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A REVERSE OSMOSIS (RO) PLANT FOR SEWAGE TREATMENT AND NUTRIENT RECOVERY – THE INFLUENCE OF PRE-TREATMENT METHODS.

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ABSTRACT

This study evaluates the performance of a one–step reverse osmosis (RO) process as a nutrient separation step added to systems treating wastewater from Hammarby Sjöstad district. The environmental goals set by the Hammarby Sjöstad project, such as effluent water standards (N_{tot}≤6mg/l, P_{tot}≤0.15mg/l) and the quality of a nutrient-rich concentrate (a by-product from RO process) for agricultural use were of great importance in this study. Three existing pre-treatment systems (line 1-aerobic activated sludge system; line 2-membrane bioreactor system; line 4-anaerobic USAB system) before an RO unit were examined in order to select the most appropriate method that in combination with RO technology could meet the set requirements. During the study, the operational aspects such as the effect of the feed pH value and volume reduction factor (VRF) were assessed.

The results showed that the produced RO effluent (mixed permeate) from all treatment lines followed the discharge standards, except for the water recovered at VRF=50 from line 4. In order to meet requirements the water recovery rate in line 4 needs to be lower. The highest quality of a water product was obtained during the treatment of the effluent water from line 2 at VRF=50 when the water recovery rate reached 98%.

Taking into consideration the heavy metal content expressed as a ratio metal/phosphorous (Me/P) it was found that the concentrate product obtained at VRF=50 from line 4 had the lowest ratio Me/P for analyzed heavy metals. Additionally, the high nutrient content contributed to its high fertilizing value.

The study revealed that the low feed pH value (around 5.6) significantly reduced the occurrence of scaling and fouling phenomena during the RO performance. Moreover, the low pH value of water incoming to the RO plant allowed for savings on acid addition during the concentration process.

The data gathered from the operation of the RO pilot enabled to select the membrane bioreactor system (line 2) as the most proper pre-treatment method before the RO unit. The water incoming to the RO plant from line 2 was positively influenced by the microfiltration process as well as robustly occurring nitrification process in MBR.

Key words: concentrate, nutrient recovery, permeate, reverse osmosis, wastewater treatment.

ACKNOWLEDGMENTS

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1 INTRODUCTION

Hammarby Sjöstad is a newly built area in the centre of Stockholm with an ambitious environmental program. The main goal of this program is to reduce half of the environmental impact compared to other construction works. The new district will be equipped with its own recycling system and a local sewage treatment plant. Storm-water will be treated locally. Energy, based on renewable fuels, will be produced in the district heating plant (Björlenius & Hellström, 2002).

Stockholm Water Company will evaluate the performance of an experimental treatment plant used for testing new treatment processes for domestic waste water from Hammarby Sjöstad. Four different treatment lines are studied with intent to reduce energy consumption and chemicals' usage as well as maximize resource recovery (energy and nutrients). The main goals for wastewater management are: recycling 95% of the phosphorous and reuse for agricultural purposes, decrease by 50% the concentration of heavy metals in the influent wastewater and other harmful components, reduction of the nitrogen content in the treated wastewater to 6 mg/l and the phosphorous content to 0.15 mg/l. The results from four parallel lines of treatment (two aerobic and two anaerobic) will be compared with the conventional methods used at Henriksdal wastewater treatment plant (Paques, 2003).

As part of an experimental set-up a cutting edge technology of membrane separation processes is applied to treat the wastewater from Hammarby Sjöstad. The main advantage of membrane technology is the fact that it normally works without the addition of chemicals, with relatively low energy consumption and generally has lower capital investment and operating cost when compared with conventional separation processes (Sirkar *et al.*, 1992). Reverse osmosis (RO), as one of the membrane methods, is used to separate the incoming water to clean water (permeate) and a concentrate with high nutrients content. Such a concentrate could then be recycled and used in agriculture. The previous study on a single-stage RO showed that the guidelines for permeate regarding phosphorous and nitrogen effluent standards were not met whereas their content in the concentrate was too low to effectively recover nutrients (Blennow, 2005). It was therefore proposed to reconstruct a RO unit to perform additional tests to find solution for these problems.

2 THESIS OBJECTIVES

The initial goal of this thesis was to investigate the use of a 2-stage reverse osmosis (RO) system for wastewater purification in order to increase water recovery rate. However, such an RO plant configuration was not available during the study period. Therefore, different water recovery rates were tested on a single membrane unit with the aim of obtaining the highest rate which allows to receive the required permeate quality. The standards for the effluent water were set according to the Hammarby Sjöstad Environmental Plan. Of great importance was nutrient recovery in a concentrate solution during the reverse osmosis treatment of effluents from three different pre-treatment methods.

Regarding the operational aspect, effects of the following factors on the single-stage RO unit performance were examined:

- The pH value of the feed water
- Comparison of pre-treatment methods to asses membrane performance
- The occurrence of scaling and fouling phenomena

A separate study was carried out to assess the content and possible removal of heavy metals (in case of their high concentration) in the RO concentrate. The precipitation methods were proposed to examine two chosen lines for both aerobic and anaerobic treatment.

3 LITERATURE REVIEW

Increased water scarcity led to development of many technologies that can help in maintaining environmental quality and decrease the impact on natural freshwater sources. Reuse of wastewater is therefore crucial to overcome natural shortage of water. Membrane technology has been widely applied over the past 30 years with the aim to produce various qualities of water. Large-scale commercial uses of membranes have displaced conventional separation processes (Sirkar *et al.*, 1992). Membrane technology has broad applications within chemical, petroleum, food, pharmaceutical, metallurgical, electronic and water treatment industries. The existing applications include: dialysis for purification of human blood, desalination of brackish water to produce potable water, desalination of seawater, sterilization of pharmaceutical and medical products, improvement of the quality of drinking water, etc. (Sirkar *et al.*, 1992). Lately, membrane separation processes were introduced to treat secondary and tertiary municipal wastewater. In wastewater treatment applications, membranes are currently being used for the removal of dissolved salts, organic compounds, phosphorus, colloidal and suspended solids, heavy metals and human pathogens, including bacteria, protozoan cysts, and viruses.
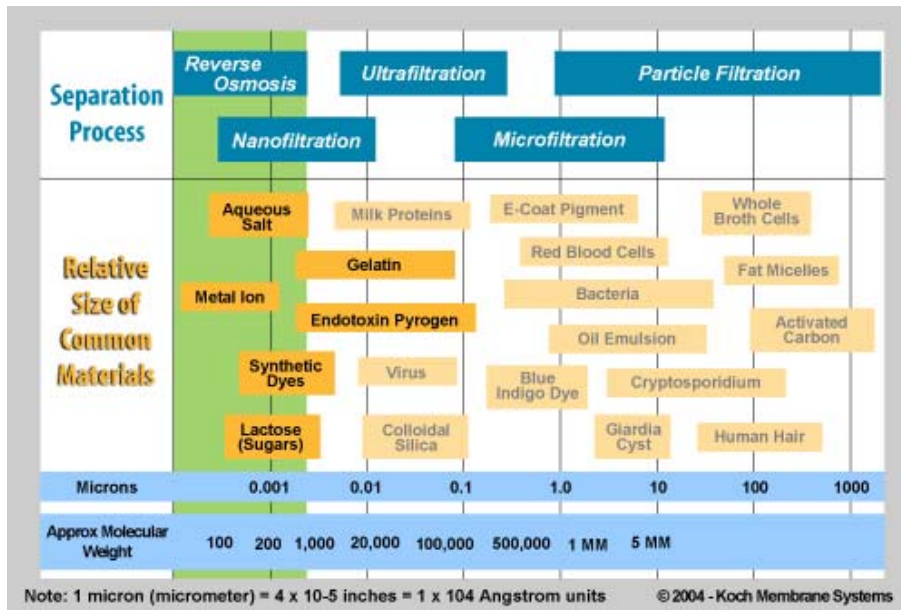
Table 1. Membrane separation process [1].

Membrane separation processes are classified into categories depending on the size of the particles they remove. The four categories, listed from the largest to the smallest pore size in the membrane, are MicroFiltration (MF), UltraFiltration (UF), NanoFiltration (NF), and Reverse Osmosis (RO) (Table 1).The MF is applied for the removal of particles at the size of 1.5-0.15μm. This range includes coarse particles, microbial cells and large colloids. The UF is used for the separation of particle having size range of 1.5-5x10^{-2}μm. This technique allows removing bacteria, suspended solids, oil and grease, macromolecules and colloids. The NF removes particle with sizes between 5x10^{-2}μm and 5x10^{-3}μm, including doubly charged ions (Ca^{2+}, Mg^{2+}, $(SO)_4^{2-}$). The RO is applied for the separation of particles at the size of 5x10^{-3}μm - 5x10^{-4}μm. This range includes apart from many others single-charged ions (Na^+, Cl^-) (Al-Enezi & Fawzi, 2002).

3.1 Reverse Osmosis Process

Reverse osmosis (RO) is a membrane process which initially was developed for the production of potable water from saline and brackish water (Sirkar *et al.*, 1992). However, the RO performance has been improved in recent years and begun to find applications in the treatment of water and hazardous waste, separation processes in the food, beverage and paper industry, as well as recovery of organic and inorganic materials from chemical processes. The process has also been applied to the treat municipal wastewater. The RO process has been used mostly for the removal of dissolved solids since they are not removed by conventional municipal treatment processes. Moreover, the RO process can also remove organics, colour, nitrate and low total dissolved solids (TDS) concentrations (Sirkar *et al.*, 1992). In the NEWater process, which is a significant part of future water policies in Singapore, reverse osmosis is used to treat domestic wastewater before discharging the effluent water back into reservoirs [2]. In the RO process turbidity, inorganics, virus, bacteria, protozoa and organics are removed from secondary effluent.Water recovery efficiency by an RO membrane was kept within the range of 80 to 82% [3]. The reverse osmosis process refers to normal osmosis phenomenon that is a natural movement of solvent (Parekh, 1988).

3.1.1 Transport models through RO membrane

In a reverse osmosis system, the driving forces that lead to solvent and solute transport through the membrane are pressure and concentration, respectively.

Numerous transport models were described in literature to present the solute and solvent flux
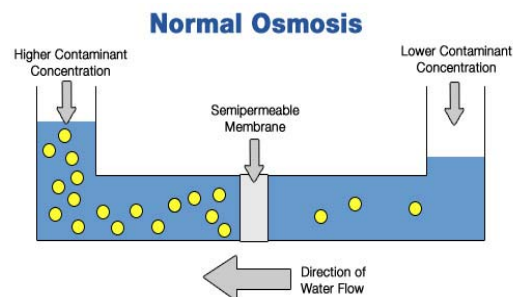
Fig. 1 Normal osmosis [4]
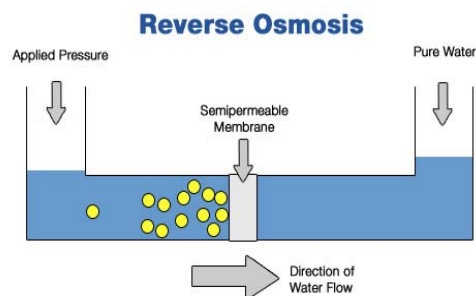
Fig. 2 Reverse osmosis [4]

through the RO membrane (Parekh, 1988). Generally they can be divided into 3 groups:

- nonporous (homogenous) models, in which it is assumed that the membrane is nonporous

- porous models, in which a membrane is assumed to be porous

- irreversible thermodynamics-phenomenological transport models in which the flow of each component in a solution is related to the flow of others components.

Most models for RO membrane use diffusion process or pore flow transport to perform the filtration process through the membrane. They are described below.

The solution-diffusion model, as an example of nonporous models, assumes that the solute and solvent dissolve in the nonporous surface layer of the membrane and then each of them diffuse across it due to its own chemical potential gradient. The differences in the solubility and diffusion of the solvent and solutes influence the flux through the membrane (Sirkar et al., 1992).

In the preferential sorption-capillary model (porous transport model) the membrane surface is microporous and transport occurs only through the pores. The membrane has stronger attraction to water, and as a result sorbed layer of almost pure water is forced through the membrane pores by pressure (Parekh, 1988).

Generally water flux, term to characterize the permeate throughput of the membrane, is expressed by equation (Parekh, 1988):

$$J = \frac{K}{l} (\ \Delta P - \Delta \pi) \qquad (1)$$

where:

J - membrane flux [l/hm²]

K- permeability (a membrane property)

l - thickness of membrane active layer

ΔP - pressure difference across membrane

$\Delta \pi$ - osmotic pressure difference across membrane (refers to the concentration difference of the solutions between the two sides of membrane).

Rejection term is used to quantify the removal of dissolved solute from the feed stream. Mathematically it is expressed as (Parekh, 1988):

$$R = \frac{Cf - Cp}{Cf} * 100\% \qquad (2)$$

where:

R-rejection [%]

Cp- concentration of solute in permeate

Cf-concentration of solute in feed

Most reverse osmosis technologies use a process known as cross-flow (Fig 3). The feed stream continuously passes over the membrane so that the fluid passes through the membrane and the rest continues downstream, sweeping the rejected species away from the membrane.
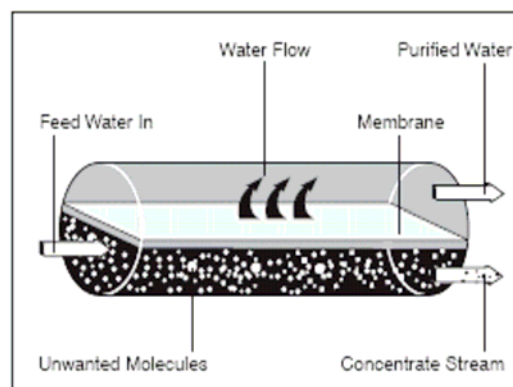
Fig.3 Reverse Osmosis Cross-Flow Filtration.

3.1.2 RO membrane types and modules

An ideal reverse osmosis membrane should be freely permeable to water and highly impermeable to soluble substances. It should withstand high operating pressures and be tolerant for wide ranges of pH. The resistance to scaling and fouling is also a factor of great importance.

Reverse osmosis membranes can be divided from a chemical point of view into celluosic or noncellulosic. Cellulosic membranes were the first commercial membrane types and are still very popular. The major advantage of these membranes is that they are chlorine insensitive and inexpensive. However, they suffer from many limitations. Their main drawback is that they do not have as high flux at comparable rejections as the noncellulosic membranes. They are susceptible to hydrolysis and operate in a narrow pH range (pH 4-6) and therefore require accurate pre-treatment methods (Parekh, 1988). However, their asymmetrical structure makes them vulnerable to compaction under high pressure.

Noncellulosic membranes are made of different types of synthetic polymers. They are characterized by higher flux and better salt and water-soluble organic rejection. They are less sensitive to pH variations. However, rapid and permanent loss in selectivity occurs when noncellulosic membranes are exposed to even low concentrations of disinfectants. As cellulosic membranes, they are also subjected to compaction at high pressures (Parekh, 1988).
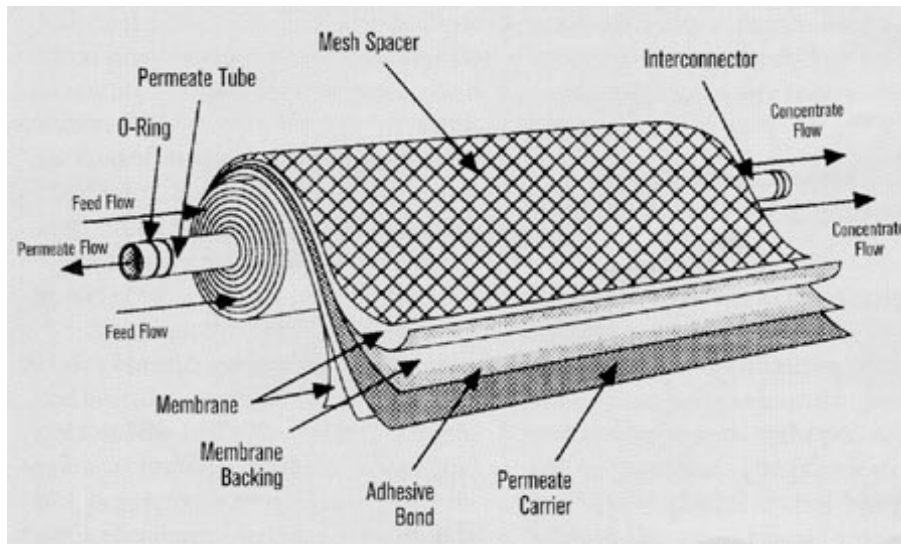
Fig.4 The spiral-wound module [6]

Regarding the physical structure, membranes can be classified as asymmetric and composite membranes. The surface of an asymmetric membrane is very thin and has very small pores or no porosity. The porosity increases with the thickness of the membrane. Solute rejection is accomplished by the thin dense surface layer and the porous substructure provides structural strength (Sirkar *et al.*, 1992). The conventional acetyl cellulose RO membranes are a common type for the asymmetric type of membrane.

The composite membrane has an extremely thin, solute rejecting surface film formed by coating on the top of a porous support. These two layers are different from one another in chemical composition. Each layer can be optimized for its function; the thin film layer can be optimized to obtain proper solvent flux and solute rejection, while the porous support layer can be optimized for maximum strength and compression resistance (Sirkar *et al.*, 1992).

The role of membrane surface morphology in colloidal fouling of cellulose acetate and composite aromatic polyamide reverse osmosis membranes was investigated by Elimelech *et al.* (1997). It was concluded that the surface roughness increases membrane fouling by increasing the rate of colloid attachment on to the membrane surface. Higher fouling rate was obtained for the thin-film composite membrane due to the surface roughness when compared with smoother active surface of the cellulose acetate membrane.

Membranes packed in containers are called modules. The aim of designing membrane modules is to isolate the feed and permeate flow and to limit membrane fouling as well as reduce the polarization layer by hydraulic design. There are four commercially available membrane modules: spiral-wound, hollow-fiber, tubular, plate and frame. At present, the spiral-would module is most widely used due to its high packing density and low price (Nicolaisen, 2002). The spiral-wound module consists of a membrane envelope (support with membrane on each side and closed on three sides) that is spirally rolled around a product water collection tube. The feed stream is passed into one end of the module. Water permeates the membrane and passes into the product channel where it travels in a spiral until it reaches the center of the module. There, it flows through the small holes in the water collection tube and exits the module. The concentrate exits the module through the concentrate outlet (Fig. 4).

3.1.3 The effect of operating parameters

The performance of a membrane unit is focused on obtaining desired solute rejections and water flux. It strongly depends on operating parameters such as the operational pressure, temperature, the pH value of the feed water, influent concentrations and feed flow rate.

The primary effect of increasing pressure is a linear increase in the water flux. Solute rejection generally increases with pressure up to a constant value. For organic solutes that strongly interact with membrane polymers, rejection often decreases with pressure (Sirkar *et al.*, 1992).

The most important effect of temperature is an increase in water flux while increasing temperature. Pure water flux change with temperature can be predicted by water viscosity change (Parekh, 1988). Generally, solute rejection decreases with increasing temperature, but for some membranes and solutes it can also remain constant over some temperature range.

The effect of pH can significantly influence the membrane performance. Process efficiency decreases irreversibly when the value of pH is too high or too low, causing a need to replace a membrane. The other effect has the pH value on ionizable organic solutes. Their separation can be strongly affected by changing pH. When the acid or base is in the ionized form the rejection is high, but in nonionized form they are not as easily rejected.

Concentrations of solutes in the feed water have a big effect on the membrane performance. An increase in

the osmotic pressure occurs parallel to an increase in concentration. Consequently, the water flux falls at a constant feed pressure. Solute rejection increases rapidly with decreasing feed concentration.

Higher flow rate causes greater water flux since it minimizes a concentration polarization by changing the mixing in the system (Hoornaert, 1984).

Additionally, the concentration polarization has a negative effect on the membrane performance. The concentration polarization is caused by an increase of the solute concentration near the membrane surface that results in a higher osmotic pressure of the feed solution and decrease in the water flux. The concentration polarization can change separation properties of a membrane, increase solute flux and lead to fouling.

3.1.4 Fouling phenomenon and the influence of pre-treatment methods

The feed solution which enters the reverse osmosis system contains contamination that can reduce membrane's productivity and shorten its life. Therefore, it is very important to pre-treat the feed waters to prevent membrane fouling. As complex phenomenon, fouling can be caused by many factors:

- metal oxides and colloids,

- biological foulants (slime forming materials on the membrane surface),

- silt - suspended solids and particles which plug module,

- scale - forming salts (e.g. $CaCO_3, CaSO_4$ which through exceeding the solubility limits in the concentration process precipitate on the membrane surface (Hoornaert, 1984),

- mechanical deterioration by the compaction of a membrane under the high working pressure,

- chemical attack (polyamide membrane are easily attacked by chlorine, cellulose acetate membranes are easily hydrolyzed)

- biofouling – the growth of bacteria on membrane surface (strongly depends on membrane composition, cellulose membranes are perfect nutrients for bacteria).

Fouling caused by silt, bacteria and organics affects the first modules in the RO plant the most. Scaling occurs to higher extent in the process supplied with the more concentrated feed water and that is why the last modules in the plant are mostly affected. They treat highly concentrated water.

The choice of pretreatment methods depends on the types and concentrations of contaminants in the feed solution and used type of module. Spiral-wound and hallow fiber modules require more extensive pretreatment system than a tubular module (Sirkar *et al.*, 1992).

Although the pretreatment system must be designed for each application and the nature of the feed water, the general RO pretreatment scheme has been developed over the years and should include (Hoornaert, 1984):

- removal of suspended solids, commonly by a series of filters,

- adjustment and control of the pH value in the feed (vital factor especially for cellulose acetate membranes),

- reduction in a tendency of the treated water to form scale (by acidification, water softening using lime or lime soda, or addition of antiscale agents-"threshold agents"),

- disinfection and prevention of slime growth

- prevention of chemical attack (e.g. dechlorination by adding $NaHSO_3$, important for polyamide membranes),

- coagulation/flocculation flowed by conventional filtration.

The literature concerning membrane technology provides wide information about feed water pretreatment techniques. Due to its sensitivity to blockage fine particles, it is a critical issue for a successful RO system. Durham and Walton (1998) suggest a pretreatment method using microfiltration (MF) membrane technology as it can reduce capital and operating costs on RO plants as well as allow the RO process to be used on a wider variety of water sources. Based on the long-term operating experience, Durham and Walton find continuous microfiltration (CMF) as an ideal pretreatment since it produces filtrate of a consistent quality irrespective of the feed water. It is pointed out that a traditional pretreatment technology for a RO system, such as deep-bed media filters, suffers from many limitations giving a variable quality of the treated water. Solids that continually escape from media filters decline RO process performance and shorten membrane life span.

In order to examine the performance of the cellulose acetate (CA) membrane with different water qualities, Lopez-Ramirez *et al.* (2002) applied three pre-treatment levels for the feed water from secondary effluent into the RO unit: intense treatment, moderated treatment and minimum treatment. The intense treatment consisted of a coagulation-sedimentation at high pH (using calcium hydroxide, ferric chloride and anionic flocculants), sand filtration, disinfection with sodium hypochlorite and UV, chemical dosing with the addition of anti-scaling, pH-value correction with hydrochloric acid and microfiltration. For the moderate treatment the same system was applied but without an addition of lime. In the minimum treatment only the process of settling, disinfection by chlorination and UV radiation, sand filtration and cartridge microfiltration were used. In terms of the wastewater reclamation process, safety and economic costs, the intense treatment turned out to be more suitable then other processes.

Currently, a trend in the feed water pre-treatment (before supplying a RO unit) is to combine microfiltration and ultrafiltration. This can replace the conventional pre-treatment, which includes the use of chemical additives and the necessity of using energy for mixing (Al-Enezi & Fawzi 2002).

3.1.5 Life span of the membrane

Membrane life expectancy is reduced with time due to irreversible fouling, boundary concentration polarization and membrane compaction. The effect of these side-processes can be minimized by choosing proper feed water pretreatment, operating parameters and cleaning procedures for membrane regeneration. Application of lower pressure and temperature can prolong membrane's life since it decreases compaction and lowers the flux that reduces fouling. It also brings savings in operating costs (electrical power costs) due to application of less expensive equipment (pumps, etc.). High temperature will reduce the membrane life causing hydrolysis of materials used to produce a module (Parekh, 1988).

To lengthen membrane's life, periodical or continuous cleaning of a contaminated membrane is required. The cleaning process should remove deposits and restore an optimal capacity and separation characteristics of a system. The frequency depends on the feed water quality and the pretreatment method.

According to Madaeni and Mansourpanah (2002), cleaning techniques can be divided into three types: physical, chemical and physio-chemical methods. Physical cleaning based on mechanical treatment removes foulants from the membrane surface. In chemical cleaning, chemical substances loose and dissolve deposits, scales and other foulants and keep them in solution to avoid new fouling. In an experiment carried out by Madaeni and Mansourpanah (2002), a variety of cleaning agents (acids, bases, enzymes and complexing agents) were examined for cleaning of the polyamide RO membrane fouled by whey. The results showed that hydrochloric acid (0.05w%) gave the maximum flux recovery and resistance removal.

Hoornaert (1984), presents different methods of membrane cleaning by: backwashing, rinsing the membrane with a separate liquid, the action of a liquid containing gas bubbles, vibration and a normal osmosis (pressure in the feed side is lowered causing water transport from the permeate side to the more concentrated side, the water transport has a cleaning action).

3.1.6 Energy consideration

Energy consumption is a major cost-effective factor in a reverse osmosis system. Energy costs include costs of pumps operation, pretreatment system and instrumentation (Sirkar et al., 1992). The biggest cost is for the pumps which transport the feed solution under high pressure through the module. The pressure has to be higher than the osmotic pressure of a feed solution. The energy costs can be lower by recovering the energy from the pressurized concentrate. Advanced reverse osmosis systems apply energy recovery devices such as Pelton well turbines or back-running turbine pumps (Parekh, 1988).

3.2 One-step RO process

The simplest design for applying the RO process is performed in single step (Fig. 5). In one-step system the feed water is directed to a membrane unit by high-pressure pump. The feed pumping pressure must provide economically feasible permeate flow and should be higher than the concentrate osmotic pressure (Al-Enezi et al., 2002).

3.3 Two-step RO process

In the literature, a 2- step RO process is often related to running two RO systems in series with the effluent permeate from the first unit acting as the feed second. The system with such configuration is called a 2-pass RO unit (Fig. 6).

Operation of a two–pass RO unit is commonly applied when a single-step RO system does not give the required quality of produced water or when additional expenses of operating the second RO system are lower than other polishing processes of the first-step permeate.

The RO system in which the concentrate from the first stage is used as a feed for the second stage is called two-stage RO system (Fig. 7). Two-stage RO system is often applied to increase an overall recovery ratio. However, no examples of using such a system were found in the reference literature to recover nutrients in the RO concentrate from municipal wastewater

Al-Enezi & Fawzi (2002) present a design consideration in the single RO unit, two-stage unit and two-pass unit configurations for brackish water.

The two-stage unit includes a number of modules connected in parallel, with lower number of the modules in the second stage. This is vital to maintain the proper velocity of the concentrate in the feed side of the second stage. Proper flow rate results in the sufficient turbulence to prevent fouling and scaling of the membrane surface. Another aspect is management of the pressure pumping units to optimize energy consumption and obtain high quality of the water product.

Al-Enezi and Fawzi (2002) suggest two options: the use of feed pumping units and intermediate pumps between two stages or a single pumping unit placed at the influent to the first stage. The first option increases the capital and operating costs, but allows avoiding excessive pressure in the first stage, which can result in higher salt passage. The other option allows for the reduction of costs due to the use of a single pumping unit but implies high operating pressure in the first stage which can lead to the increase of salt passage to the permeate.
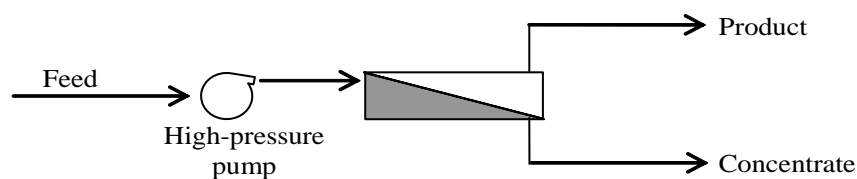
Fig. 5 One-step flow (Al-Enezi & Fawzi, 2002)
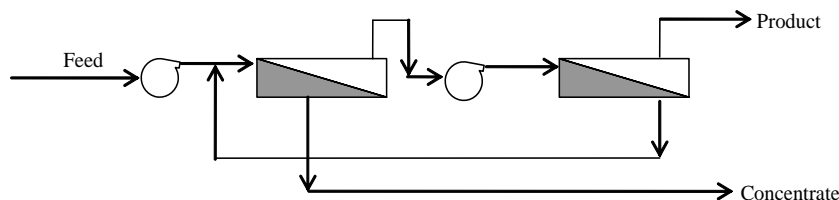
Fig. 6 Two-pass flow (Al-Enezi & Fawzi, 2002).
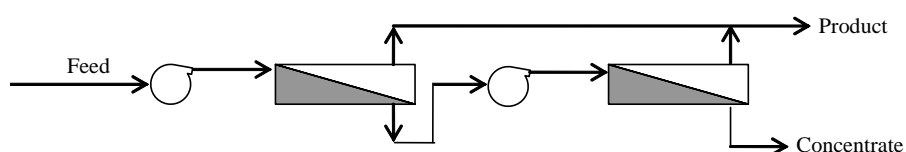
Fig.7 Two-stage flow (Al-Enezi & Fawzi 2002).

Taniguchi *et al.* (2000) used a concentrate conversion two-stage process in seawater desalination. The second stage was added to a conventional RO unit, and the concentrate from the first unit was further desalinated in the second step to increase water recovery ratio over 40 up to 60%. The main advantages of two-stage process are small plant size and low water production cost.

Hafez and El-Manharawy (2004) applied two-stage/two-pass RO membrane system for chromium removal from tannery wastewater. Chemically pre-treated chromium effluent was directed to a membrane separation unit to obtain the chromium recovery level of 60%. The concentrate from the first stage was further concentrated by the second RO membrane unit (Cr recovery level= 55%). The recovered permeate from both stages was further treated by a RO polishing membrane unit (Cr recovery level= 70%). The total removal efficiency of chromium by the RO membrane system was estimated as 99.5

3.4 Nutrients' recovery by RO process

Membrane technology literature provides some examples of nutrient removal from wastewater by RO membranes. Voorthuizen *et al.* (2005) investigated the possibility of nutrient recovery from black water using the RO technology. In the study, anaerobic treatment of black water was applied before an RO unit. After the anaerobic system, the major part of nutrients (ammonium and phosphate) remained in the effluent. Ammonium and phosphate rejection was measured for synthetic single salt, multi-ion mixture and in an anaerobic effluent. The results showed that the rejection of ammonium was between 80-90% and phosphate removal was above 90%. Regarding the salt mixture and anaerobic effluent, the results showed

that the guideline for water reuse as potable water was almost met in the case of phosphate removal. The rejection of ammonium was not sufficient in this regard.

Kurnna *et al.* (2002) tested RO membranes to remove high ammonia concentration from a wastewater plant effluent. The results obtained in this study indicated that the RO was an effective method for removing ammonium from the analyzed water. The concentration of ammonium was decreased from 6.5 mg/l to 0.2 mg/l with recovery rate of a 96.9%. Kurnna *et al.* (2002) suggested adding a RO unit at a wastewater treatment plant between the fine sand filter and the pure water storage tank.

Nitrogen separation by the RO process with tubular and spiral-wounded membrane modules was investigated in Norway on domestic wastewater (Bilstad, 1995). The obtained efficiency for total nitrogen removal was 95%. Regarding economic reasons, tubular membranes were considered unrealistic for high volume feed flow such as domestic effluents.

3.5 Removal of heavy metals by RO process

The conventional treatment option for wastewater containing heavy metals is chemical precipitation. To meet environmental regulations, big amount of chemicals are used to decrease the level of heavy metals in treated wastewater. In precipitation method, the chemical sludge has to be dewatered and disposed on landfills, which brings additional costs (Qdais & Moussa 2004).

Reverse osmosis has been applied in many studies for heavy metal removal, mostly for industrial wastewater, as a method that allows recovering valuable metals and preventing environmental degradation. Padilla and Tavani (1999) used polyamide a RO membrane to

remove chromium (III) from the tanning wastewater. The result showed an effective separation of chromium where only low metal content (7-10 mg/l) was present in the permeate. Ozaki *et al.* (2002) presented the feasibility of using an ultra-low pressure, aromatic polyamide RO membrane to separate heavy metals (copper, nickel and chromium (VI)) from synthetic wastewater and wastewater from the heavy metal industry. The study revealed the rejection of heavy metals greater than 95%. The application of RO technology was also investigated by Qadis and Moussa (2004) for treatment of wastewater containing copper (Cu^{2+}) and cadmium (Cd^{2+}). High removal efficiency was achieved by the RO process, as 98% of the copper and 99% of the cadmium was recovered. The effectiveness of the RO membrane technology in treating wastewater containing mixed heavy metals was also tested. The result showed that the RO membrane was able to reduce initial ion concentrations of 500ppm in wastewater to 3ppm with removal efficiency equal to 99.4%.

3.5.1 Concentrate application in agriculture

As one of the goals of the Hammarby Sjöstad project is to maximize resource recovery, it was proposed to use a concentrate with high nutrient content for agriculture purposes. However, to be able to utilize concentrate from a reverse osmosis process as a fertilizer it is essential to reduce the amount of heavy metals that can lead to serious soil contamination.

Precipitation is a method widely employed for heavy metal removal. Heavy metals are precipitated as hydroxide through the addition of lime ($Ca(OH)_2$) or caustic (NaOH) to a pH of minimum solubility (Munter, 1999). The main problem associated with this process is that hydroxides of different metals have different pH levels for minimum solubility. For example, nickel hydroxide has its lowest solubility at the pH value of 10.5-11 but chrome hydroxide is at a minimum solubility at the pH value 7.5-8 [7]. Therefore this method can lead to high levels of some metals still remaining in a solution. Another drawback of using lime for heavy metal removal from the concentrate is that it leads to phosphate precipitation and that separation of the phosphate from heavy metals will not be achieved.

Soluble metals can also be removed by precipitating them with sulfide by the addition of hydrogen sulfide to a solution [7]. At reducing conditions (low pE-values) heavy metals such as cadmium sulphides are precipitated (Fig. 8) while phosphates are soluble. This method gives therefore a more selective metal removal than using hydroxide precipitation. However, the need to regulate the excess sulfides makes the method more expensive and not as widely used as hydroxide precipitation [7]
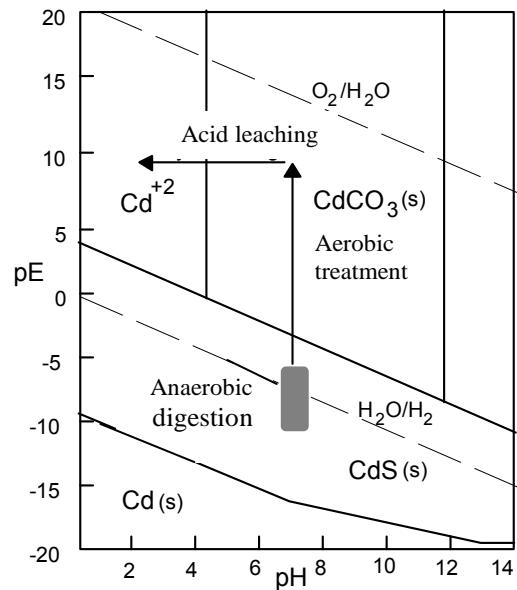
Fig. 8 Stability area for cadmium compounds in a diagram with pE against pH (Levlin et al. 1996, from Hayes et al., 1980).

In reference literature there are no direct guidelines concerning the limit values of heavy metals in the concentrate, which can be applied to soil. It was proposed to apply the ratio metal/phosphorous as a factor estimating maximum metal content in the concentrate. When fertilising with recovered phosphate it is the quotient of metal to phosphorous that decides the amount of metal transferred to the soil with fertilizer (Levlin, 1999). The quotient for maximum metal content in the stabilized sludge approved for agriculture use in Sweden (Swedish legislation SFS 1998:994) for the phosphorous content of 3% is shown in Table 2. The metal quotients in the concentrate higher than in approved sludge could be regard as inappropriate for agriculture application.

Table 2. Maximum metal content in sludge approved for agricultural use (Levlin, 1999).

Heavy metals in sludge approved for agriculture	mg Me/g P
Cadmium (Cd)	0.0667
Chromium (Cr)	3.33
Copper (Cu)	20
Lead (Pb)	3.33
Mercury (Hg)	0.0833
Nickel (Ni)	1.67
Zinc (Zn)	26.7

4 METHODOLOGY

4.1 The reverse osmosis (RO) plant

The Reverse Osmosis (RO) membrane plant used in the performed experiments was fed with the effluent from a chosen treatment line at Hammarby Sjöstad wastewater treatment plant. The RO unit consisted of a transition pump (power 0.49 kW), a feed tank (V=200 l), a high-pressure pump (power 4 kW), a single RO membrane module and a mixed permeate tank (V=200 l) in which produced clean water was stored (Fig.9).

to the inlet of the membrane element. A valve on the concentrate pipe allowed adjusting the pressure on the feed side of the membrane. The more the valve is screwed the higher pressure and the bigger the permeate flow. The feed water flow through the high-pressure pump was constant of 1200 l/h.

As the water passes through the RO system the concentrate stream gradually warms up due to the pressure drop over the valve. To be able to keep a constant temperature of the process and not allow the concentrate to reach too high temperature, the temperature control was set for 25ºC. Whenever the concentrate temperature exceeds 25ºC, cold tap water

Fig.9 The RO plant scheme (HE-heat exchanger; Pi-pressure meter; Ti-temperature meter)

The research was carried out with the use of the SW30-2540 spiral composite membrane from Filmtec (Dow). The membrane characteristics are presented in Table 3.

The first step of the system was a tank filled with effluent water from the chosen line. The transition pump directed the collected water to the feed tank. To diminish the risk of membrane fouling, an additional cartridge filter (pore size 10μm) was installed just after the transition pump in the tests with the effluent water from line 1. For the outcoming water from line 4, the sand filter was used instead of the cartridge filter to reduce the amount of suspended solids. From the feed tank, the water was pumped by a high-pressure pump

flows through the heat exchanger and cools down the concentrate. Due to safety precautions, the pressure meter is equipped with two safety cut-out switches. At pressure below and over the range of 8-55 bars the high-pressure pump is automatically switched off.

4.2 Pre treatment

All lines at the Hammarby Sjöstad plant with the RO unit as the last treatment step can be regarded as pre-treatment systems before the RO plant. Three different pre-treatment lines were tested in order to select the system that in combination with RO technology meets the environmental goals set by the Hammarby Sjöstad plant.

Table 3. The membrane characteristics.

Product name	Surface Area (m²)	Permeate Flow Rate (m³/d)	Stabilized Salt Rejection (%)
FILMTEC SW30-2540	2.8	2.6	99.4

The performance of the spiral-wound membrane strongly depends on the particle content in incoming water to the RO unit.

4.2.1 Line 1 – aerobic activated sludge system

The previous line 1 configuration consisted of an activated sludge system with biological phosphorous and nitrogen removal, hydrolysis and reverse osmosis for the recovery of residual nutrients. For the experiment purpose, the line was reconstructed to obtain highly nutrient-loaded water incoming to the RO plant (40-50 mg/l NH_4-N, 6-8 mg/l PO_4-P). The current line 1 scheme is shown in Figure 10.

The first step of the pre-treatment line included a primary sedimentation tank to separate suspended solids from the wastewater (the influent wastewater had already passed through the screens and the grid chamber before it entered the treatment line). The next section was an aerobic tank in which the organic material was oxidized to carbon dioxide. The produced sludge containing microorganisms and non-biodegradable suspended solids was removed in post-sedimentation tank. The final step before the nutrient removal in the RO process consisted of the sand filter where smaller particles were separated.

4.2.2 Line 2 – aerobic MBR system

The second line applied, as line 1, aerobic methods for wastewater treatment (Fig.11). After the pre-treatment consisting of a screen and a grit chamber sand, gravel, sticks and other large objects were removed. In the primary treatment, the drum filter was used instead of a pre-sedimentation to separate a portion of suspended solids from wastewater. The next step was the secondary treatment that included a biological treatment process to remove dissolved organic matter. Here, the membrane bioreactor (MBR) has been utilised to simultaneously use both membrane technology and biological technology. Membrane separation method replaced conventional secondary tank. A micro filter (Kubota-membrane 0.4μm) was placed at the bottom of the reactor. The filtrated permeate was directed to the RO unit.

In order to obtain highly nutrient-loaded water incoming to the RO plant, the effluent from the rotary filer was directly pumped to the aerobic zone in the MBR, bypassing anaerobic and anoxic zones. This MBR configuration allowed oxidizing the organic matter and avoiding biological phosphorous and nitrogen removal. The high concentration of phosphorous in soluble phase was possible to reach as P-accumulating organisms are not able to synthesize new polyphosphates in aerobic conditions without passing through the anaerobic zone. There, bacteria hydrolyze accumulated polyphosphates to use released energy to absorb biodegradable organic material. The biological removal of nitrogen was also stopped as the level of nitrate formation under anoxic conditions did not take place in the presented MBR configuration.
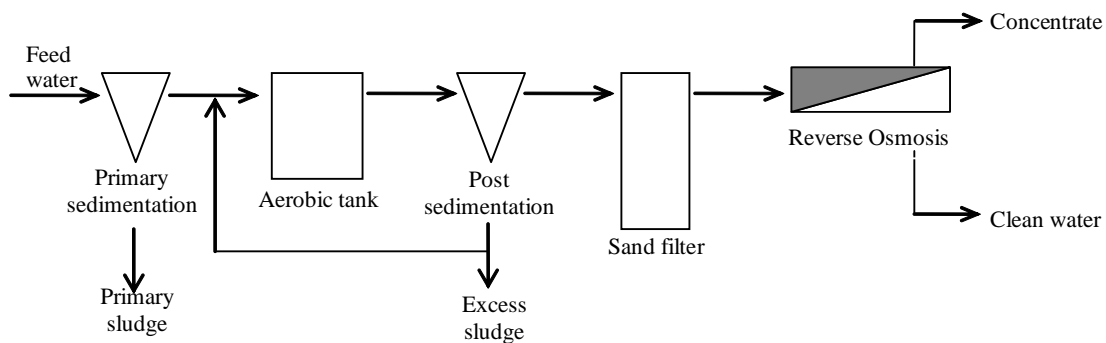
Fig. 10 The scheme of line 1.
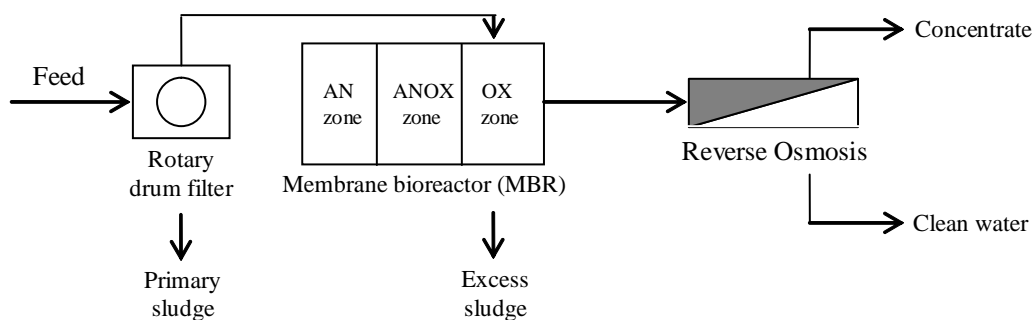
Fig. 11 The scheme of line 2 (AN-anaerobic zone, ANOX-anoxic zone, OX-aerobic zone)

However, the only measure undertaken to control the oxygen concentration in the aerobic zone was maintaining the high concentration of mixed liquor suspended solids (MLSS) amounting to 16-17 g/l. Having such a high MLSS concentration the nitrification process was unavoidable and the RO unit was supplied with nitrogen mainly in the form of nitrate.

4.2.3 Line 4 – anaerobic UASB system

Line 4 utilises an anaerobic treatment process to purify the wastewater from Hammarby Sjöstad (Fig.12). Before the influent water enters the treatment line it passes through the screens and the grit chamber where larger particles are separated from the wastewater stream.

After the pre-treatment units before line 4 the incoming water was directed to a primary sedimentation tank in order to remove suspended solids. Next step applied the process of organic matter decomposition in two UASB reactors (Upflow Anaerobic Sludge Blanket). The design of UASB reactors allows a wastewater stream to enter the reactor at the bottom and flow upwards through the floating granule bed. The granules are formed by anaerobic microorganisms and have excellent sedimentation properties that enable bacteria to stay in the reactor even in conditions of high wastewater flow. In the upper part of the reactor the clean water was separated from the produced gas and sludge. After passing through UASB reactors the effluent water was pumped to the bio-polishing step. Previously this section had been used for the biological nitrogen removal. During the experiments with the RO plant the bio-polishing step played a role mainly in reducing the organic matter content. In order to obtain highly nutrient–loaded water incoming to the RO plant and minimize nitrification process the oxygen concentration in the aerobic tank was decreased to 1 mg/l. Nitrification reactions were also inhibited by removal of a part of biofilm from the aerobic tank. The drum filter which followed the bio-polishing step allowed reducing a reduction of amount of suspended solids in the treated water. To obtain higher reduction efficiency the filter cloth was changed to the one with smaller pore size (10μm). In order to diminish the risk of membrane fouling the sand filter was utilized as the last step of the treatment process before the RO unit.

4.3 Determination of the volume reduction factor (VRF) and the water recovery rate

Volume reduction factor (VRF) was used to estimate the maximum water recovery rate. VRF is a ratio between total feed volume and concentrate volume and indicates how many times feed water was concentrated.

$$VRF = \frac{\text{Total feed volume}}{\text{Concentrate volume}}$$

The highest acceptable VRF is limited by the flux value and permeate quality.

In order to determine the maximum volume reduction factor (VRF) of a single membrane module, a test in a batch mode was run. The effluent water from the chosen treatment line was used as the feed water and stored in the feed tank. The test was done by directing the permeate stream into a second container (mixed permeate tank) while returning the concentrate stream to the feed tank (Fig. 13). The samples were collected at the outflow from the membrane unit (permeate stream), in the mixed permeate stored in the effluent tank and in the recirculated concentrate. The mixed permeate can represent the average effluent water from the full scale RO plant with several membrane modules. At each volume reduction step (VRF=1, 2, 5, 10, 20, 30, 50) the permeate stream was returned to the feed tank for 15 minutes to achieve stable flow conditions. Then the permeate flow was measured.

During the concentration process successive volume reduction steps VRF=1,2,5,10,20,30,50 allowed to obtained the water recovery rates of 0%, 50%, 80%, 90%, 95%, 96.7%, 98%, respectively (Fig. 14).
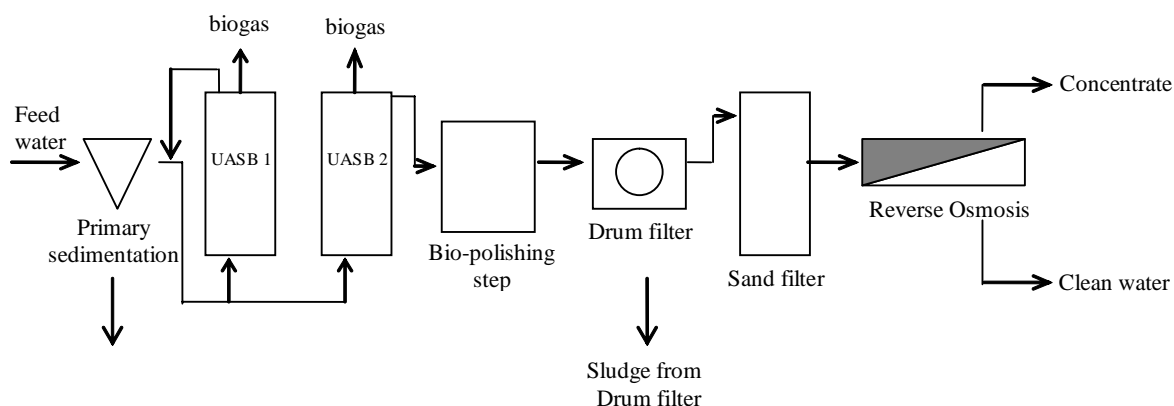
Fig.12 The scheme of line 4 (UASB-Upflow Anaerobic Sludge Blanket reactor).
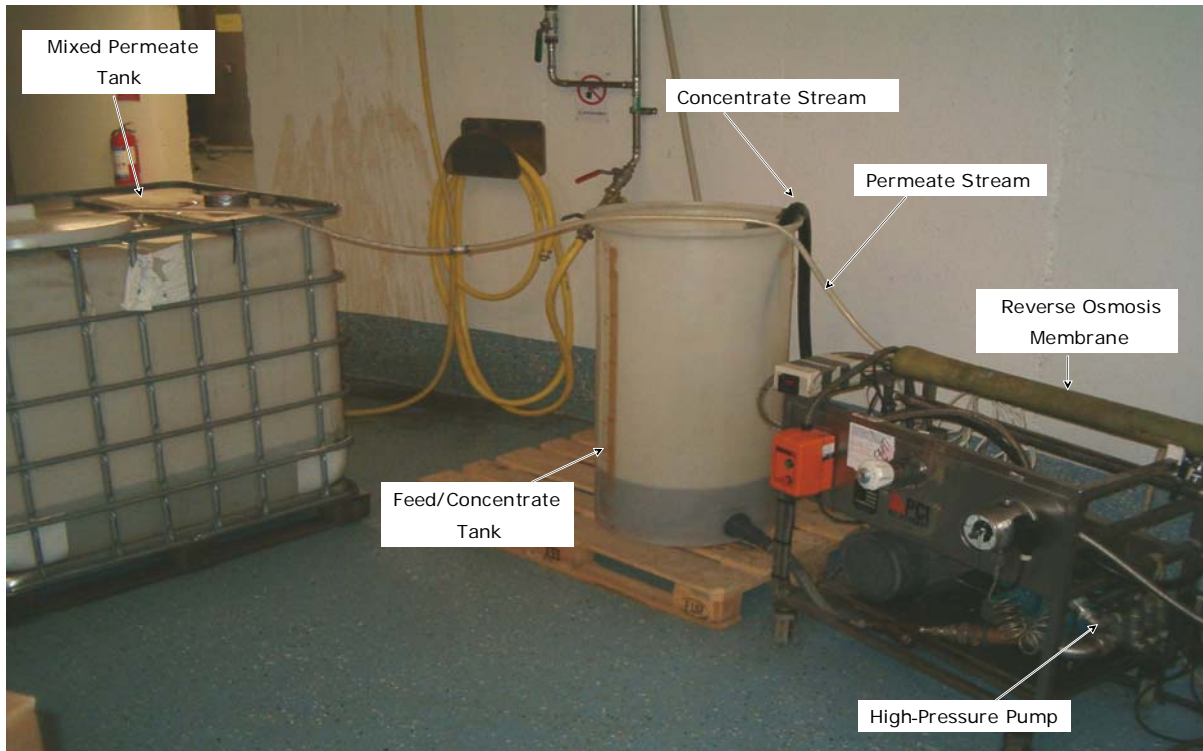
Fig.13 The RO plant.

Parameters of conductivity, pH and total solids (TS) in the concentrate were measured at all relevant reduction steps. In the feed water the concentration of suspended solids (SS) was also monitored. The test was run at a temperature of 25°C and a 40-bar pressure. Phosphate phosphorous (PO$_4$-P), ammonium (NH$_4$-N) and nitrate (NO$_3$-N) nitrogen were analyzed with HachLange spectrophotometer, model Xion 500. The acceptable limits for nitrogen and phosphorous concentrations in the RO plant effluent (mixed permeate) is 6 mg/l and 0.15 mg/l, respectively.

The collected samples from test 3 and 4 carried out for line 2 as well as the samples from all tests for line 4 were sent to Stockholm Waters' accredited laboratory. Total phosphorus (PO$_4$-Ptot), Kjeldahl nitrogen (Kjel-N), nitrite nitrogen (NO$_2$-N) and heavy metals (Cd, K, Hg, Ag, Pb, Mo, Cu, As, Zn, Ni, Cr, and V) were additionally analyzed.

In order to check the membrane stability and detect the occurrence of the fouling effect, a batch test was repeated several times. At the successive tests, a higher volume reduction factor was achieved in the experiment with the feed water taken from the line 1 effluent. The tests for line 2 and 4 were continued until VRF=30. A single experiment was also performed for line 2 and 4 testing the concentration process up to VRF=50.

4.4 The cleaning procedure

Membrane cleaning with base chemicals (pH=11), was performed after each batch test. The P3 ultrasil detergent solution was used at the final concentration of 0.2 %. The base chemicals are mainly used for the removal of organic contamination and bacteria from the membrane surface. The cleaning procedure was carried out using warm tap water (45°C) into which the detergent solution was added. The procedure was done at pressure equal to 8 bars and lasted 40 minutes. After the chemical cleaning, the membrane was rinsed out from detergents with warm tap water at the same conditions.

In case of not regaining membrane's initial capacity after washing with base solution membrane cleaning,

Fig.14 The effect of water recovery rate on VRF

with 2% citric acid solution (pH=2), was applied with the same procedure as described above. The acid chemicals allow removing accumulated inorganic constituents on the membrane surface.

4.5 Clean water test

The water test was performed after the cleaning procedure to control membrane performance before and after each run. The test checked to what extent the membrane capacity and salt reduction efficiency have been changed after each experiment. The conductivity parameter was measured in the concentrate and in the permeate to estimate the salt reduction. The permeate flow was also monitored. A significant decrease in salt reduction efficiency and permeate flow in relation to the water test performed before the experiment could indicate membrane fouling and scaling phenomena. The water test was carried out at temperature of 25°C and 40-bars pressure.

For the water test tap water was used. The typical tap water composition is presented in Appendix I.

5 RESULTS AND DISCUSSION

Before the RO plant was used in the first experiment, it was cleaned with washing powder (pH=8) at a temperature of 40°C and at low pressure (8 bars). The water test that was run after the cleaning at a temperature of 25°C and a 40-bar pressure showed a permeate flow of 78 l/h and a salt reduction of 99.4%.

5.1 Line 1

The results of analyses from the executed tests on line 1 are shown in Appendix II.

Test 1, line 1

The first test was performed with the feed volume V=200 l and stopped at VRF=10. The remained volume in the feed water tank was 20 l. At VRF=10, the recovery rate reached a value of 0.9 which is rather low for this kind of membrane. Ammonium nitrogen was the main source of nitrogen in the feed water from line 1. The limit for the nitrogen concentration in the effluent permeate was reached at VRF=5, where its reduction was estimated to 94.5%. However, in the mixed permeate the nitrogen concentration at VRF=10 was still below set limit and its removal efficiency equaled to 97.7%. The phosphorous reduction was estimated as 99.3%, both in the effluent permeate stream and the mixed permeate at VRF=10 where its concentration did not exceed the standards for the required permeate quality.

Taking into consideration the obtained removals for nitrogen and phosphorous in the mixed permeate it is possible to further increase the VRF in order to get good permeate quality. However, as constitutes in the
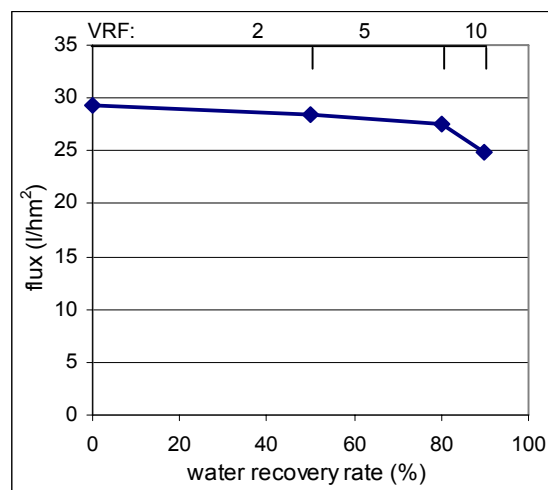
Fig.15 Permeate flux vs. recovery rate, test 1, line 1.

feed water accumulate more on the membrane surface with higher volume reduction factor, the pressure builds up on the feed side and the flux starts to decrease (Fig.15).

After the experiment, the membrane was rinsed twice with hot water at a pressure of 8 bars. During the water test the permeate flow was 76 l/h. A slight decrease in the permeate flow can be noticed when comparing the value from the water test done before the experiment (78 l/h).

Test 2, line 1

Before the second batch test run, the membrane was cleaned with chemicals (pH=11). During the water test the permeate flow came to 90 l/h and salt reduction was estimated to 99%.

The aim of the second test was to obtain a higher volume reduction factor and at the same time receive the required permeate quality. The feed water volume taken to the experiment was 400 l. However, the effluent water from line 1 contained low concentration of nitrogen and phosphorous due to the difficulties that occurred in the treatment process operation in line 1. The test was stopped at VRF=20 when the recovery rate reached 0.95. The set limit for nitrogen concentration in the permeate stream was exceeded at VRF=10. However, in the mixed permeate stored in the tank the nitrogen concentration was still bellow 6 mg/l, even at VRF=20. At this concentration step the nitrogen reduction efficiency amounted to 87.6%. The phosphorous concentration in both effluent permeate stream and mixed permeate was at a acceptable level, even at VRF=20, where the phosphorous reduction reached 98%.

The significant decrease in phosphorous concentration was noticed in the concentrate starting at VRF=5 (Fig. 16). The phosphorus concentration decline could have occurred due to its precipitation in the conditions of the increasing pH value in the concentrate tank.
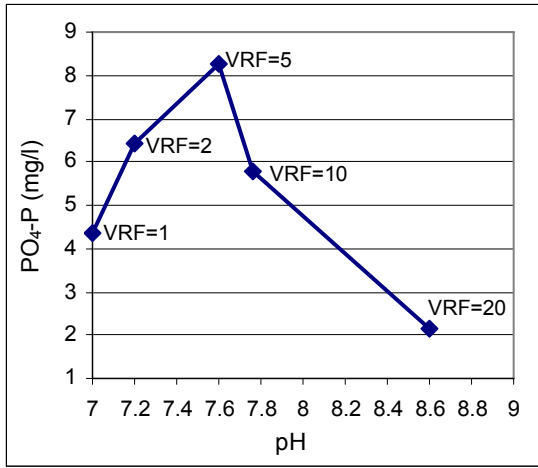
Fig.16 PO4-P concentration vs. the pH value in the concentrate, test 2, line 1.
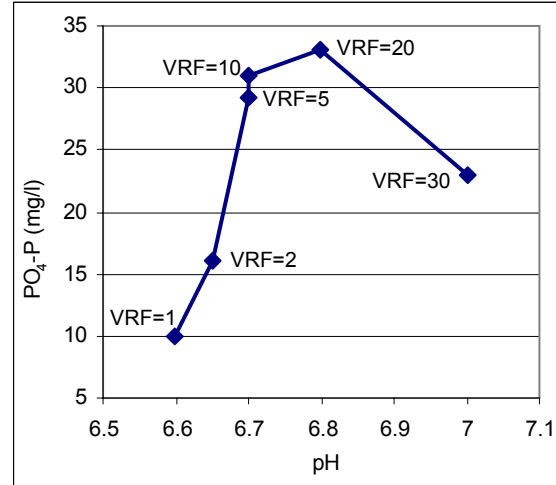
Fig.18 PO$_4$-P concentration vs. the pH value in the concentrate, test 3, line 1

Fig.17 Permeate flux vs. recovery rate, test 2, line 1.
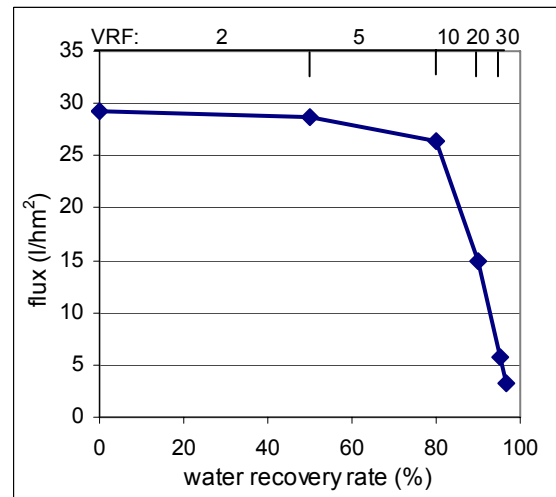
Fig.19 Permeate flux vs. recovery rate, test 3, line 1.

A considerable drop in the permeate flux (from 30 l/hm² to 3 l/hm²) appeared during the concentration process as a result of an increasing content of salts in the feed tank. This can signify the build up of different constitutes on the membrane surface due to e.g. scale formation or fouling phenomenon (Fig. 17).

After the experiment the membrane was chemically washed. The water test showed a significant decrease in permeate flow (from 90 l/h to 74 l/h), which could be evidence of membrane fouling and scaling. The salt reduction amounted to 97.8%. A decline in salt reduction during the water test (from 99% to 97.8%) indicated that the membrane performance deteriorated after the performed experiment.

Test 3, line 1

The third batch test was run with the feed water volume V=300 l and stopped at VRF=30. To inhibit the scale formation and the phosphorous precipitation phenomenon, the pH value of the water in the feed tank was adjusted at each VRF during the concentration process. Hydrochloric acid, with a concentration of 32% was added to maintain the pH

value in the range 6-7. However, inaccurate dosage of hydrochloric acid could influence unlinear increase of phosphorous concentration in the concentrate stream and its partial precipitation. As the pH value of the concentrate at VRF=30 reached the value of 7, no acid was added which resulted in a slight decline in phosphorous concentration in the concentrate stream (Fig. 18).

As in the previous experiments the permeate flow gradually decreased during the experiment due to material accumulation on the membrane surface (Fig.19).

At VRF=10 the nitrogen concentration reached 6 mg/l in the effluent from the membrane (permeate stream). However, in the mixed permeate the concentration of phosphorous and nitrogen analyzed to be under the set limits, even at VRF=30, with a reduction efficiency of 99.5% and 94.7%, respectively. The recovery rate reached 0.96 at the final reduction step.

After the experiment the membrane was cleaned with base chemicals. During the water test the permeate

Table 4. The NH₄-N and PO₄-P reduction, line 1.

VRF	NH$_4$-N reduction (%)			PO$_4$-P reduction (%)		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
1	95.3	97.7	97.6	95.3	98.8	99.2
2	96.1	96.8	98.0	99.6	99.2	99.4
5	94.6	95.9	98.9	99.6	99.4	99.6
10	89.6	94.3	98.4	99.8	97.6	99.6
20	-	87.6	96.4	-	98	99.6
30	-	-	94.7	-	-	99.8

flow increased 90 l/h which was the result of pH adjustment during the experiment. The salt reduction was estimated to 99.4%.

Discussion, line 1

The experiments aiming at determining the volume reduction factor (VRF) showed that it was possible to reach a VRF=30 and at the same time get the required permeate quality. However, during the concentration tests a systematic decline in permeate flow occurred which did not make the process cost-effective and indicated occurrence of membrane fouling.

The average flux obtained during the first test, when the VRF=10 was reached, amount to 27 l/hm². At this volume reduction factor the recovery rate was estimated to 0.9. The second test with VRF=20 resulted in the average flux equal to 25 l/hm². The recovery rate reached 0.95. In the last test (VRF=30) the average flux amounted to 23 l/hm² with the recovery rate value of 0.96.

The pH adjustment of the concentrate at each volume reduction step in test 3 resulted in higher reduction of ammonium than in the other two tests (Table 4 and Fig.20). Ammonium nitrogen exists in aqueous
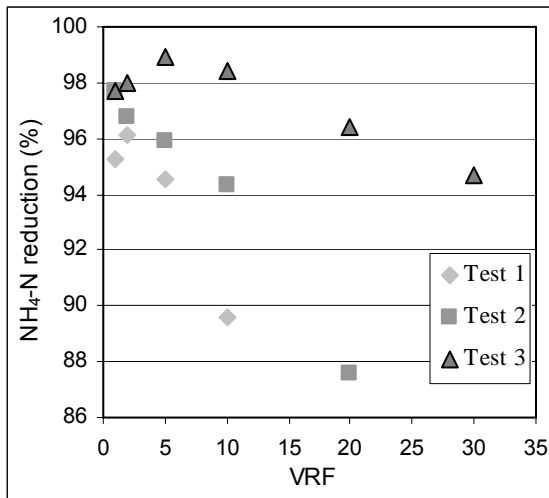
solution as either the ammonium ion (NH$_4^+$) or ammonia gas (NH$_3$) depending on the pH of the solution. According to the equilibrium reaction:

$NH_4^+ \longrightarrow NH_3 + H^+$ with increasing pH value nitrogen appears in gaseous form (pH>9) and faster diffuses through the membrane. To avoid the nitrogen loss from the concentrate it is important to adjust the pH value.

The phosphorous reduction efficiency showed a slight difference between tests 1 and 3 (Fig.21). During test 2 the phosphorous precipitation in the RO plant in conditions of increasing pH value resulted in lower reduction.

During the concentration process the decrease in permeate flux was monitored in all tests. The decline of flux is strongly depended on the increasing concentration of salts in the feed tank (Fig.22). The primary reason for this effect is the increase of osmotic pressure with an increasing concentration, which leads to a decrease of pressure difference between the two sides of the membrane and results in a flux decline in the condition of constant operating

Fig.21 PO₄-P reduction vs. VRF in test 1, 2 and 3, line 1.
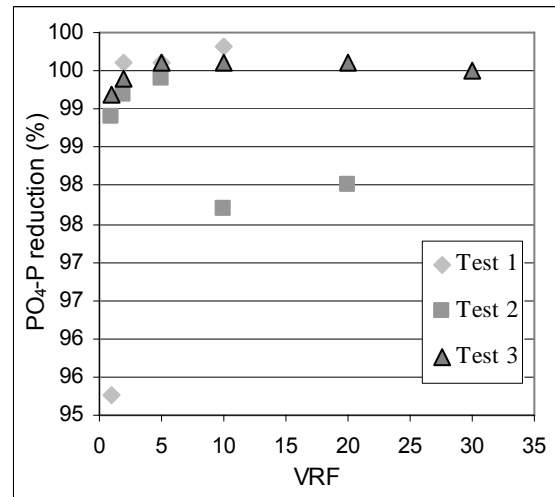
Fig.20 NH₄-N reduction vs. VRF in test 1, 2 and 3, line 1.
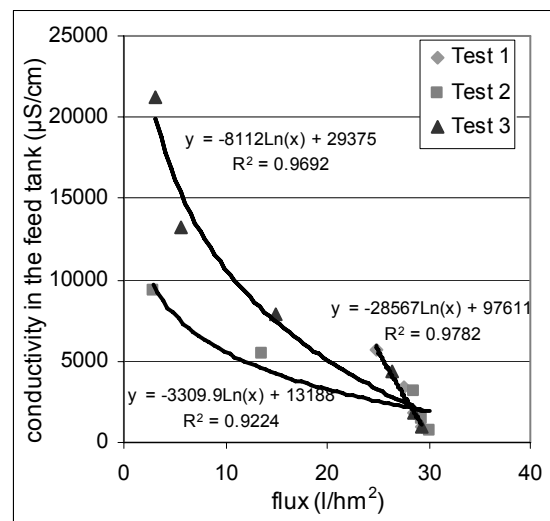
Fig.22 Conductivity in the feed tank vs.flux in tests 1, 2 and 3, line 1.
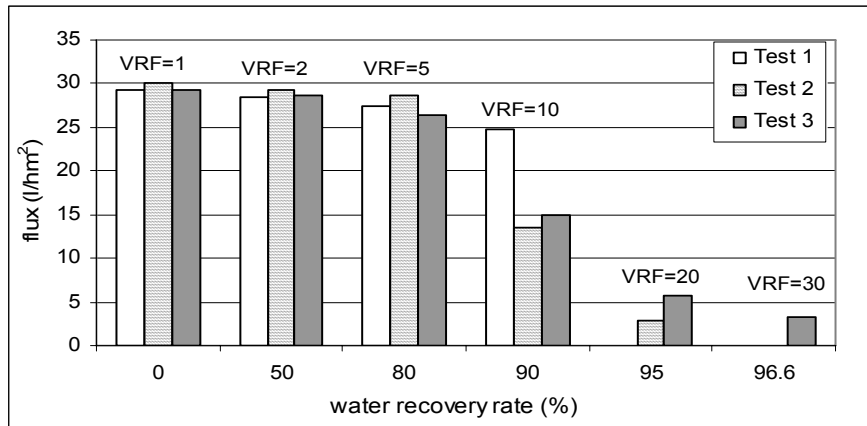
Fig.23 Flux comparison during the tests at successive recovery rates, line 1.

pressure.

In the last test performed on line 1 the feed water contained high concentration of SS (10mg/l). Their possible deposition on the membrane surface could influence faster flux decline than in other tests in the beginning of the experiment (Fig.23). However, due to the pH adjustment it was possible to reach VRF=30 with higher flux values in the end of the concentration process.

Conclusions, line 1:

- It was possible to efficiently concentrate the effluent water from line 1 thirty times (VRF=30) and obtain the water recovery rate equal to 96.6%.

- The produced mixed permeate at VRF=30 met the standards set by Hammarby Sjöstad for discharge water (N≤ 6mg/l, P≤0.15 mg/l).

- In order to be able to carry out an efficient process and inhibit scaling phenomenon (caused by e.g. phosphorous compounds precipitation) the pH value of incoming water to the RO membrane, had to be adjusted (pH in the range 6-7) during the concentration process.

5.2 Line 2

Four experiments were performed with the effluent from line 2. They were aiming at estimating the proper volume reduction factor of the RO plant. During three tests the feed water was concentrated 30 times. The fourth test was executed in order to check if it is possible to achieve VRF=50 and still obtain the required quality of mixed permeate.

The results of the analyses from the executed tests on line 2 are shown in Appendix III.

Test 1, line 2

During the first test the characteristics of the incoming water to the RO unit differed from the feed water in the tests performed later. It could be noticed that the pH value was higher and the concentration of NO_3-N and PO_4-P was lower when compared with later tests. Probably this difference was caused by unstable processes in the aerobic zone after reconstructing the MBR.

During the concentration process an increasing content of different salts in the concentrate caused systematic decline of the flux. However, at VRF=10 a drastic flux drop was observed and this effect progressed at further VRF steps until the end of the experiment (Fig.24).
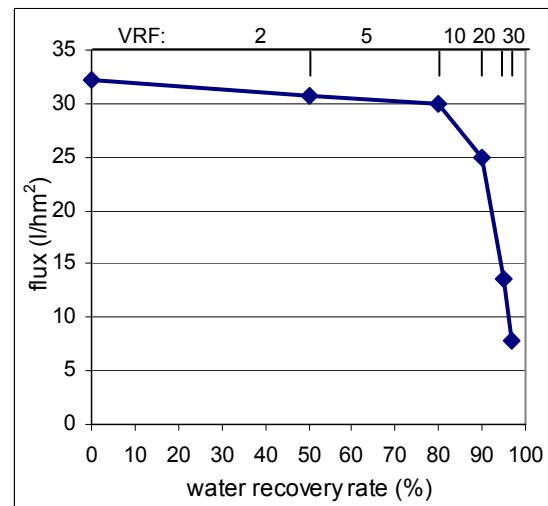
Fig. 24 Permeate flux vs. recover rate, test 1, line 2.

At VRF=10 a significant decrease in phosphorous concentration occurred. This is illustrated by Fig. 25. This phenomenon occurred due to phosphate precipitation on the membrane surface in conditions of increasing pH value in the concentrate. Additionally, a significant flux decrease at the same VRF can confirm the scale formation (pH>7).

Nitrate nitrogen was the main source of nitrogen in the effluent water from line 2 as a result of the nitrification process that took place in the aerobic zone of the MBR. The set limits for nitrogen content was exceeded only at VRF=30 in the permeate stream, whereas in the mixed permeate stored in the tank its concentration was still much below 6 mg/l. The phosphorous concentration in both permeate and mixed permeate was at acceptable level during the
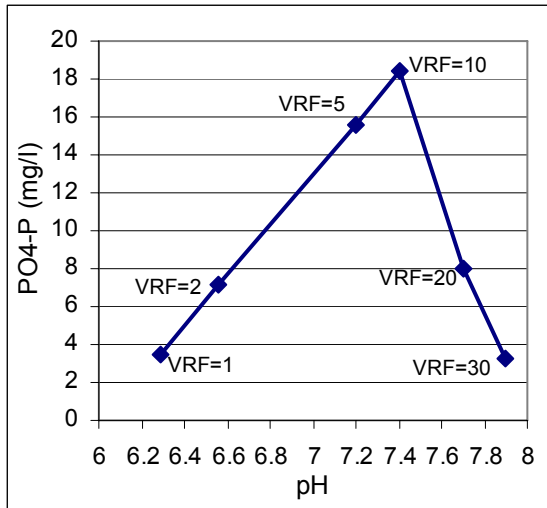
Fig.25 The PO₄-P concentration vs. the pH value in the concentrate, test 1, line 2.

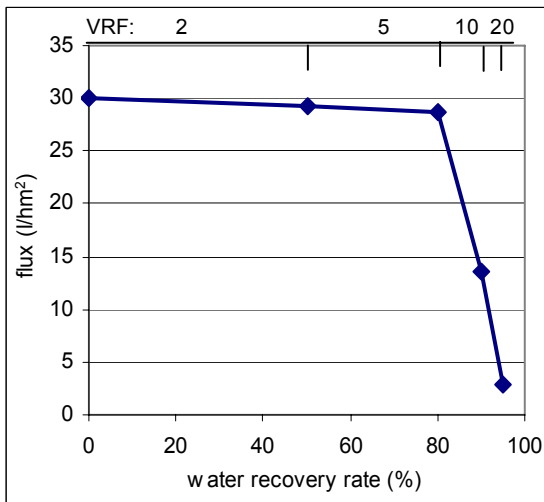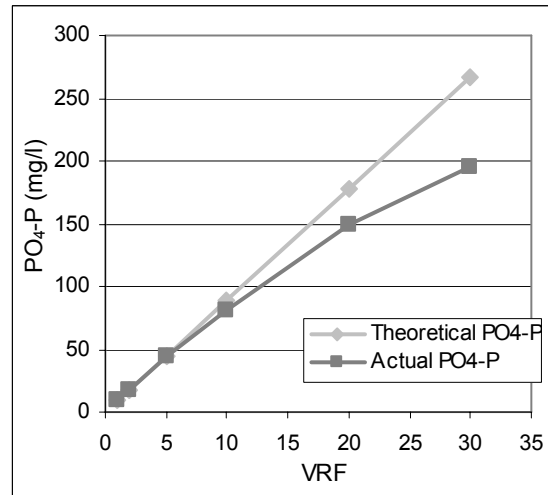**Fig. 27 PO₄-P concentration in the concentrate vs. VRF, test 2, line 2.**

Fig. 26 Permeate flux vs. recovery rate, test 2, line 2.

Fig. 28 NO₃-N concentration in the concentrate stream vs. VRF, test 2, line.
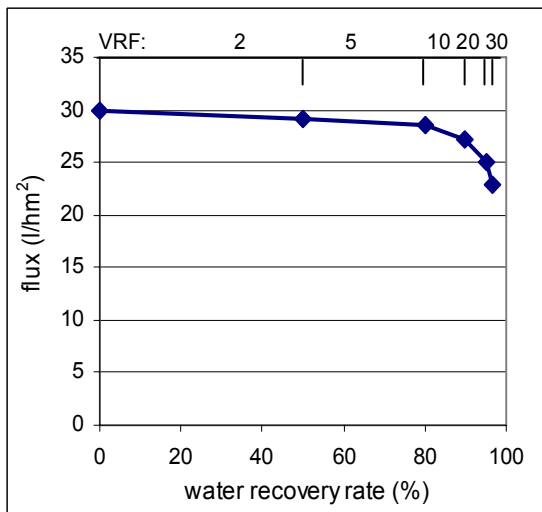
whole concentration process. In the mixed permeate the reduction efficiency of phosphorus and nitrogen (NO_3-N + NH_4-N) was estimated to 98.8% and 98.5%, respectively.

After the experiment the membrane was cleaned with base chemicals. The water test showed a significant decline in permeate flow (from 90 l/h to 76 l/h). This could indicate membrane fouling and scale formation. The salt reduction amounted to 99%.

In order to recover the membrane flux and be able to analyze the amount of phosphate which could possibly precipitate from the concentrate during the next experiment, cleaning with citric acid was performed. During the water test performed after washing with acid chemicals the permeate flow reached 84 l/h.

Test 2, line 2

The influent pH value of 5.5 and a higher concentration of NO_3-N and PO_4-P (36.7 mg/l and
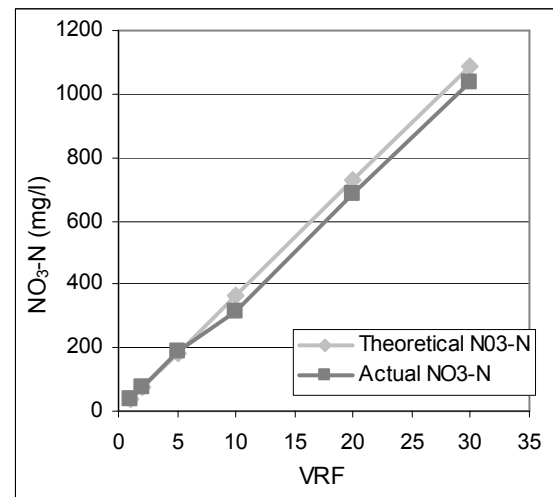
9.1 mg/l, respectively) indicated that the treatment process in MBR reached steady state.

During the concentration process the flux declined gradually having still at VRF=30 high value (23 l/hm²). The average flux obtained during the test came to 29 l/hm² (Fig.26).

Contrary to the previous experiment no decrease in phosphate concentration in the concentrate stream took place as the highest pH value at VRF=30 was below pH=7. However, the phosphate content in the concentrate was lower at VRF=20 and 30 than what was expected from theoretical calculations (Fig.27). This phenomenon could be influenced by the precipitation of different phosphate compounds e.g. $MgNH_4PO_4$.

The separation of nitrate nitrogen did not show a considerable difference between actual concentration in the concentrate stream and the theoretical one suggested by the volume reduction factor (Fig. 28).
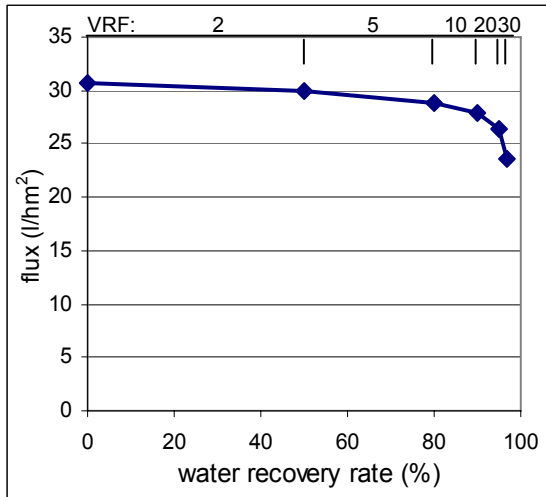
Fig. 29 Permeate flux vs. recovery rate, test 3, line 2.
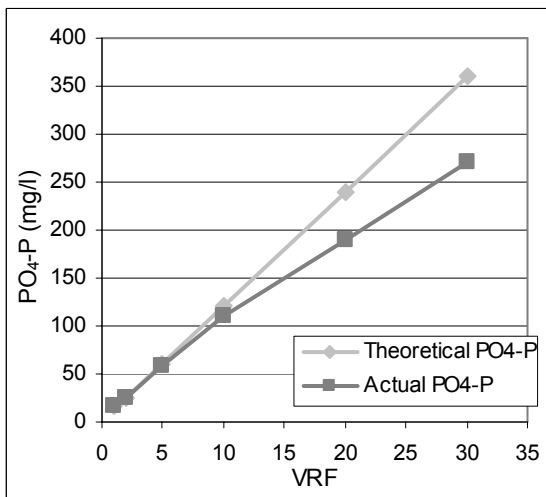
Fig. 30 PO₄-P concentration in the concentrate stream vs. VRF, test 3, line 2.

The concentration of phosphorous and nitrogen in both permeate stream and mixed permeate was below set limits even at VRF=30. The reduction efficiency amounted to 99.9% for phosphorous and 99.5% for nitrogen (NO_3-N+NH_4-N).

After the experiment the membrane was cleaned with acid chemicals (pH=2). During the water test permeate flow increased from 84 to 86l/h. The salt reduction was estimated to 99%.

Test 3, line 2

The third test was executed in order to verify the results obtained in the previous experiment.

During the concentration process a slightly better flux was noticed at each volume reduction step, with the average flux higher than 29 l/m²h (Fig.29).

As in the second . experiment, the phosphate phosphorous concentration in the concentrate stream at VRF=20 and 30 were lower than the theoretical

Fig. 31 NO₃-N concentration in the concentrate stream vs. VRF, test 3, line 2.

(Fig. 30) probably due to precipitation of different phosphate compounds.

During the test the nitrate nitrogen separation did not act in the same manner as indicated by theory. Consequently, lower than expected concentrations of NO_3-N were found in the concentrate stream (Fig.31)

The phosphorous limit was already reached at VRF=10 in the permeate stream, while in the mixed permeate the phosphorous and nitrogen concentration were still below 0.15mg/l and 6 mg/l, respectively. During the experiment phosphorous reduction came to 99.9% and for nitrogen (NO_3-N+NH_4-N) it was equal to 99.3%.

After the test, the membrane chemical cleaning procedure (pH=11) was carried out. During the water test the permeate flow raised to 90l/h. The salt reduction remained at the same level as before the experiment (99%).

Test 4, line 2

The aim of the fourth test was to examine if it is possible to further concentrate the feed water from line 2 (up to VRF=50) and at the same time receive the required permeate quality.

Like in previous tests the water flux was gradually declining due to the increasing salt content in the feed tank during the concentration process (Fig.32). The estimated average flux in the experiment was marginally lower than during the previous tests.

The samples from the concentrate stream, permeate stream and the tank with mixed permeate were taken only at VRF=20 and 50 during the last test. The analyses of phosphate phosphorous and nitrate nitrogen showed a difference between the actual concentrations in the concentrate stream and the theoretical ones. The biggest variation was noticed at VRF=50, where 67% and 69% of the theoretical phosphate phosphorous and nitrate nitrogen concentrations respectively were found in the residual stream.
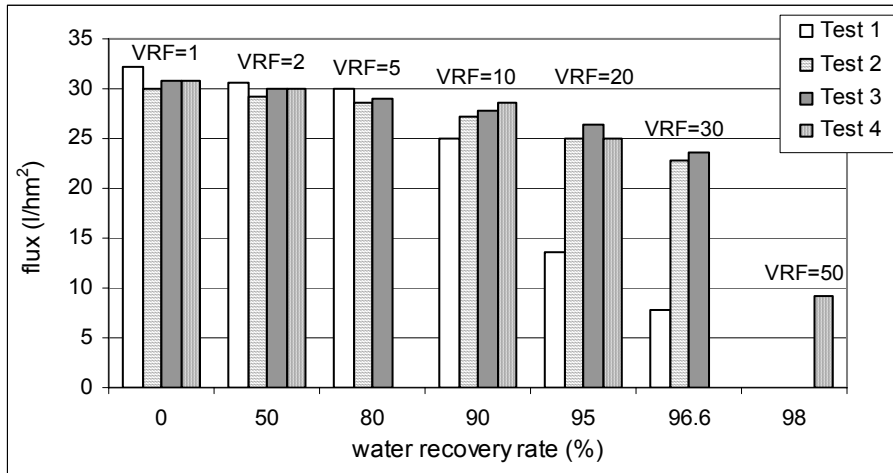
Fig. 33 Permeate flux comparison during the tests at successive recovery rates, line 2.

The standards for the permeate quality were exceeded in the permeate stream at VRF=10. However, in the mixed permeate tank the nitrogen and phosphorous concentration were still below the set limits, even at VRF=50. At this step phosphorous reduction efficiency came to 99.8% and for nitrogen (NO_3-N+NH_4-N) it reached 98.7%.

Discussion, line 2

The performed concentration processes demonstrated that, at constant operating pressure, the permeate flux decreased gradually due to higher salt content in the feed tank with the successive volume reduction step (Fig.33). However, the estimated average flux indicates that the process can be efficient even at VRF=50 (average flux around 29 l/hm²).

During the three last tests low pH values (5.4-5.6) of the water incoming to the RO plant could positively influence the flux. The effluent water from line 2 was acidified due to the robustly occurring nitrification

process in the MBR ($NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + 2H_2O$). As a result of the pretreatment method before the RO unit the scale formation and fouling phenomenon was minimized.

One important factor, which determines the amount of ions passing through the membrane is charge. In general, multi charged ions are better retained than a single charged because they interact more with the polymer the membrane is built up. However, during the tests only a slight difference in reduction efficiency between nitrate nitrogen and phosphate phosphorus could be noticed (Table.5).

The lowest phosphate phosphorous reduction efficiency was observed during the first test when the pH value of incoming water to the RO plant was higher than in the other tests (Fig.34).

The comparison of NH_4-N and NO_3-N reduction efficiency shows that the removal of nitrate nitrogen is higher than ammonium nitrogen (Fig.35, 36). NO_3^- ions have bigger molecular weight and therefore are better separated by the membrane.
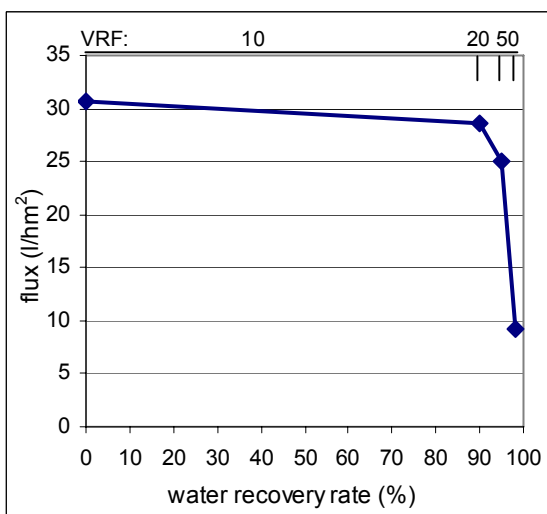
Fig. 32 Permeate flux , test 4, line 2.
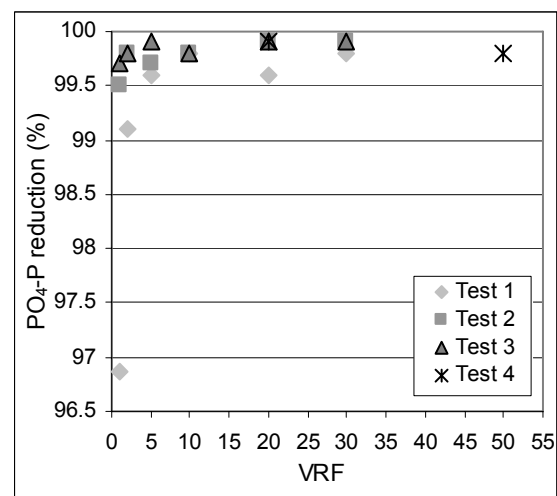
Fig. 34 PO4-P reduction vs. VRF in test 1, 2, 3 and 4, line 2

Table 5. The NH₄-N, NO₃-N and PO₄-P reduction efficiency, line 2.

VRF	NH$_4$-N reduction (%)				NO$_3$-N reduction (%)				PO$_4$-P reduction (%)			
	Test1	Test2	Test3	Test4	Test1	Test2	Test3	Test4	Test1	Test2	Test3	Test4
1	96.7	92.5	-	-	98.2	99.9	98.9	-	96.9	99.5	99.7	-
2	96.3	94.5	-	-	99.1	99.2	99.1	-	99.1	99.8	99.8	-
5	95.9	96.6	-	-	99.3	99.3	99.3	-	99.6	99.7	99.9	-
10	95.1	97.3	45	-	99.5	99.4	99.4	-	99.8	99.8	99.9	-
20	93.5	97.7	81.2	96.4	99.2	99.6	99.4	99.5	99.6	99.9	99.9	99.9
30	92.0	97.9	66.6	-	98.8	99.5	99.5	-	98.9	99.9	99.9	-
50	-	-	-	97.4	-	-	-	98.8	-	-	-	99.8

The analyzed concentrations of PO$_4$-P and NO$_3$-N content were lower than the theoretical values expected at different volume reduction steps. It could be especially noticed at VRF equal to 30 and 50. The difference between the actual PO$_4$-P and NO$_3$-N concentrations in the concentrate stream and the theoretical concentrations could occur due to loss of ions in the RO system. However, no analyses of PO$_4$-P and NO$_3$-N concentration were done in the water from the chemical cleaning.

Based on the parameters of total solids (TS) and conductivity, it is possible to recalculate the volume reductions steps that were obtained during the test runs. The term total solid refers to the suspended and dissolved matter (such as mineral ions calcium, phosphorous, iron, sulfur and bicarbonate) in water or wastewater.

The conductivity is a measure of the ability of water to pass electrical current. Conductivity in water is affected by the presence of inorganic dissolved solids such as chloride, nitrate, sulfate and phosphate anions or sodium, magnesium, calcium iron and aluminum cations. Organic compounds do not conduct electrical current very well and therefore have a low conductivity value in water. The conductivity parameter provides information concerning chemical composition of water and is directly linked to the concentration of the ions and their mobility.

The volume reduction factors were calculated as a ratio expressing increasing concentration of total solids-VRF (TS), and conductivity-VRF (Cond) during the concentration process in the feed tank. Taking into account the VRF (TS) values it can be noticed that they approximately represent the concentration steps that were estimated based on water volume in the feed tank, with an exception for the test 4 (Table 6). In tests 1, 2 and 3 marginally lower VRF (TS) values were obtained due to possible sedimentation of particles in the feed tank. During the concentration process, the content of particles increased per water unit and the probability of sedimentation got enhanced. The difficulties that occurred during the RO plant operation at the highest VRF could strongly influence
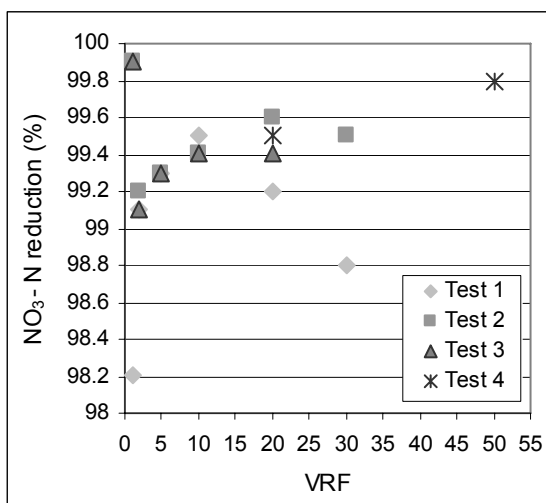
Fig. 35 NO₃-N reduction vs. VRF in test 1, 2, 3 and 4, line 2.
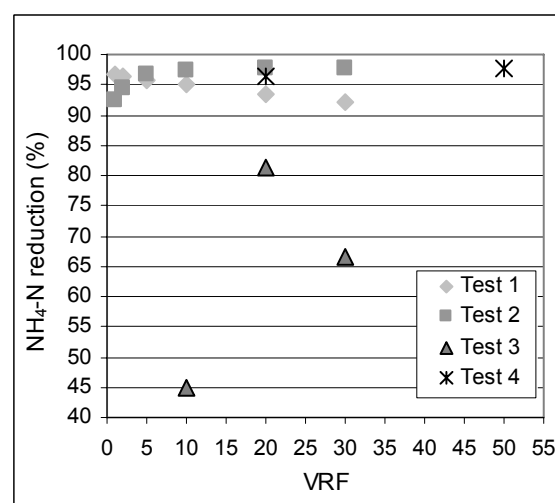
Fig. 36 NH₄-N reduction vs. VRF in test 1, 2, 3 and 4, line 2.

Table 6. Comparison of theoretical VRF and calculated VRF from TS and conductivity, line 2.
(Cond-conductivity, TS-total solids)

VRF	Test 1			Test 2			Test 3			Test 4		
	VRF (TS)	VRF (Cond)		VRF (TS)	VRF (Cond)		VRF (TS)	VRF (Cond)		VRF (TS)	VRF (Cond)	
		with ion losses to permeate	without losses to permeate		with ion losses to permeate	without losses to permeate		with ion losses to permeate	without losses to permeate		with ion losses to permeate	without losses to permeate
2	2.2	2.0	2.0	1.9	1.9	1.9	2.2	2.0	2.0	-	-	-
5	5.1	4.5	4.5	5.2	4.6	4.5	5.6	4.5	4.5	-	-	-
10	9.8	7.9	7.9	9.3	7.9	7.7	10.5	8.1	8.0	21.7	8.2	8.0
20	16.8	13.8	13.0	18.5	14.5	14.0	17.9	13.1	12.9	24.2	15.6	15.
30	26.5	19.6	18.7	28.5	21.9	20.4	27.0	19.1	18.6	-	-	-
50	-	-	-	-	-	-	-	-		35.7	27.9	25.6

much lower values of VRF in the test 4.

The VRF (Cond) results showed to be much lower than the theoretical VRF (Table 6). The difference in the theoretical and calculated values could be noticed starting at VRF=10 and enlarged with successive reduction steps. Conductivity was compared with theoretical conductivity values calculated for analyzed ions (Appendix V). These calculations demonstrated that the parameter was mostly influenced by other ions whose concentrations were not analyzed during the experiments e.g. Na^+, Cl^-, Ca^{2+}. Their precipitation from the feed solution probably resulted in the significantly lower value of VRF (Cond) than the theoretical VRF value. Ion loss through the membrane to the permeate stream marginally contributed to the lower value of VFR.

The difference in VRF (TS) and VRF (Cond) suggests that the precipitation process is more depended on the concentration than the sedimentation process (Tab. 6). Precipitation occurs when concentration of different ions increases in the feed tank. Precipitation on the suspended solid particles in the feed tank causes growth of solid particles that leads to an enhancement of the sedimentation process.

Conclusions, line 2:

- The effluent water from line 2 was efficiently concentrate up to VRF=50 and obtain water recovery rate reached 98%.
- The quality of produced mixed permeate at VRF=50 did not exceed the limits set by Hammarby Sjöstad for wastewater effluent plant (N≤ 6mg/l, P≤0.15 mg/l).
- Slightly acid characteristics of incoming water to RO plant (due to the nitrification process in MBR) positively influenced the flux and minimized the occurrence of scaling and fouling phenomena.

5.3 Line 4

Four tests were executed with the effluent water from line 4 in order to reach the highest possible VRF. The quality of mixed permeate before discharge was of great importance.

The results from the tests done on line 4 are shown in Appendix IV.

Test 1, line 4

The first test was stopped at VRF=10. At that concentration level a significant decrease of flux occurred and prevented the process to continue efficiently (Fig. 37). The drastic flux drop was probably influenced by the precipitation of phosphates and the scale formation on the membrane surface with an increasing value of pH in the concentrate during the process.

The analyses of phosphate phosphorous in the concentrate at VRF=10 demonstrated much lower concentration than expected to obtain. Only 18.3% of the PO_4-P concentration was present in the concentrate stream, which indicates the phosphate phosphorous precipitation in the RO system.

The ammonium nitrogen concentration in the concentrate also occurred to be lower. 80% of the expected concentration value was found in the concentrate at VRF=10. Probably, the missing 20%
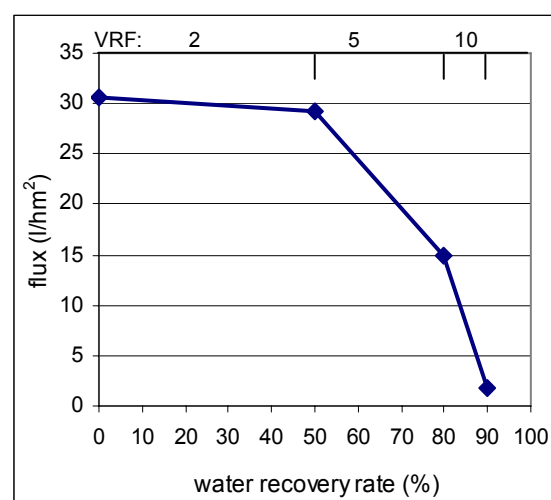
Fig. 37 Permeate flux vs. recovery rate, test 1, line 4.

were lost in the form of ammonium gas (NH₃) due to high pH value of the concentrate (pH=8).

The nitrate nitrogen content in the concentrate stream did not show big variations between expected and obtained concentrations.

In the permeate stream, the set limits for the effluent water were exceeded at VRF=10 by both nitrogen and phosphate parameters. Their reduction efficiency amounted to 89.9% and 90.9%, respectively. However, the mixed permeate represented met the required quality (N≤6 mg/l, P≤0.15 mg/l) at VRF=10.

After the experiment, the membrane was washed with base chemicals. The water test performed after the cleaning showed a drastic decline in permeate flow. The flow was now 34 l/h, compared to 78 l/h before the experiment. The salt reduction efficiency also occurred to be lower after the executed experiment and was calculated to 96.9% (before the test 99%). Both permeate flow and salt reduction efficiency decrease can indicate the occurrence of scaling and fouling phenomena during the concentration process. The membrane contaminations were not possible to remove with membrane cleaning by a base solution.

To restore the initial membrane capacity and regain the satisfactory reduction efficiency the membrane was washed with citric acid solution. During the water test carried out after the cleaning with acid chemicals, the permeate flow increased up to 84 l/h and the salt reduction efficiency came to 99.2%.

Test 2, line 4

The second batch test was run with pH adjustment in order to inhibit scale formation and precipitation of different salt compounds on the membrane surface. The 32%-hydrochloric acid was added to the feed tank at each VRF to maintain the pH value in the range of 6-7. Total volume of acid used during the experiment equaled to 140 ml per 300 l of feed water from line 4.

As a result of the pH adjustment the flux decreased gradually during the concentration process having still high value at VRF=30 (Fig.38). Compared with test 1,
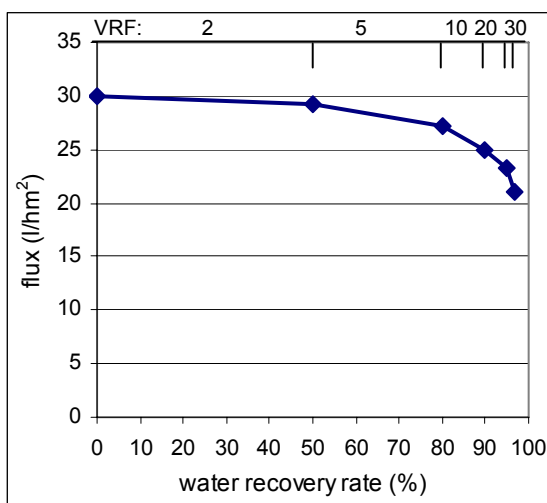
the flux at VRF=10 was five times higher than in test 1.

The analyzed concentrations of phosphate phosphorous in the concentrate at VRF=10 and 30 showed approximately the same values as the ones indicated by corresponding volume reduction step. This was the consequence of the hydrochloric acid addition during the test (Fig.39). At VRF=20 the pH was not adjusted as at VRF=10 to much acid had been added in the feed tank and the pH value dropped to 5.5. However, during the concentration process up to VRF=20 the pH value increased and influenced the PO₄-P concentration. It seemed to be lower than the theoretical value. At VRF=20 the precipitation of different compounds such as $Ca_{10}(PO_4)_6(OH)_2$ and $MgNH_4PO_4$ could have possibly occurred which could be confirmed by the loss of NH₄-N in the concentrate stream (Fig.40).

Slight variations between the ammonium and nitrate nitrogen content in the concentrate stream were observed and compared to the theoretical concentrations estimated from the adequate volume reduction factors (Fig. 40 and Fig.41).

The concentration of nutrients exceeded the standards for the required permeate quality at VRF=20 in the permeate stream. However, the nitrogen and phosphorus content in the mixed permeate was much below set limits even at VRF=30. The reduction efficiency at the final VRF reached 99.9% for nitrogen (the sum of NH₄-N, NO₃-N and NO₂-N) and it was equal to 99% for phosphorous (PO₄-P).

Membrane cleaning with base chemicals was performed after the experiment. The permeate flow rose to 88l/h which was a consequence of the pH adjustment during the concentration process. The salt reduction equaled 99%.

Test 3, line 4

During the test the feed water to the RO plant had a lower concentration of nitrate nitrogen than in the previous tests. This was a consequence of decreasing the dissolved oxygen concentration in the tank at the

Fig. 38 Permeate flux vs. recovery rate, test 2, line 4.
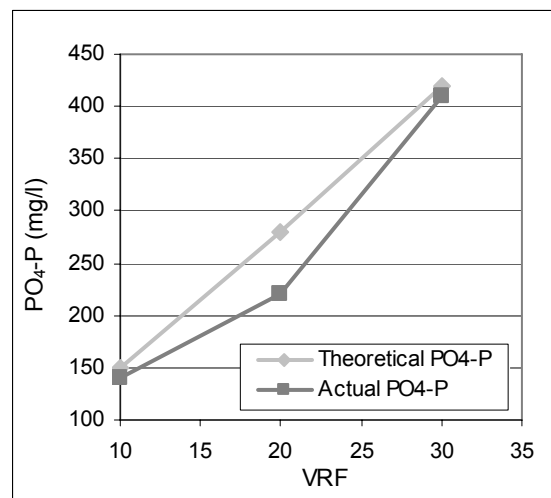
Fig. 39 PO₄-P concentration in the concentrate stream vs. VRF, test 2, line 4.
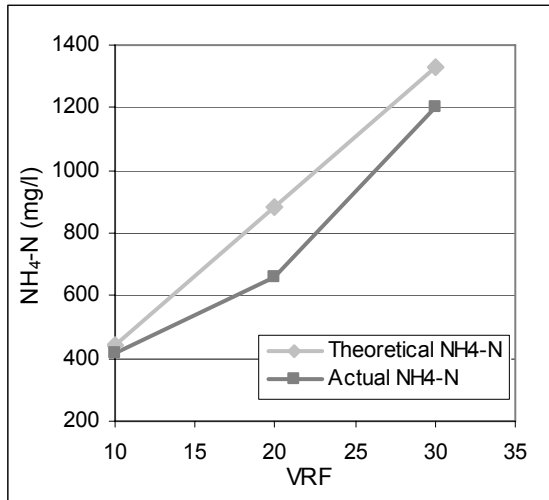
Fig. 40 NH₄-N concentration in the concentrate stream vs. VRF, test 2, line 4.
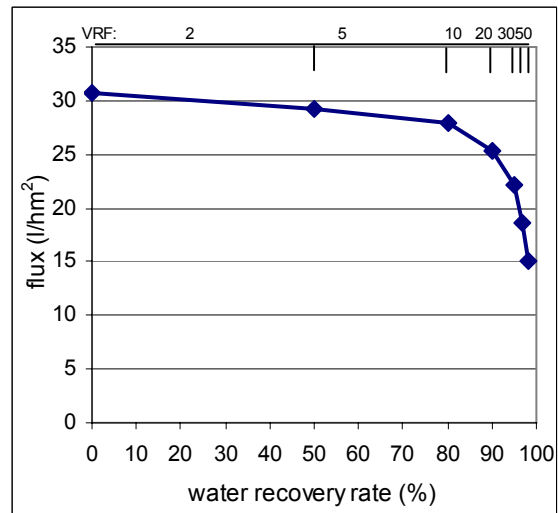
Fig. 42 Permeate flux vs. recover rate, test 3, line 4.
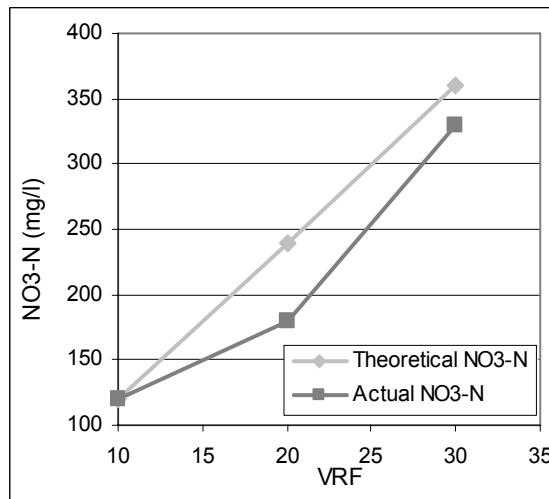
Fig. 41 NO₃-N concentration in the concentrate stream vs. VRF, test 2, line 4.
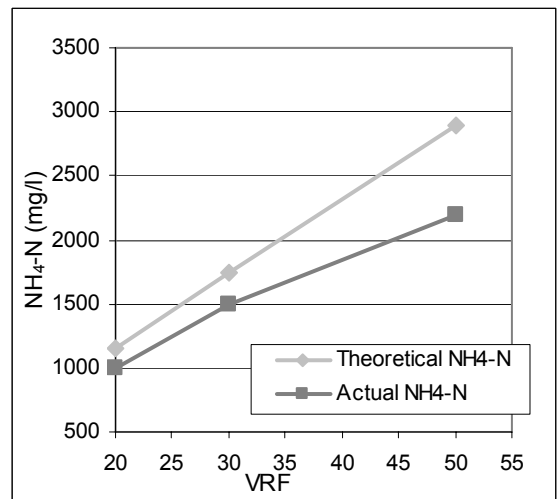
Fig. 43 NH₄-N concentration in the concentrate stream vs. VRF, test 3, line 4.

polishing step in order to suppress the nitrification process.

The aim of the test was to check the process performance at higher volume reduction factors (up to VRF=50). The previous experiment (test 2) showed that it was possible to concentrate the effluent water from line 4 thirty times and achieve final concentrations in the mixed permeate which did not exceed the set standards.

To be able to obtain higher VRF the pH value of the water in the feed tank was adjusted at each volume reduction step due to the same reasons as in test 2. The total volume of the hydrochloric acid used in the experiment came to 200 ml per 400 l of the feed water from line 4.

As a result of an increasing salt concentration in the feed tank the flux declined gradually at constant operating pressure (Fig. 42). The average flux during

the experiment was 28.3 l/hm² which allowed to carry out the efficient process even at VRF = 50.

Comparison of the concentration of ammonium nitrogen in the concentrate at the successive reduction steps demonstrated deviations from the theoretical concentration calculated at each VRF (Fig. 43).

During the experiment the nitrate nitrogen seemed not to increase in the same manner as it is indicated by VRF and lower than expected concentrations of NO₃-N were present in the concentrate stream (Fig. 44).

The analyses of phosphate phosphorous showed that its concentration in the concentrate differed from theoretical values with higher reduction steps. Lower values of the PO₄-P content were obtained during the test (Fig. 45).
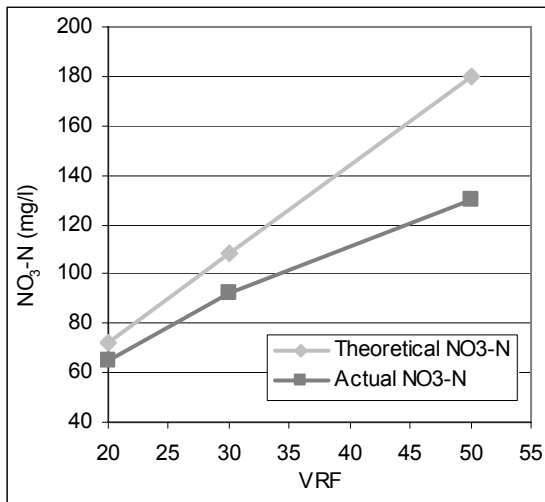
Fig. 44 NO₃-N concentration in the concentrate stream, test 3 line 4.
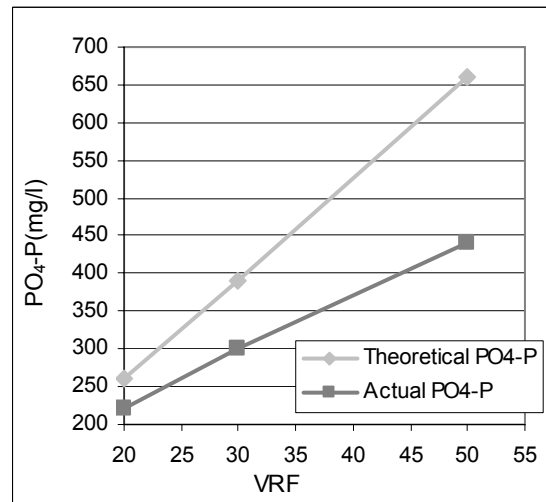
Fig. 45 PO₄-P concentration in the concentrate stream vs. VRF, test 3, line 4

Similar to test 2, the nutrients concentrations in the permeate highly exceeded the standards for the effluent water from the treatment plant at VRF=20. At the final concentration step the nitrogen (the sum of NH_4-N, NO_3-N and NO_2-N) reduction efficiency came to 99.1% whereas the phosphorous (PO_4-P) reduction equaled to 99.9%.

At VRF=50 the phosphate phosphorous concentration in the mixed permeate exceeded three times the effluent standards whereas the nitrogen content was still below set limits. The amount of organic compounds was marginal (TOC<2 mg/l).

The performed test demonstrated that even though the concentration process could be carried out with high average flux, the final quality of the mixed permeate did not allow to discharge it as an effluent from the wastewater treatment plant.

After the conducted experiment cleaning of the membrane (pH=11) was executed. During the water test, the permeate flow was maintained at the same level as before the experiment (88l/h). The salt reduction efficiency was estimated to 99%.

Test 4, line 4

In the last test the pH adjustment of the water in the feed tank was performed with a mixture of 63%-nitric acid (HNO_3) and 85%-phosphoric acid (H_3PO_4). The aim of adding the acid mixture was to achieve better ratio between the nutrients in the final concentrate that could be used for agricultural purposes. By this method undesirable chloride ions originating from applying hydrochloric acid could be replaced in the soil with macroelements such as nitrogen and phosphorous. Chloride ions can negatively influence the crop growth. The nutrient content in the soil vary a lot depending on its type. However, almost every type of soil used in agriculture has a shortage of nitrogen and phosphorous. To estimate the needed ratio between P and N in the fertilizer it is necessary to estimate the amount of nutrients taken up by the crops from the soil. Stig A. (2001) gives an example of the wheat harvest that amounts to 5 tons per hectare. A wheat grain contains 1.6% of nitrogen and 0.4% of phosphorous that gives a loss of 80 kg N and 20 kg P per hectare. That is why it seems reasonable to estimate the ratio to be 1:4 between phosphorous and nitrogen in the concentrate that is planed to be used as a fertilizer product. The estimated ratio P:N in the final concentrate was 1:6.

The total volume of the acid mixture used in the experiment was equaled to 111 ml per 300l of the feed water from line 4.

During the concentration process flux declined in the same manner as in the last two tests. In the beginning of the process slightly higher values of the flux were observed (Fig.46) The average flux in the experiment came to 30.5 l/hm².

The analyses of ammonium nitrogen concentration in the concentrate stream appeared to fall below the calculated value according to the stepwise increase in the VRF (Fig. 47).

As a result of the pH adjustment with the mixture of nitric and phosphoric acids, the concentration of NO_3-N and PO_4-P increased in the concentrate stream exceeding significantly the values expected during the concentration process (Fig.48 and Fig.49). The obtained ratio between P:N in the concentrate was estimated to 1:6.

At VRF=30 the mixed permeate still maintained required quality. However, nitrogen and phosphorous concentrations in the permeate stream exceeded set standards already at VRF=10. The efficiency of nutrient reduction at the final reduction step was 99.9% for phosphorous and 99% for nitrogen.

After the experiment the membrane was chemically washed (pH=11). During the water test permeate flow rose to 90l/h. The salt reduction remained at the same level as before the experiment (99%).
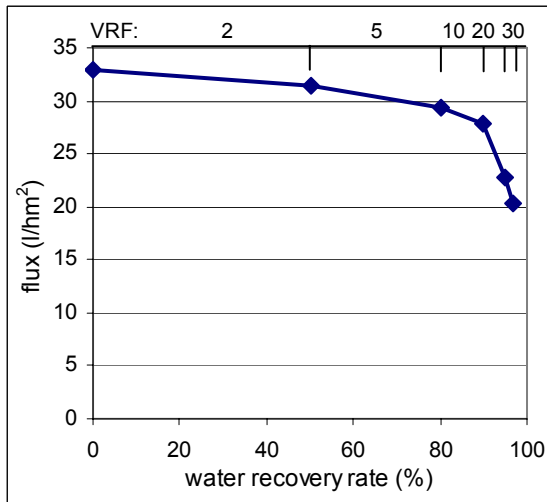
Fig. 46 Permeate flux vs. recovery rate, test 4, line 4.
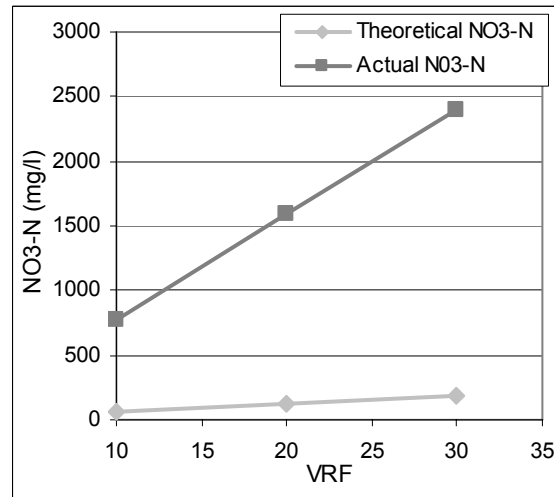
Fig. 48 NO$_3$-N concentration in the concentrate stream vs. VRF, test 4, line 4.
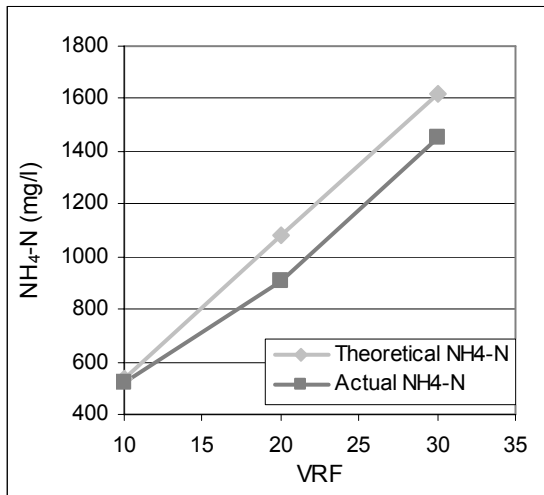
Fig. 47 NH$_4$-N concentration in the concentrate stream vs. VRF,
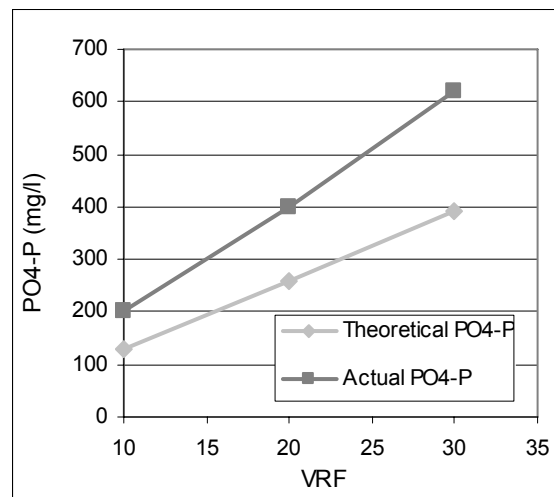
Fig. 49 PO$_4$-P concentration in the concentrate stream vs. VRF, test 4, line 4.

Discussion, line 4

The conducted tests aiming to estimate the adequate volume reduction factor for the effluent water from line 4 demonstrated that the produced mixed permeate at VRF=50 did not fulfill the requirements for outgoing water from the wastewater treatment plant. The parameter for which the concentration highly exceeded set limit was phosphate phosphorous (Appendix IV). Although the average permeate flux (28.3 l/hm²) allowed to efficiently concentrate the feed water at VRF =50, the process has to be stopped at lower reduction step.

To be able to reach a high VRF value for the process, pH adjustment is a crucial factor. Otherwise, the flux drastic decline caused by the occurrence of scale and fouling phenomena makes the process inefficient, like in test 1 (Fig.50). The highest flux, with an average value of 30.5 l/hm², was obtained in test 4 where the

pH value was adjusted with the mixture of nitric and phosphoric acids. However, its addition to the feed tank caused an increase in the PO$_4$-P and NO$_3$-N concentration in the mixed permeate at VRF=30. The set limits for the nutrient content were almost reached in the mixed permeate effluent.

In the tests 2, 3 and 4 the nitrate nitrogen reduction showed slightly lower efficiency than the ammonium nitrogen removal. The molecular weight of a NO$_3^-$ ion is higher than a NH$_4^+$ ion and therefore this ion should be better separated by the membrane. An artificially decreased pH value in the feed tank resulted in no loss in the ammonium nitrogen through ammonia stripping. Due to this procedure the ammonium reduction efficiency was enlarged (Table 7, Fig. 51 and Fig.52

25
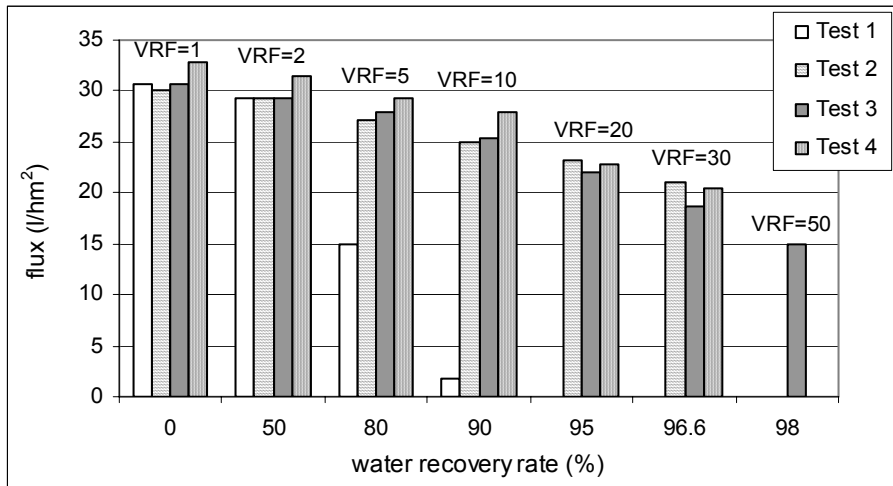
Fig. 50 Permeate flux comparison during the tests at successive recovery rates, line 4.

Table 7. The NH₄-N, NO₃-N and PO₄-P reduction efficiency, line 4.

VRF	NH$_4$-N reduction (%)				NO$_3$-N reduction (%)				PO$_4$-P reduction (%)			
	Test1	Test2	Test3	Test4	Test1	Test2	Test3	Test4	Test1	Test2	Test3	Test4
10	89	99.3	-	98.7	92.0	89.9	-	98.7	98.9	99.9	99.9	99.9
20	-	99.3	99.2	98.9	-	99.1	98.6	98.9	-	99.9	99.9	99.9
30	-	99.2	99.3	99.0	-	98.2	98.5	99.0	-	99.9	99.9	99.9
50	-	-	99.2	-	-	-	98.2	-	-	-	99.9	-

During the tests with pH adjustment the phosphate phosphorous reduction efficiency reached almost 100% (Fig.53). In test 1 it showed the lowest value due to phosphate precipitation on the membrane surface in the condition of increasing pH value in the feed tank.

The effect of pH adjustment in tests 2, 3 and 4 can also be noticed when comparing theoretical and VRFs (TS) results (Tab. 8). The term total solids refers to suspended and dissolved solids. By adding acid the amount of dissolved solids increases. As a consequence, the calculated values for higher values of VRF (TS) exceeded than theoretical VRF values.

Taking into consideration the values of the final VRFs (Cond) (VRF=20, 30 and 50), it can be concluded that the difference from the theoretical VRF was mainly caused by the precipitation process of different ions in the RO system (Tab.8). The variations between VRFs
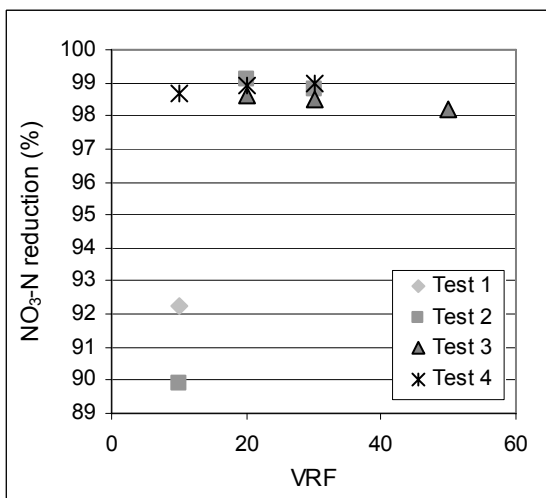
Fig. 51 NO₃-N reduction vs. VRF in test 1, 2, 3 and 4, line 4.
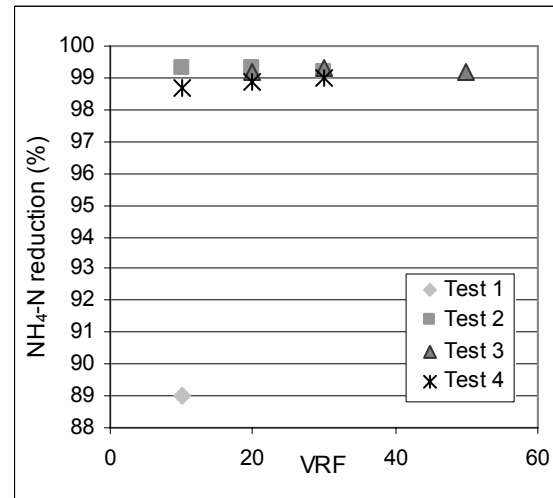
Fig. 52 NH₄-N reduction vs. VRF in test 1, 2, 3 and 4, line 4.
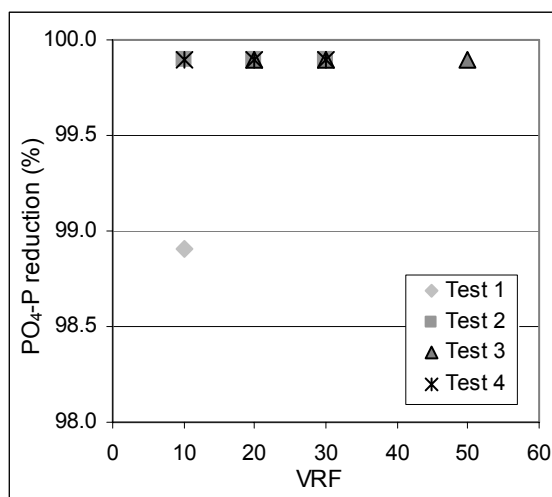
Fig. 53 PO$_4$-P reduction vs. VRF in test 1, 2, 3 and 4, line 4.

were marginally influenced by the losses of ions through the membrane to the permeate stream.

Conclusions, line 4:

- Even though the effluent water from line 4 was efficiently concentrated up to VRF=50, the produced mixed permeate did not fulfill requirements for discharge water (the limit for phosphorous concentration was exceeded three times).

- In order to receive required mixed permeate quality, the concentration process needs to be stopped at a reduction step lower then VRF=50 (30<VRF<50).

- To be able to reach high water recovery rate pH adjustment of water incoming to the RO plant needs to be performed to decrease scaling and fouling tendencies.

5.4 Heavy metals in the concentrate

The recover of nutrients in the produced concentrate,

which are planned to be used as a fertilizer, fulfils the sustainability principle. On the other hand, the produced concentrate may contain harmful chemicals, so its use in agriculture may cause a risk to both the environment and human health. One of the most important factors which determine its utilization is the content of heavy metals. Long-term fertilization with a RO concentrate may cause accumulation of heavy metals in the soil and reduce its biological activity. Additional threat may be posed by increased concentration of heavy metals in the crops. For these reasons, it is very important that a produced concentrate follows the requirements set for the products used in agriculture. The content of heavy metals was analyzed at the final reduction steps (VRF=10, 20, 30 or 50) for chosen tests for all lines (Appendix VI). Table 9 presents the concentrations of the most harmful heavy metals in the concentrates produced at the highest VRF at each treatment line.

Because the concentration of heavy metals varied with different VRF, and depending on their content in the incoming water to the RO plant, the quota mg metal per g phosphorous was used. This parameter is commonly utilized to asses and compare the quality of different stabilized sludges. The lower the values the higher quality of the sewage sludge.

In Table 10, it can be noticed that the highest values of metal/phosphorous were obtained for the concentrate product from line 1. It also represented lower reduction step than the final concentrate from line 2 and 4. This was a consequence of low phosphorous content due to the extended precipitation process of phosphate compounds from the concentrate.

The best quality of the final product was obtained in the experiment in line 4. The Me/P ratios were slightly higher than for the concentrate from line 2.

The obtained Me/P ratio in the concentrate products are presented in Appendix VII (only the tests with heavy metal content were analyzed).

Table 8. Comparison of theoretical VRF and calculated VRF from TS and conductivity, line 4. (TS-total solids; Cond-conductivity)

VRF	Test 1			Test 2			Test 3			Test 4		
	VRF (TS)	VRF (Cond)		VRF (TS)	VRF (Cond)		VRF (TS)	VRF (Cond)		VRF (TS)	VRF (Cond)	
		with losses to permeate	without losses to permeate		with losses to permeate	without losses to permeate		with losses to permeate	without losses to permeate		with losses to permeate	without losses to permeate
2	2.0	2.0	2.0	2.0	2.2	2.2	2.2	2.3	2.3	2.3	2.2	2.2
5	5.1	4.5	4.4	6.2	5.8	5.8	5.5	5.4	5.4	5.4	5.2	5.1
10	8.2	7.6	6.9	12.8	10.3	10.1	11.5	10.8	9.9	12.7	9.5	9.2
20	-	-	-	20.4	15.9	15.4	23.1	18.2	17.6	27.1	16.8	16.1
30	-	-	-	32.9	27.0	26.1	32.3	25.6	23.9	43.6	25.8	24.6
50	-	-	-	-	-	-	57.9	37.4	36.6	-	-	-

Table 9. Heavy metals content in the final concentrate product.

	Heavy metals μg/l						
	Cd	**Hg**	**Pb**	**Cu**	**Zn**	**Ni**	**Cr**
Line 1, VRF=30 (test 3)	0.1	0.05	0.6	140	94	14	43
Line 2, VRF=50 (test 4)	0.4	0.04	2.3	370	520	150	30
Line 4, VRF=50 (test 3)	0.2	0.2	2.9	550	560	210	22

Table 10. The ratio metal/phosphorous as mg Me/g P in the final concentrate product.

	mg metal/g phosphorous						
	Cd	**Hg**	**Pb**	**Cu**	**Zn**	**Ni**	**Cr**
Line 1, VRF=30 (test 3)	0.0030	0.0020	0.026	6.08	4.08	1.86	0.34
Line 2, VRF=50 (test 4)	0.0015	0.0001	0.008	1.37	1.92	0.55	0.11
Line 4, VRF=50 (test 3)	0.0004	0.0004	0.006	1.25	1.27	0.48	0.05

5.5 Energy consumption

The biggest cost of energy consumption in the RO plant is for the pump that transports the feed solution under high pressure through the membrane. The used high-pressure pump in the Hammarby Sjöstad plant had a maximum power of 4kW. It was impossible to asses the actual energy input to the plant and therefore it was assumed that the high-pressure pumped worked with the maximum power during the concentration process. With an additional assumption that the RO plant works with its dimensional flow of 108 l/h (Table 3 in chapter 4.6) the energy consumption was calculated to be 37 kWh/m^3. Such an energy use seems to be high when compared to RO plant utilized in the previous experiments in the Hammarby Sjöstad plant (Blennow, 2005). In that case study the total energy consumption came to 23 kWh/m^3 and was regarded as unacceptable.

The estimated energy use in a full-scale RO plant would approximately be equal to 5-10 kWh/h^2 (Bergström, 2006).

6 GENERAL DISCUSSION

6.1 Water product – mixed permeate quality

The performed study demonstrated that the application of reverse osmosis technology as a last step in a sewage treatment plant can provide a high quality water product. The obtained water recovery rate results indicate that the process can be carried out efficiently. The concentration of nutrients and TOC in the mixed permeates produced at the highest VRF at each treatment line are presented in Table 11. (The content of the final mixed permeates from all tests is shown in Appendix VIII).

Hammarby Sjöstad effluent limits for the treated wastewater were nor exceeded in the water products recovered from all lines, except for the mixed permeate obtained at VRF=50 for the effluent water from line 4. At this reduction step, the phosphate phosphorous concentration exceeded three times the limit of the treatment plant effluent. In order to follow the standards the concentration process needs to be stopped between VRF equal to 30 and 50. Nevertheless, such a high recovery rate demands adjustment of the pH value in the feed water.

The highest quality of a water product was obtained for the effluent water from line 2. At VRF=50, the water recovery rate reached 98% and all concentrations of analyzed parameters were still much below set limits. Because of the chosen pretreatment methods before the RO plant no pH adjustment was necessary during the concentration process. Membrane Bioreactor showed to be the best alternative for the wastewater treatment before its polishing in a RO system. Low concentration of suspended solids as well as slightly acid characteristics

Table 11. The content of the mixed permeates produced at the highest VRFs.

	TOC	**PO$_4$-P**	**NH$_4$-N*/NO$_3$-N+NH$_4$-N**
	mg/l	mg/l	mg/l
Line 1, VRF=30 (test 3)	-	0.07	2.7*
Line 2, VRF=50 (test 4)	<2	0.06	1.3
Line 4, VRF=50 (test 3)	<2	0.47	2.9

of the incoming water to an RO membrane resulted in low fouling and scaling tendency in the RO operation. The nitrate nitrogen, which was the main source of nitrogen in the effluent water from line 2, occurred to be better separated than ammonium nitrogen in the incoming water from line 4. NO_3^- ions have high molecular weight and are therefore more effectively stopped by the membrane. During the tests on line 2, the reduction efficiency of NO_3-N was calculated to 97.5% at VRF=50. At the same reduction step during the experiments on line 4 ammonium nitrogen was separated with the efficiency of 96%.

In all water products the content of organic compounds was marginal (TOC<2 mg/l).

Due to higher mobility of H^+ ions than OH^- ions through the membrane the produced permeate becomes acidified. Before the effluent water from the RO plant can be discharged to the recipient its neutralization might be required. In the tests executed on line 1 and 4, in which the pH adjustment was not performed, the pH value in the final mixed permeate was maintained in the range of 5.5-6.3. However, the dosage of acid during the experiments performed on line 1 and 4 as well as low pH of the feed water from line 2 resulted in higher acidification of the produced effluent water. The pH value varied between 4.6 and 5.5 in these tests.

To avoid additional acidification of the produced water by the addition of acid during the concentration process and control formation of scale the following methods can be applied (Metcal, 2003):

- reducing calcium concentration by ion exchange or lime softening
- adding a scale inhibitor (antiscalant) to increase the solubility of $CaCO_3$ in the concentrate stream
- lowering the product recovery rate.

6.2 Concentrate product

Sustainable agriculture emphasizes the importance of the nutrient recirculation from the costumer back into the agricultural system. It is especially important in terms of depleting phosphate mineral deposits. The nutrient recovery in the concentrate, a byproduct from a RO process, and its application in agriculture can decrease the amount of needed chemical fertilizers.

6.2.1 Heavy metals

The utilization of the produced concentrate may pose the risk of introducing undesirable chemicals to the soil. The concentration of heavy metals in the product used in agriculture is of great importance. No standards for the RO concentrate as a fertilizer were found. Therefore, heavy metal concentrations were compared with the maximum metal content in the sludge approved for agricultural purposes expressed by the ratio Me/P (Table 12).

It can be concluded that phosphorous recovered in the RO concentrate was not contaminated with heavy metals originating from the effluent water from line 2 and 4. In line 1 only the nickel content in the concentrate that exceeded sludge standards. This was the effect of at least ten times lower concentration of phosphorous than expected after the concentration process due to phosphorus precipitation from the concentrate.

The comparison between standard values and obtained ratios of metal/phosphorous in the concentrate are presented in Appendix VII.

Low concentrations of heavy metals in the concentrate product were the consequence of water pretreatment methods performed on each line before the RO plant (removal of suspended solids where the adsorption of heavy metals occurs). However, to ensure the low metal/phosphorous ratio, the phosphate precipitation during the concentration process needs to be inhibited by the pH adjustment of the effluent water from line 1 and 4.

It is also recommended to analyze the content of chloride ions in the concentrate, when pH adjustment with hydrochloric acid is performed, as high concentration of these ions can negatively influence the crop growth.

6.2.2 Organic contaminations

The danger of using the RO concentrate on agricultural land due to the content of toxic organic compounds is rather small. Most of the organic contaminations in the concentrate are water-soluble as the majority of fat-soluble compounds (e.g. PCB, dioxins) are removed with the excess activated sludge in the pretreatment process before an RO plant. By

Table 12. The ratio metal/phosphorous as mg Me/g P in the final RO concentrate product and maximum metal content in sludge approved for agricultural use (Levlin, 1999).

	Cd	Hg	Pb	Cu	Zn	Ni	Cr
				mg metal/g phosphorous			
Line 1,VRF=30 (test 3)	0.003	0.002	0.026	6.08	4.08	**1.86**	0.34
Line 2,VRF=50 (test 4)	0.0015	0.0001	0.008	1.37	1.92	0.55	0.11
Line 4,VRF=50 (test 3)	0.0004	0.0004	0.006	1.25	1.27	0.48	0.05
Sludge approved for agriculture, mg Me/g P	**0.0667**	**0.0833**	**3.33**	**20**	**26.7**	**1.67**	**3.33**

spreading the concentrate on a soil, organic compounds will be exposed to numerous processes, of which chemical and biological decomposition, performed by soil micro flora, are of great importance (Levlin *et al.*, 1996).

The total organic carbon (TOC) parameter was used in this study as a measure of organic pollutions in the concentrate from line 2 and 4 (Appendix VIII). At VRF=50 the content of TOC in the concentrate from line 4 was approximately two times higher than in the final product from line 2 (Table 13). This was an effect of different pretreatment methods.

Table 13. The concentration of TOC in the concentrates produced at the highest VRFs.

	TOC
	mg/l
Line 1, VRF=30 (test 3)	-
Line 2, VRF=50 (test 4)	300
Line 4, VRF=50 (test 3)	580

Organic contaminations may enter the food chain through greezing animals. For that reason, Sweden introduced restrictions to use of byproducts from sewage treatment in the feed crops [9].

Of great importance are residues of medicines and pharmaceuticals in the RO concentrate. Their content is recommended to analyze before concentrate utilization in agriculture.

6.2.3 Nutrients

The required nutrient input in the fertilizer is strongly depended on their content in the field and the crop requirements. The nutrient contribution from the fertilizer should be of the same size as the amount of nutrients removed. It is necessary to perform a nutrient balance and use it when planning a fertilization procedure (Munter, 2000). For soils that are rich in phosphorous, like for instance it is in Central Europe, the application of RO technology might not be desirable due to high phosphate content.

e content of nutrients in the concentrates produced at the highest VRF from each line are presented in Table 14. (The nutrient content in the final concentrates from all tests is shown in Appendix VIII).

6.3 pH adjustment in the RO process

The conducted studies using the reverse osmosis plant demonstrated that the feed pH has a significant effect on the RO membrane performance. During the concentration process, H^+ ions pass through the membrane with higher mobility than OH^- ions causing an increase in the pH value of the concentrate. Depending on the recovery rate, the concentration of salts increases with higher VRF and leads to the possibility of exceeding the solubility product of calcium carbonate and other scale-forming compounds (Metcal, 2003). The precipitation process of different salts occurs at lower pH.

The influence of the phosphate compounds on the pH value can be easy noticed in Fig. 54. In general, there is a tendency of phosphate precipitation that occurs at different pH values. This phenomenon is depended on the initial concentration of PO_4-P and the influent pH value.

High concentrations of ammonium nitrogen at high pH-levels indicate that precipitation of ammonium nitrogen did not show the same strong dependence on the pH value as for phosphate phosphorous. However, precipitation of struvite ($MgNH_4PO_4$) can result in an increased precipitation of ammonia at higher pH values. As the NH_4-N content was higher than the PO_4-P content, the $MgNH_4PO_4$ precipitation gave a larger relative reduction of phosphate phosphorous compared to the reduction of ammonium nitrogen. This could be noticed during test 2 and 3 performed on line 2 (Fig. 55). The slowdown in ammonium nitrogen concentration occurred at the same point as the phosphate concentration decreased.

During the experiments performed on lines 1 and 4, the effluent water had an average pH value of 7. In the tests carried out without pH adjustment, the pH value rapidly increased causing formation of scale and deterioration in performance of the RO membrane. In the mass balance estimations (Appendix IX), it can be noticed that during these tests high losses of nutrient compounds occurred. The phosphorous loss was substantially influenced by its precipitation on the membrane surface. The highest losses amounted to 95% for line 1 at VRF=20, whereas for line 4 they reached 80% at VRF=10. Similar tendency was observed for nitrogen. The nitrogen loss was mainly affected by the increasing pH value in the concentrate stream, which led to appearance to the gaseous form of nitrogen (NH_3). The significant nitrogen loss (67%) occurred during the first test performed on the effluent water from line 1. On line 4, the loss of nitrogen came to 14% during the test without pH adjustment.

Table 14. The nutrient content in the concentrates produced at the highest VRFs.

	PO₄-P	tot N/NH₄-N*/NO₃-N+NH₄-N**	K
	mg/l	mg/l	mg/l
Line 1, VRF=30 (test 3)	23	999*	-
Line 2, VRF=50 (test 4)	270	1243**	910
Line 4, VRF=50 (test 3)	460	2300	1000
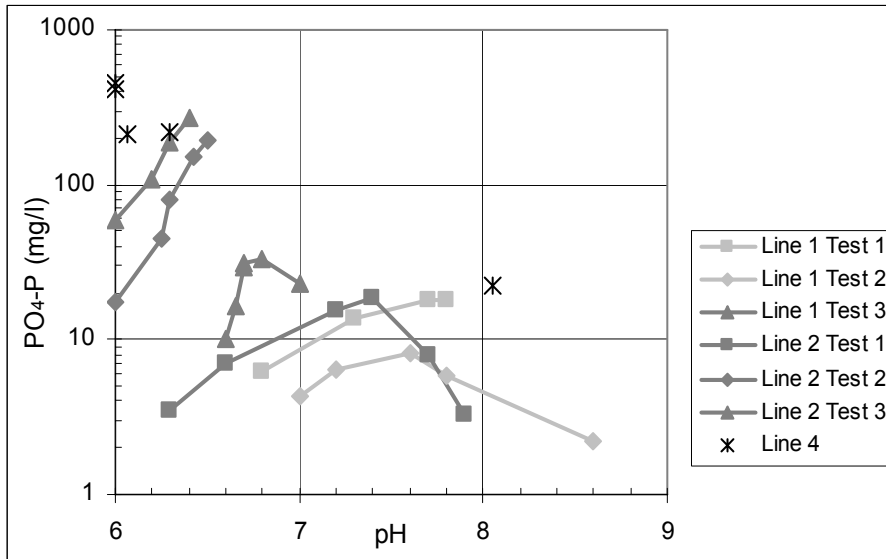
Fig. 54 The effect of pH on the phosphate phosphorous concentration in the concentrate.
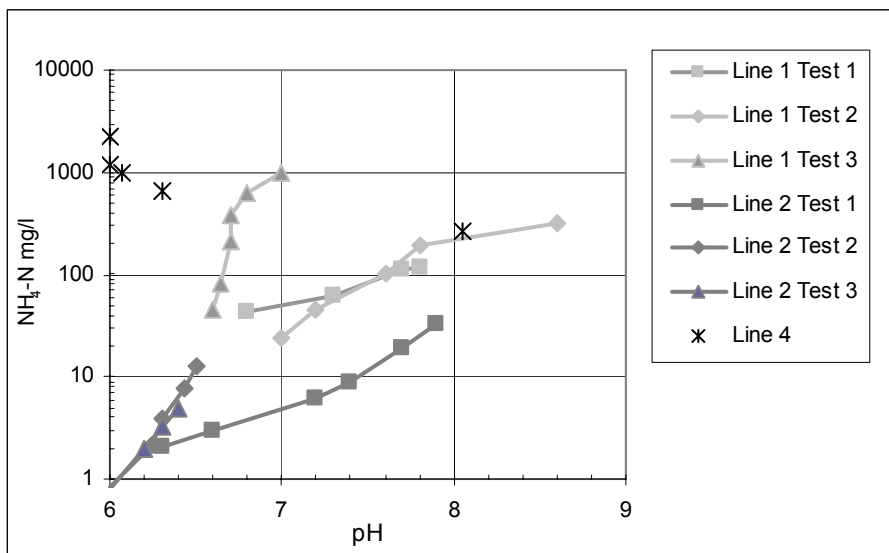
Fig. 55 The effect of pH on the ammonium nitrogen concentration in the concentrate.

To mitigate the scaling phenomenon in the RO plant acidification of water incoming to the RO membrane unit was necessary at each reduction step. One positive effect of the pH adjustment was higher water recovery rate in tests performed on line 1 and 4, at VRF=30 and VRF=50, respectively. The acid dosage also resulted in lower nutrient losses than in tests performed without pH adjustment. However, with the successive VRFs nutrient losses became bigger as an effect of precipitation processes and nutrients retention in the system in the conditions of increasing salt concentrations in the water pumped to the RO module. The same tendency was noticed in test 4, line 4. In that test high percentages of nutrient losses were affected by the addition of nitric and phosphoric acids which in turn led to an increase of the nutrient content in the feed tank.

The pH value of the effluent water from line 2, treated in the RO module was on average equal to 5.5. During the concentration processes on that line the pH did not exceed 6.5 in the concentrate. Up to the VRF=50

the experiment was efficiently conducted without the addition of acid. The mass balance calculations for nutrients (Appendix IX) performed for line 2 showed higher losses than in tests with pH adjustment on line 4. The losses of phosphates occurred to be lower during the tests on line 2 than in test with the acid addition on line 1. In the first test performed with the effluent water from line 2 an intense precipitation process of phosphorous compounds resulted in their big loss (93%). During this test, the feed water to the RO plant was characterized with higher by a pH than in other tests due to unstable conditions in the MBR after reconstructions of the reactor.

It can be concluded that the feed pH value had a significant impact on the occurrence of scaling. Feed water with the pH value of 5.5 resulted in low a scaling tendency of the RO membrane operation and saved on acid additions in the treatment of the effluent water from line 2.

Membrane fouling is one of the main causes of permeate flux decline and the loss of product quality

in the reverse osmosis process. This phenomenon is strongly depended on the organic compound content in the feed water to RO. The results of the effluent water from line 4 showed high concentrations of TOC, (average TOC=15 mg/l) which could possibly cause organic fouling of the RO membrane. Additionally, the brown color of the water due to chemical washings can indicate bacterial fouling (Bergström *et al.*, 2002)

6.4 Decision matrix

The conducted studies demonstrated that applied pre-treatment methods before the RO plant have a significant influence on its performance. To be able to compare and select the most proper treatment line a decision matrix was built. In Table 15 different aspects were considered as important according to environmental goals set by Hammarby Sjöstad. A large variety of decision factors exist and they might vary for each specific reverse osmosis plant. Factors such as energy consumption, maximum resource recovery and required treated wastewater quality (N≤6mg/l; P≤0.15 mg/l) are the main targets of the environmental program for the new built district, Hammarby Sjöstad. The quality of the RO concentrate with recovered nutrients for agricultural use was also considered. Regarding the operational aspects of the RO plant performance, factors such as fouling and scaling tendency as well as a need of the feed pH value adjustment were assessed in the decision matrix. Additionally, possible savings on biological nutrient removal in a pre-treatment line as well as the necessity of supplementary suspended solids removal before a RO unit were taken into account.

All presented aspects in the decision matrix were evaluated according to the results of the experiments performed with different pre-treatment effluents on the RO plant. Moreover, each decision aspect had a different weight depending on its importance in Hammarby Sjöstad Environmental Plan. Then the total score for each pre-treatment line was calculated.

Based on the results of the decision matrix, the aerobic treatment line 2 proved to be the most proper pre-treatment method. Line 2 combined with the RO unit met the environmental goals set by Hammarby Sjöstad.

Concentrate quality produced after line 1 greatly contributed to the lowest score obtained in the decision matrix. The heavy metal content measured as metal/phosphorous ratio occurred to be the highest in line 1 when compared with the final concentrate produced from the effluent from line 2 and 4. This was the result of phosphorous precipitation from the concentrate. Additionally, the ratio of nickel/phosphorous exceeded permissible values for sludge used in agriculture.

The medium score obtained for line 4 was mainly affected by the water product quality which did not fulfil the standards for the treated effluent at VRF=50. Therefore, to be able to meet the limits the water recovery rate needed to be lower than 98% (30<VRF<50).

Both line 1 and 4 required adjustment of the feed pH value in order to inhibit scale and fouling formation and to reach a high recovery rate. A large amount of acid needed during the concentration process contributed to higher operating cost of the RO plant.

Aspects	Weight %	Line 1	Line 2	Line 4
Effluent quality	15	0	+	-
Water recovery rate	15	0	+	+
Concentrate product	15	-	0	+
Savings on energy use	15	-	0	0
Savings on additional SS removal	5	-	+	-
Scaling and fouling avoidance	10	-	0	-
Savings on pH adjustment	10	-	+	-
Savings on biological nutrient removal	10	+	-	+
Produced resources during pre-treat. line	5	-	-	+
Total:	100%	1.4	2.3	2.05
+ high(3); 0 medium(2); - low(1)		Maximal 3 points		

Table. 15 Matrix for selection of a pre-treatment method before an RO polishing step combined with the RO plant performance.

A supplementary cost of SS removal before the RO plant had to be undertaken in lines 1 and 4 and contributed to the low scores for these lines.

The factor assessment in the decision matrix showed the highest score for line 2. The Membrane Bioreactor (MBR), regarded as the "heart" of line 2, applies both membrane and biological technology. Thanks to the microfiltration process in the MBR, the concentration of suspended solids in the water incoming to the RO plant was marginal. Therefore, the cost of additional SS removal can be eliminated.

Due to the problems of controlling the oxygen concentration in the aerobic zone in the MBR, it was impossible to avoid a robustly occurring nitrification process. However, this process positively influenced the outgoing water from the MBR, which was acidified. As a result of low pH value in the incoming water to the RO plant, low scaling tendency occurred during its operation. No pH adjustment was necessary and additional savings on acid addition could be made. As a consequence of low concentration of organic compounds (TOC=8 mg/l), compared with the effluent water from line 4 (TOC=17 mg/l), the fouling process did not occur to be significant.

The water recovery reached the highest rate of 98% in the test performed on the effluent from line 2. At this point water incoming to the RO plant was concentrated fifty times (VRF=50) and the water product had the best quality.

The energy consumed by the RO plant during the concentration of the effluent from the pre-treatment lines 2 and 4 can be assumed as similar. In both lines, during the tests where VRF=50 was obtained, the average flux maintained at the same level (28 l/hm²) which can indicate the same energy consumption. In a full scale RO plant, the concentration process with the feed water from line 4 ought to be stopped between VRF=30 and VRF=50 in order to meet effluent standards. This will contribute to lower energy use as the time needed for operating a high-pressure pump becomes shorten for lower VRF values.

The use of energy in tests with the effluent water from line 1 can be assumed as high when compared with tests performed on line 2 and 4, although the concentration process was stopped at VRF=30. During test 3 on line 1 the average flux occurred to be low (23 l/hm²) which resulted in longer operation time of the high-pressure pump in order to obtain VRF=30.

7 FINAL CONCLUSIONS

This thesis presents the evaluation of the performance of the one-step RO plant as a final stage of wastewater treatment at the Hammarby Sjöstad plant. Of great importance in this work was the qualities of the final mixed permeate as it represents the average effluent water from the RO plant with several membrane modules in a full-scale RO plant. The nutrient recovery in the concentrate, a by-product from an RO process, and its quality for application in agricultural was also examined. Results from the experimental part supported the choice the optimal pre-treatment method for proper performance of the pilot-scale RO plant.

The results from the experiments led to thefollowing conclusions:

- Hammarby Sjöstad standards for discharge water (N≤6mg/l, P≤0.15mg/l) were met by water products recovered from all lines, except for the mixed permeate obtained at VRF=50 for the effluent water from line 4 (phosphorous concentration exceeded three times the limit).

- The highest quality of the water product was obtained for the effluent water from line 2 when the water recovery rate reached 98% (VRF=50).

- Before the effluent water from an RO plant can be discharged, its neutralization might be required (especially in tests where pH adjustment was performed).

- The concentrate product with recovered nutrients from line 4 occurred to have the best quality for agricultural purposes. In line 1 only the nickel content in the concentrate exceeded standards for sludge approved for usage in agriculture. This was the effect of low phosphorous content due to its precipitation during the concentration process.

- The feed pH value has a significant effect on the RO performance.

- With an increase of the pH value in the concentrate during the concentration process, the precipitation of scale-forming compounds is enhanced.

- With higher salt concentrations in the concentrate (higher VRF) the precipitation of different salts occurs at lower pH values.

- The low feed pH (around 5.5), like in line 2 reduces the occurrence of scaling and fouling phenomena during the RO membrane performance

- Based on the factor assessment in the decision matrix, the aerobic treatment in line 2 consisting of a drum filter and a MBR reactor was selected as the most appropriate pre-treatment method. Line 2 combined with the single-stage RO unit meets the environmental goals set in Hammarby Sjöstad's Environmental Plan.

It is recommended for future research to test a continuously running RO-plant.

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APPENDIXES I-IX

Appendix I

Typical tap water composition from Norsborg Water Plant [9]

Drinking Water Quality at the Norsborg and Lovö Water Work in Stockholm 2004

Parameter		Unit	Drinking water Norsborg mean	Drinking water Lovö mean	Limits [1]
Temperature		°C	8,9	7,9	20
Colour	Pt	mg/l	6	< 5	15
Turbidity		FNU	0,07	0,07	0,5
Conductivity, 25°C		mS/m	20,5	27,4	-
Total organic carbon	TOC	mg C/l	3,6	4,1	5,5 [3][4]
Odour	THV		none	none	weak [4]
Taste			none	none	weak [4]
pH			8,5	8,5	should be 7,5-9,0 [4]
Total hardness	$CaCO_3$	mg/l	73	102	267 [4]
Calcium	Ca	mg/l	23	33	100 [4]
Magnesium	Mg	mg/l	3,9	4,8	30 [4]
Iron	Fe	mg/l	< 0,02	< 0,02	0,100
Manganese	Mn	mg/l	< 0,001	< 0,001	0,050
Aluminium	Al	mg/l	0,029	0,022	0,100
Lead	Pb	mg/l	< 0,001	< 0,001	0,010 [4]
Cadmium	Cd	mg/l	< 0,00005	< 0,00005	0,0050 [4]
Mercury	Hg	mg/l	< 0,00005	< 0,00005	0,0010 [4]
Copper	Cu	mg/l	0,002	0,001	0,20 [4]
Arsenic	As	mg/l	< 0,001	< 0,001	0,010 [4]
Pesticides, total		mg/l	< 0,000050	< 0,000050	0,00050 [4]
Polyaromatic hydrocarbons, total	PAH	mg/l	< 0,000005	< 0,000005	0,00010 [4]
Trihalomethanes, total	THM	mg/l	0,0053	0,0015	0,050 [4]
Alkalinity	HCO_3	mmol/l	0,80	1,2	-
Sulphate	SO_4	mg/l	35	43	100 [4]
Chloride	Cl	mg/l	12	16	100 [4]
Fluoride	F	mg/l	< 0,2	< 0,2	1,5 [4]
Ammonia	NH_4	mg/l	0,06	0,07	0,50 [4]
Nitrite	NO_2	mg/l	< 0,02	< 0,02	0,10
Nitrate	NO_3	mg/l	< 2	< 2	20 [4]
Total chlorine residual [2]	Cl_2	mg/l	0,27	0,27	0,4
Microorganisms, 22°C, 3days		per/ml	1	< 1	10
Slow-growing bacteria, 22°C, 7 day		per/ml	2	1	5000 [4]
Coliform bacteria, 35°C		per 100 ml	< 1	< 1	detected
Escherichia coli		per 100 ml	< 1	< 1	detected
Clostridium perfringens		per 100 ml	< 1	< 1	detected [4]

Comments :

The results are mean annual values. Basic analysis are made three times a week. Additional analysis are carried out four times a year. The analyses has been performed on SWC´s accredited laboratory or by another accredited laboratory.

The sign " < " is used to illustrate " smaller than " when not detected.

The data consist of means for the period concerned.

1) Limits for acceptable values water without remarks in drinking, according to the Swedish regulation SLV FS 2001:30.
2) During the colder part of the year a smaller dosage desinfectant is used, giving a chlorine residual in the outgoing drinking water on 0,2 mg Cl_2/l. During the warmer part on the other hand, the chlorine residual is made 0,3 mg Cl_2/l.
3) Based om relationship between TOC and COD_{Mn}. Corresponds to a oxidizability of 4,0 mg O_2/l as COD_{Mn}.
4) User´s limit value. No limit value is applied by the water works.

Appendix II

The results of analyzes from line 1: test 1, test 2 and test 3.

Test 1	cond µS/cm	pH	SS mg/l	PO4-P mg/l	NO3-N mg/l	NH4-N mg/l	Flow l/h	Flux l/m2h
Feed water	906	7.1	4	6.91	0.38	44.30	-	
Perm. VR1	11.30	4.8	-	0.294	<0.023	2.02	82	29.3
Conc.VR1	935	6.8	-	6.22	0.389	42.9	-	
Perm. VR2	26.3	5.6	-	0.054	<0.023	2.41	80	28.6
Conc.VR2	1 795	7.3	-	13.55	0.672	62	-	
Mixed perm. VR2	15	5.3	-	0.09	<0.023	1.14	-	
Perm. VR5	64.30	7.0	-	0.07	<0.023	5.98	77	27.5
Conc.VR5	3 400	7.7	-	17.9	1.38	110	-	
Mixed perm. VR5	22.3	5.6	-	0.09	<0.023	1.86	-	
Perm. VR10	120	7.3	-	0.034	<0.023	12.40	62	22.1
Conc.VR10	5 730	7.8	-	18.1	2.34	119	-	
Mixed perm. VR10	31.7	6.0	-	0.05	<0.023	2.71	-	

Test 2	cond µS/cm	pH	SS mg/l	PO4-P mg/l	NH4-N mg/l	Flow l/h	Flux l/m2h
Feed water	730	7.0	4.0	3.68	24	-	-
Perm. VR1	8.2	5.8	-	<0.05	0.55	85	30
Conc.VR1	785	7.0	-	4.37	24.2	-	
Perm. VR2	18.1	6.2	-	<0.05	1.4	82	29
Conc.VR2	1 442	7.2	-	6.4	44.3	-	
Mixed perm. VR2	14	5.7	-	<0.05	0.90	-	
Perm. VR5	44	6.4	-	<0.05	4.2	80	29
Conc.VR5	3 210	7.6	-	8.25	102	-	
Mixed perm. VR5	21.8	5.9	-	<0.05	1.47	-	
Perm. VR10	134.5	6.5	-	0.136	10.9	38	14
Conc.VR10	5 450	7.8	-	5.8	190.5	-	
Mixed perm. VR10	33	6.0	-	<0.05	1.94	-	
Perm. VR20	265.0	8.4	-	0.043	38.7	8	3
Conc.VR20	9 400	8.6	-	2.2	311	-	-
Mixed perm. VR20	35.0	6.3	-	0.063	2.62	-	-

Test 3	cond µS/cm	pH	SS mg/l	TS g/l	PO4-P mg/l	NH4-N mg/l	Flow l/h	Flux l/m2h
Feed water	906	6.4	10	-	7	41.2	-	-
Perm. VR1	13.2	5.5	-	-	0.08	1.05	82	29.3
Conc.VR1	1 024	6.6	-	0.47	10	44.8	-	-
Perm. VR2	23.4	4.7	-	-	0.09	1.64	80	28.6
Conc.VR2	1 808	6.7	-	0.8	16.05	81.6	-	-
Mixed perm. VR2	15	5.0	-	-	0.275	0.80	-	-
Perm. VR5	34.5	4.4	-	-	0.128	2.33	74	26.4
Conc.VR5	4 410	6.7	-	2.16	29.3	212.4	-	-
Mixed perm. VR5	18.9	5.2	-	-	0.075	1.24	-	-
Perm. VR10	71.5	5.2	-	-	0.133	5.9	42	15.0
Conc.VR10	7 860	6.7	-	4.26	31	375	-	-
Mixed perm. VR10	33	5.3	-	-	0.077	1.69	-	-
Perm. VR20	255	4.9	-	-	0.138	22.8	16	5.7
Conc.VR20	13 270	6.8	-	7.4	33.1	626	-	-
Mixed perm. VR20	23.5	5.5	-	-	0.075	1.88	-	-
Perm. VR30	546	5.1	-	-	0.121	52.8	9	3.2
Conc.VR30	9200	7.0	-	11.6	23	999	-	-
Mixed perm. VR30	31.9	5.7	-	-	0.069	2.7	-	-

Appendix III

The results of analyzes from line 2: test 1, test 2, test 3 and test 4.

Test 1	cond µS/cm	pH	SS mg/l	TS g/l	PO$_4$-P mg/l	NO$_3$-N mg/l	NH$_4$-N mg/l	Flow l/h	Flux l/m2h
Feed water	656	6.4	3	0.42	3.02	29.5	0.18	-	
Perm. VR1	11.8	5	-		0.108	0.622	0.07	90	32.1
Conc.VR1	687	6.3	-	0.46	3.44	34.6	2.06	-	-
Perm. VR2	13.9	5	-	-	0.067	0.513	0.11	86	30.7
Conc.VR2	1 308	6.6	-	0.93	7.11	58	2.91	-	-
Mixed perm. VR2	10.5	5.3	-	-	0.159	0.793	0.41	-	-
Perm. VR5	22.6	5.3	-	-	0.064	0.974	0.25	84	30
Conc.VR5	2 930	7.2	-	2.13	15.6	138	6.22	-	-
Mixed perm. VR5	11.7	4.9	-	-	0.065	0.969	0.12	-	-
Perm. VR10	42.5	5.6	-	-	0.039	1.44	0.44	70	25
Conc.VR10	5 160	7.4	-	4.1	18.4	270	8.98	-	-
Mixed perm.VR10	12.8	4.9	-	-	0.069	0.646	0.12	-	-
Perm. VR20	65.9	5.7	-	-	0.029	3.85	1.25	38	13.6
Conc.VR20	8 550	7.7	-	7.06	8	459	19.1	-	-
Mixed perm.VR20	13.3	5.3	-	-	0.081	0.78	0.18	-	-
Perm. VR30	131.3	6.3	-	-	0.039	8.93	2.65	22	7.85
Conc.VR30	12 260	7.9	-	11.15	3.26	735	33.2	-	-
Mixed perm.VR30	14.7	5.3	-		0.096	1.4	0.20	-	-

Test 2	cond µS/cm	pH	SS mg/l	TS g/l	PO$_4$-P mg/l	NO$_3$-N mg/l	NH$_4$-N mg/l	Flow l/h	Flux l/m2h
Feed water	678	5.5	3.3	0.46	9.14	36.7	0.77	-	-
Perm. VR1	8.7	4.1	-	-	0.045	0.406	0.045	84	30
Conc.VR1	712	5.6	-	0.52	8.91	36.3	0.60	-	-
Perm. VR2	11.5	4.10	-	-	0.042	0.58	0.045	82	29.2
Conc.VR2	1 311	5.95	-	0.87	17.3	76	0.82	-	-
Mixed perm.VR2	9	4.0	-	-	0.116	0.823	0.10	-	-
Perm. VR5	26	4.5	-	-	0.129	1.27	0.074	80	28.6
Conc.VR5	3 070	6.25	-	2.38	44.65	188	2.16	-	-
Mixed perm.VR5	10.5	4.3	-	-	0.058	0.636	0.06	-	-
Perm. VR10	27.3	4.9	-	-	0.152	1.88	0.107	76	27.1
Conc.VR10	5 230	6.3	-	4.27	80.5	316	3.93	-	-
Mixed perm. VR10	12	4.6	-	-	0.051	0.646	0.058	-	-
Perm. VR20	65.5	5.0	-	-	0.169	3.04	0.173	70	25.0
Conc.VR20	9 520	6.43	-	8.53	149.6	684	7.54	-	-
Mixed perm. VR20	14.5	4.7	-	-	0.059	0.728	0.049	-	-
Perm. VR30	97.3	5.2	-	-	0.205	4.75	0.271	64	22.8
Conc.VR30	13 800	6.5	-	13.11	195	1038	12.90	-	-
Mixed perm. VR30	18.8	5.3	-	-	0.06	0.91	0.07	-	-

M. Perm-mixed permeate

Test 3	cond µS/cm	pH	SS mg/l	TS g/l	PO₄-P mg/l	NO₃-N mg/l	NH₄-N mg/l	Flow l/h	Flux l/m2h
Feed water	644	5.5	3	0.4	12	33	<0.5	-	-
Perm. VR1	9.9	4.4	-	-	0.04	<0.5	<0.5	86	30.71
Conc.VR1	828	5.6	-	0.55	16	44	<0.5	-	-
Perm. VR2	10.4	4.5	-	-	0.04	0.6	<0.5	84	30.00
Conc.VR2	1 288	5.8	-	0.88	25	68	<0.5	-	-
Mixed perm. VR2	9	4.5	-	-	0.03	<0.5	<0.5	-	-
Perm. VR5	17.8	4.7	-	-	0.08	1.1	<0.5	81	28.93
Conc.VR5	2 900	6	-	2.22	59	160	0.8	-	-
Mixed perm. VR5	10.1	4.6	-	-	0.03	0.6	<0.5	-	-
Perm. VR10	27.3	4.8	-	-	0.14	1.8	1.1	78	27.86
Conc.VR10	5 130	6.2	-	4.18	110	280	2	-	-
Mixed perm. VR10	11.2	5	-	-	0.04	0.7	<0.5	-	-
Perm. VR20	38.9	4.9	-	-	0.19	2.8	0.6	74	26.43
Conc.VR20	8 280	6.3	-	7.17	190	510	3.2	-	-
Mixed perm. VR20	12	5.2	-	-	0.04	0.7	<0.5	-	-
Perm. VR30	52.5	5.1	-	-	0.24	4	1.7	66	23.57
Conc.VR30	11 980	6.4	-	10.8	270	780	4.9	-	-
Mixed perm. VR30	13.1	5.3	-	-	0.05	0.8	<0.5	-	-

Test 4	cond µS/cm	pH	SS mg/l	TS g/l	PO₄-P mg/l	Tot-P mg/l	NO₃-N mg/l	NH₄-N mg/l	Kjel-N mg/l	Tot-N mg/l	TOC mg/l	Flow l/h	Flux l/m2h
Feed water	662	5.6	2	0.41	8.1	9	35	<0.5	-	-	8.4	-	-
Perm. VR1	10.1	4.6	-	-	-	-	-	-	-	-	-	86	30.7
Conc.VR1	708	6.1	-	0.44	-		-	-	-	-	-	-	-
Perm. VR10	28.4	4.6	-	-	-	-	-	-	-	-	-	80	28.6
Conc.VR10	5 300	6.6	-	8.89	-	-	-	-	-	-	-	-	-
M.Perm. VR10	12.7	4.7	-	-	-	-	-	-	-	-	-	-	-
Perm. VR20	44.5	4.7	-	-	0.15	0.14	3.2	0.8	<1	4.2	<2	70	25
Conc.VR20	10 260	6.6	-	9.91	170	170	620	22	39	660	160	-	-
M.Perm. VR20	14.4	4.6	-	-	0.04	0.04	0.8	<0.5	<1	1.8	<2	-	-
Perm. VR30	-	-	-	-	-	-	-	-			-	-	-
Conc.VR30	-	-	-	-	-	-	-	-			-	-	-
M.Perm. VR30	-	-	-	-	-	-	-	-			-	-	-
Perm. VR50	172	5.1	-	-	0.55	0.56	14	1.1	<1	15	<2	26	9.29
Conc.VR50	17 600	6.4	-	14.65	270	270	1 200	43	67	1300	300	-	-
M.Perm. VR50	17	4.7	-	-	0.06	0.04	0.9	<0.5	<1	1.9	<2	-	-

M. Perm-mixed permeate

Appendix IV

The results of analyzes from line 4: test 1, test 2, test 3 and test 4.

Test 1	cond µS/cm	pH	SS mg/l	TS g/l	PO₄-P mg/l	Tot-P mg/l	NO₃-N mg/l	NH₄-N mg/l	Kjel-N mg/l	TOC mg/l	Flow l/h	Flux l/hm2
Feed water	183.3	6.8	5	0.39	12	11	21	33	34.00	12	-	-
Perm. VR1	2.37	4.8	-	-	-	-	-	-	-	-	86	30.7
Conc.VR1	190.6	6.9	-	0.40	-	-	-	-	-	-	-	-
Perm. VR2	3.51	5.0	-	-	-	-	-	-	-	-	82	29.3
Conc.VR2	366	7.2	-	0.87	-	-	-	-	-	-	-	-
M.Perm. VR2	3.25	5.3	-	-	-	-	-	-	-	-	-	-
Perm. VR5	8.64	5.5	-	-	-	-	-	-	-	-	42	15
Conc.VR5	813	7.4	-	2.07	-	-	-	-	-	-	-	-
M. perm. VR5	3.55	5.1	-	-	-	-	-	-	-	-	-	-
Perm. VR10	60.1	8.6	-	-	0.24		14	29		<2	5	1.8
Conc.VR10	1,270	8	-	3.18	22	22	180	260	260	92	-	-
M.Perm. VR10	5.55	5.5	-	-	0.1		0.8	2.4		<2	-	-

Test 2	cond µS/cm	pH	SS mg/l	TS g/l	PO₄-P mg/l	Tot-P mg/l	NO₃-N mg/l	NO₂-N mg/l	NH₄-N mg/l	Kjel-N mg/l	Tot-N mg/l	TOC mg/l	Flow l/h	Flux l/hm2
Feed water	198.4	6.8	8.0	0.44	15	15	12	1	44	45		14	-	-
Perm. VR1	3.88	4.1	-	-	-	-	-	-	-	-	-	-	84	30
Conc.VR1	218	6.0	-	0.45	-	-	-	-	-	-	-	-	-	-
Perm. VR2	4.85	4.0	-	-	-	-	-	-	-	-	-	-	82	29.3
Conc.VR2	435	6.0	-	0.88	-	-	-	-	-	-	-	-	-	-
M.Perm. VR2	3.3	4.2	-	-	-	-	-	-	-	-	-	-	-	-
Perm. VR5	8.66	4.2	-	-	-	-	-	-	-	-	-	-	76	27.1
Conc.VR5	1144	6.0	-	2.73	-	-	-	-	-	-	-	-	-	-
M.Perm. VR5	4.36	4.7	-	-	-	-	-	-	-	-	-	-	-	-
Perm. VR10	13.71	4.0	-	-	0.12	-	1.3	0.2	3.1	-	-	<2	70	25
Conc.VR10	1994	5.5	-	5.63	140	140	120	11	420			140	-	-
M.Perm. VR10	6.42	4.7	-	-	0.04		0.3	<0.1	1.4	-	-	<2	-	-
Perm. VR20	15.77	4.9	-	-	0.21		1.7	0.2	4.5			<2	65	23.2
Conc.VR20	3050	6.3	-	9.0	220	210	180	17	660	690	870	220	-	-
M.Perm. VR20	8.44	4.9	-	-	0.03		<0.5	<0.1	1.4	-	-	<2	-	-
Perm. VR30	29.8	5.4	-	-	0.4		3.8	0.5	10			<2	59	21.1
Conc.VR30	5160	6.0	-	9.0	410	410	330	34	1200	1300	1600	410	-	-
M.Perm. VR30	10.92	5.0	-	-	0.04		<0.5	<0.1	1.5	-	-	<2	-	-

M. Perm-mixed permeate

Test 3	cond µS/cm	pH	SS mg/l	TS g/l	PO₄-P mg/l	Tot-P mg/l	NO₃-N mg/l	NH₄-N mg/l	Kjel-N mg/l	Tot-N mg/l	TOC mg/l	Flow l/h	Flux l/hm2
Feed water	216	7.3	9	0.40	13	14	3.6	58	69		17	-	-
Perm. VR1	3	6	-	-	-	-	-	-	-	-	-	86	30.7
Conc.VR1	225	6	-	0.49	-	-	-	-		-	-	-	-
Perm. VR2	5.5	4.3	-	-	-	-	-	-	-	-	-	82	29.3
Conc.VR2	493	6.1	-	0.89	-	-	-	-	-	-	-	-	-
M.Perm. VR2	3.9	4.8	-	-	-	-	-	-	-	-	-	-	-
Perm. VR5	9.2	4.4	-	-	-	-	-	-	-	-	-	78	27.9
Conc.VR5	1161	6.1	-	2.18	-	-	-	-	-	-	-	-	-
M.Perm. VR5	4.8	4.9	-	-	-	-	-	-	-	-	-	-	-
Perm. VR10	15.05	4.5	-	-	-	-	-	-	-	-	-	71	25.4
Conc.VR10	2130	6.1	-	4.58	-	-	-	-	-	-	-	-	-
M.Perm. VR10	5.7	4.7	-	-	-	-	-	-	-	-	-	-	-
Perm. VR20	13.3	4.8	-	-	0.14	-	0.9	8.3	-	-	<2	62	22.1
Conc.VR20	3810	6.1	-	9.23	210	220	65	1000	1000	1100	270	-	-
M.Perm. VR20	6.2	4.9	-	-	0.04	-	<0.5	2.3	-	-	<2	-	-
Perm. VR30	30.7	5.2	-	-	0.24	-	1.4	10	-	-	<2	52	18.6
Conc.VR30	5160	5.8	-	12.92	300	300	92	1500	1500	1600	390	-	-
M.Perm. VR30	6.62	4.9	-	-	0.04	-	<0.5	2.3	-	-	<2	-	-
Perm. VR50	56.1	5.5	-	-	0.48	-	2.4	18	-	-	<2	42	15
Conc.VR50	7910	6.0	-	23.19	460	440	130	2200	2300	2400	580	-	-
M.Perm. VR50	7.3	4.8	-	-	0.47	-	<0.5	2.4	-	-	<2	-	-

Test 4	cond µS/cm	pH	SS mg/l	TS g/l	PO₄-P mg/l	Tot-P mg/l	NO₃-N mg/l	NO₂-N mg/l	NH₄-N mg/l	Kjel-N mg/l	Tot-N mg/l	TOC mg/l	Flow l/h	Flux l/hm2
Feed water	213	7.0	4	0.44	13	13	6	0.5	54	44		14	-	-
Perm. VR1	4.2	4.7	-	-	-	-	-	-	-	-	-	-	92	32.9
Conc.VR1	238	6.3	-	0. 6	-	-	-	-	-	-	-	-	-	-
Perm. VR2	6.9	4.2	-	-	-	-	-	-	-	-	-	-	88	31.4
Conc.VR2	464	5.8	-	1.01	-	-	-	-	-	-	-	-	-	-
M.Perm. VR2	4.1	4.4	-	-	-	-	-	-	-	-	-	-	-	-
Perm. VR5	10.8	4.2	-	-	-	-	-	-	-	-	-	-	82	29.3
Conc.VR5	1080	5.9	-	2.58	-	-	-	-	-	-	-	-	-	-
M.Perm. VR5	5	4.5	-	-	-	-	-	-	-	-	-	-	-	-
Perm. VR10	18.5	4.5	-	-	0.18		6	-	6.9			<2	78	27.9
Conc.VR10	1962	5.9	-	5.59	200		770	-	520			140	-	-
M.Perm. VR10	6.4	4.7	-	-	0.06		1.2	-	2.2			<2	-	-
Perm. VR20	30.5	4.7	-	-	0.39	-	13	-	10	-	-	<2	64	22.9
Conc.VR20	3420	5.7	-	11.93	400	400	1600	-	910	930	2500	240	-	-
M.Perm. VR20	6.5	5.1	-	-	0.08	-	1.5	-	2.5	-	-	<2	-	-
Perm. VR30	33.5	4.9	-	-	0.58	-	20	-	15	-	-	<2	57	20.4
Conc.VR30	5230	5.8	-	19.18	620	590	2400	-	1400	1400	3800	370	-	-
M.Perm. VR30	7.1	5	-	-	0.13	-	1.9	-	2.5	-	-	<2	-	-

M. Perm-mixed permeate

Appendix V

The conductivity of analyzed ions in the concentrate, test 2, line 2.

The conductivity caused by different analyzed ions was estimated using the constant-molar (equivalent) conductivity for common ions at infinite dilution (Stig, 2001).

Test 2, VRF=1, line 2

pH=5.6, PO4-P=8.91 mg/l, NO3-N=36.3 mg/l, NH4-N=0.6 mg/l

$[H^+] = 10^{(-pH+3)}$ mole/m³ $= 10^{-2.6}$ mole/m³ $= 2.5118*10^{-3}$ g/m³

$Cond_{[H+]} = 2.5118*10^{-3}$ mole/m³ $* 350$ (10^{-4} m²S/mole) $= 0.8791$ μS/cm

$[OH^-]=10^{(-14+pH)}$ mole/liter $= 10^{(-11+pH)} = 10^{(-11+pH)} / 17$ (g/m³) $= 10^{-5.4}/17 = 2.3418*10^{-7}$

$Cond_{[0H-]} = 2,51 \ 10^{-6}$ mole/m³ 198 (10^{-4} m²S/mole) $= 7.88258 \ 10^{-4}$ μS/cm

$Cond[H2PO4-] = 8.91$ g/m³ $* [33$ (10^{-4} m²S/mol)$/31$(g/mole)$] = 9,5337$ μS/cm

$Cond[NO_3^-]= 36.3$ g/m³$* [71$ (10^{-4} m²S/mol)$/ 14$(g/mole)$]=184.09$ μS/cm

$Cond[NH_4^+]= 0.6$ g/m³$* [73$ (10^{-4} m²S/mol)$/ 14$(g/mole)$]= 3.128$ μS/cm

The total conductivity is the sum of the conductivity for the individual ions:

$Cond_{[H+]}$	0.8791
$Cond_{[NH4+]}$	3.128
$Cond_{[0H-]}$	0.00078825
$Cond_{[H2PO4-]}$	9.5337
$Cond_{[NO3-]}$	184.09
Sum of conductivity:	**197.63**

At VRF=1 estimated Cond=198 цS/cm, during the test measured Cond = 712 μS/cm.

Appendix VI

Concentrations of heavy metals in the concentrate, line 1, 2 and 4.

Line 1	*Heavy metals*	*K mg/l*	*Cd µg/l*	*Hg µg/l*	*Ag µg/l*	*Pb µg/l*	*Mo µg/l*	*Cu µg/l*	*As µg/l*	*Zn µg/l*	*Ni µg/l*	*Cr µg/l*	*V µg/l*
Test 3	Con. 20		0.2	0.2	0.6	1.5	11	130	17	210	30	52	6.9
	Con. 30		0.1	0.05	0.2	0.6	13	140	20	94	14	43	8

Line 2	*Heavy metals*	*K mg/l*	*Cd µg/l*	*Hg µg/l*	*Ag µg/l*	*Pb µg/l*	*Mo µg/l*	*Cu µg/l*	*As µg/l*	*Zn µg/l*	*Ni µg/l*	*Cr µg/l*	*V µg/l*
Test 1	con.20	330	0.1	0.07	0.2	1.1	19	44	12	270	64	3.5	13
	con.30	560	0.2	0.1	0.3	1.7	32	81	19	420	110	5.4	23
Test 2	con.20	460	0.3	0.08	0.6	1.4	13	280	15	530	66	7.4	12
	con 30		0.4	0.1	0.8	2.8	21	450	23	480	20	110	12
Test 3	con.20	420	0.4	0.1	0.5	1.2	14	240	15	480	55	8.5	12
	con.30	610	0.3	0.1	0.6	1.7	22	89	25	290	9.6	12	17
Test 4	con.20	500	0.3	0.02	0.3	2	17	210	20	550	75	9.9	17
	con.50	910	0.4	0.04	0.5	2.3	32	370	14	520	150	30	30

Line 4	*Heavy metals*	*K mg/l*	*Cd µg/l*	*Hg µg/l*	*Ag µg/l*	*Pb µg/l*	*Mo µg/l*	*Cu µg/l*	*As µg/l*	*Zn µg/l*	*Ni µg/l*	*Cr µg/l*	*V µg/l*
Test 1	con.10	180	0.05	0.05	0.08	0.3	9	69		68	42	2	
Test 2	con.20	380	0.2	0.11	0.3	3.7	21	190	38	260	100	9.4	49
	con 30	700	0.3	0.15	0.4	6.1	34	450	79	390	190	17	81
Test 3	con.30	660	0.1	0.2	0.2	2	30	330	120	420	150	15	110
	con.50	1000	0.2	0.2	0.3	2.9	46	550	170	560	210	22	160
Test 4	con 20	450	0.1	0.08	0.2	1.5	21	120	42	260	110	7.3	22
	con 30	680	0.2	0.18	0.2	1.5	28	210	74	370	180	11	36

Appemdix VII

The ratio metal/phosphorus as mg Me/g P in the concentrates from line 1, line 2 and line 4.

Line 1	Test 3		Sludge approved for agriculture, mg Me/P
	con.20 mg Me/gP	con.30 mg Me/gP	
Cd	0.006	0.003	0.0667
Hg	0.006	0.002	0.0833
Ag	0.018	0.008	
Pb	0.045	0.026	3.33
Mo	0.33	0.56	
Cu	3.92	6.08	20
As	0.51	0.86	
Zn	6.3	4.08	26.7
Ni	1.57	1.86	1.67
Cr	0.2	0.34	3.33
V	0.9	0.6	

Line 2	Test 1		Test 2		Test 3		Test 4		Sludge approved for agriculture mgMe/gP
	con.20 mg Me/gP	con.30 mg Me/gP	con.20 mg Me/gP	con.30 mg Me/gP	con.20 mg Me/gP	con.30 mg Me/gP	con.20 mg Me/gP	con.50 mg Me/gP	
Cd	0.013	0.061	0.002	0.002	0.002	0.001	0.0018	0.0015	0.0667
Hg	0.0087	0.031	0.00054	0.00051	0.00052	0.00037	0.00011	0.00014	0.0833
Ag	0.025	0.092	0.0040	0.0041	0.0026	0.0022	0.0018	0.0019	
Pb	0.13	0.52	0.009	0.0143	0.0063	0.0062	0.0118	0.0085	3.33
Mo	2.37	9.81	0.086	0.107	0.073	0.081	0.10	0.118	
Cu	5.5	**24.8**	1.8	2.3	1.26	0.32	1.23	1.37	20
As	1.5	5.8	0.10	0.11	0.08	0.09	0.11	0.051	
Zn	**33.7**	**128.8**	3.5	2.5	2.5	1.07	3.23	1.92	26.7
Ni	**8**	**33.7**	0.44	0.10	0.29	0.03	0.44	0.55	1.67
Cr	0.43	1.65	0.049	0.56	0.04	0.04	0.058	0.11	3.33
V	1.62	7.05	0.08	0.06	0.063	0.062	0.1	0.111	

BOLD-over limit

Line 4	Test 1	Test 2		Test 3		Test 4		Sludge approved for agriculture mgMe/gP
	con.10 mg Me/gP	con.20 mg Me/gP	con.30 mg Me/gP	con.30 mg Me/gP	con.50 mg Me/gP	con.20 mg Me/gP	con.30 mg Me/gP	
Cd	0.002	0.0009	0.0007	0.0003	0.0004	0.0003	0.0003	0.0667
Hg		0.0005	0.0004	0.0006	0.0004	0.0002	0.0003	0.0833
Ag		0.001	0.00098	0.0007	0.0007	0.0005	0.0003	
Pb	0.01	0.017	0.015	0.0067	0.0066	0.0037	0.0024	3.33
Mo	0.41	0.095	0.083	0.1	0.105	0.052	0.042	
Cu	3.14	0.86	1.09	1.1	1.25	0.3	0.34	20
As		0.17	0.19	0.4	0.38	0.10	0.11	
Zn	3.091	1.2	0.9	1.4	1.27	0.65	0.59	26.7
Ni	**1.90**	0.45	0.46	0.5	0.48	0.27	0.29	1.67
Cr	0.09	0.04	0.04	0.05	0.05	0.018	0.018	3.33
V		0.227	0.197	0.366	0.366	0.055	0.058	

BOLD-over limit

Appendix VIII

Concentrations of nutrients and TOC in final mixed permeate and concentrate, line 1, line 2 and line 4.

Concentration of nutrients and TOC in the final mixed permeates

Concentration TOC (mg/l)	Test 1	Test 2	Test 3	Test 4
Line 1	-	-	-	-
Line 2	-	-	-	<2
Line 4	<2	<2	<2	<2

Concentration NH4 N*/ NO3-N+NH4-N** (mg/l)	Test 1	Test 2	Test 3	Test 4
Line 1*	2.71	2.62	2.7	-
Line 2	1.6	0.98	1.3	1.3
Line 4	3.2	2.1	2.9	4.4

Concentration tot-P/PO4-P (mg/l)	Test 1	Test 2	Test 3	Test 4
Line 1	0.05	0.063	0.069	-
Line 2	0.096	0.06	0.05	0.06
Line 4	0.1	0.04	**0.47**	0.13

Concentration of nutrients and TOC in the final concentrates

Concentration TOC (mg/l)	Test 1	Test 2	Test 3	Test 4
Line 1	-	-	-	-
Line 2	-	-	-	300
Line 4	92	410	580	370

Concentration tot-N/NH4-N* /NO3-N+NH4-N** (mg/l)	Test 1	Test 2	Test 3	Test 4
Line 1*	119	311	999	-
Line 2**	768	1051	785	1243
Line 4	440	1600	2300	3800

Concentration tot-P/PO4-P (mg/l)	Test 1	Test 2	Test 3	Test 4
Line 1	18.1	2.2	23	-
Line 2	3.26	195	270	270
Line 4	22	410	460	620

Concentration TOC (mg/l)	Test 1	Test 2	Test 3	Test 4
Line 1	-	-	-	-
Line 2	-	-	-	300
Line 4	92	410	580	370

Appendix IX

Mass balance for nitrogen and phosphorus, line 1, 2 and 4

Mass balance for PO$_4$-P, line 1.

Test no.	VRF	Effluent (g P)	Acid addition	Mixed Permeate (g P)	Concentrate (g P)	Loss (%)	Reduction (%)
1	10	1.38	-	0.009	0.362	73.1	99.3
2	20	1.47	-	0.023	0.044	95.3	98.4
3	30	2.1	HCl	0.02	0.23	88	99.0

Mass balance for NH$_4$-N, line 1.

Test no.	VRF	Effluent (g P)	Acid addition	Mixed Permeate (g P)	Concentrate (g P)	Loss (%)	Reduction (%)
1	10	8.86	-	0.487	2.38	67.6	94.5
2	20	9.6	-	0.995	6.22	24.8	89.6
3	30	12.36	HCl	0.783	9.99	12.8	93.6

Mass balance for PO$_4$-P, line 2.

Test no.	VRF	Effluent (g P)	Acid addition	Mixed Permeate (g P)	Concentrate (g P)	Loss (%)	Reduction (%)
1	30	0.906	-	0.027	0.032	93.4	97.5
2	30	2.74	-	0.017	1.95	28.2	99.3
3	30	3.6	-	0.014	2.7	24.6	99.6
4	50	3.24	-	0.023	2.16	32.6	99.2

Mass balance for NO$_3$-N, line 2.

Test no.	VRF	Effluent (g P)	Acid addition	Mixed Permeate (g P)	Concentrate (g P)	Loss (%)	Reduction (%)
1	30	8.85	-	0.406	7.35	12.4	95.4
2	30	11.01	-	0.26	10.38	3.4	97.6
3	30	9.9	-	0.23	7.8	18.8	97.6
4	50	14	-	0.35	9.6	28.9	97.5

Mass balance for PO4-P, line 4.

Test no.	VRF	Effluent (g P)	Acid addition (g P)	Mixed Permeate (g P)	Concentrate (g P)	Loss (%)	Reduction (%)
1	10	3.6	-	0.027	0.66	80.9	99.2
2	30	4.5	HCl	0.011	4.1	8.6	99.7
3	50	5.2	HCl	0.18	3.68	25.7	96.4
4	30	3.9	H_3PO_4+HNO_3 5.19 gP	0.035	6.2	31.4	99.1

Mass balance for total P, line 4.

Test no.	VRF	Effluent (g P)	Acid addition (g P)	Mixed Permeate (g P)	Concentrate (g P)	Loss (%)	Reduction (%)
1	10	3.3	-	0.027	0.66	79.2	99.2
2	30	4.5	HCl	0.011	4.1	8.6	99.7
3	50	5.6	HCl	0.18	3.52	33.9	96.7
4	30	3.9	H_3PO_4+HNO_3 5.19 gP	0.037	5.9	34.7	99.0

Mass balance for NH4-N, line 4

Test no.	VRF	Effluent (g P)	Acid addition (g P)	Mixed Permeate (g P)	Concentrate (g P)	Loss (%)	Reduction (%)
1	10	9.9	-	0.648	7.92	13.4	93.5
2	30	13.2	HCl	0.435	12	5.8	96.7
3	50	23.2	HCl	0.94	17.6	20	95.9
4	30	16.2	H_3PO_4+HNO_3 31.7 gN	0.725	14.5	68.2	95.5

Mass balance for NO_3-N, line 4.

Test no.	VRF	Incoming (g N)	Added acid (g N)	Mixed Permeate (g N)	Concentrate (g N)	Loss (%)	Reduction (%)
1	10	6.3	-	0.216	5.4	10.8	96.6
2	30	3.6	HCl	0.116	3.3	5.1	96.8
3	50	1.4	HCl	0.196	1.04	11.7	86.0
4	30	1.8	H_3PO_4+HNO_3 31.7 gN	0.551	24	26.7	69.4

Mass balance for total N, line 4.

Test no.	VRF	Incoming (g N)	Added acid (g N)	Mixed Permeate (g N)	Concentrate (g N)	Loss (%)	Reduction (%)
1	10	16.5	-	0.864	13.2	14.8	94.8
2	30	17.4	HCl	0.609	16	4.5	96.5
3	50	25.4	HCl	1.14	19.2	20.1	95.5
4	30	15.2	H_3PO_4+HNO_3 31.7 gN	1.27	37	18.3	91.6