.049	0.034	31	1.6	0.51	68

Table 2. Laboratory results from bypass simulation

Inflow	BW	Al ³⁺ dose	pol.	pH		BOD (mg/l)			N _{tot} (mg/l)		
m ³ /h	%	mg/l	mg/l	IN	OUT	IN	OUT	Red %	IN	OUT	Red %
10	25	2.0	1.0	7.5	7.5	62	36	42	54	53	2
10	15	1.0	2.0	7.5	7.6	54	34	37	55	53	4
10	19	2.0	2.0	7.6	7.7	48	30	38	53	51	4
10	32	3.5	2.0	7.5	7.5	59	18	69	52	49	6

Table 21. Sludge samples from bypass simulation.

Al³⁺ dose	polymer	SS	pH	BOD	N_{tot}	P_{tot}
mg/l	mg/l	mg/l		mg/l	mg/l	mg/l
2.0	1.0	1300	7.4	560	94	25
1.0	2.0	3000	7.3	1400	130	43
1.9	2.0	1600	7.4	670	98	22