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# Cost and environmental impact of nanofiltration in treating chemically pre-treated surface water

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## Abstract

Nanofiltration is an effective technique in improving the organic matter removal from coagulated surface water, but the process should also be economically feasible and environmentally sustainable when applied. Cost and environmental impact of nanofiltration installed after conventional surface water treatment were calculated and evaluated at different operating parameters in this study. The installation of nanofiltration after conventional surface water treatment would increase the cost of treated water in a minimum by 0.11 €/m$^3$ in the studied case. The least cost was gained at the higher studied recovery (83%) at the driving pressure of 6 bar, where also the total environmental impact was well balanced. However, the installation of nanofiltration would increase the environmental impact of water treatment remarkably and improvements should be done to minimise these effects. The main ways to minimise the cost of nanofiltration were related to recovery of the process, energy consumption, membrane lifetime and membrane cleaning, whereas the environmental impact minimisation was mostly related to recovery of the process and energy consumption.

*Keywords*: Nanofiltration; Surface water treatment; Cost; Environmental impact

## 1. Introduction

Nanofiltration (NF) has proved to be effective in improving the quality of coagulated and sand filtered surface water [1,2]. The main benefits of NF are high removal of organic matter and bacteria and consequent low formation potential of harmful disinfection-by-products. In some cases efficient removal of multivalent ions is important as well.

High quality requirement for NF feed water, membrane fouling, high energy consumption, large volume of water lost as retentate and overall

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cost of the NF process are the main barriers that arise when considering NF for improving conventional surface water treatment. When NF is applied the process should be technically and economically feasible and the best performing and the most economical options of process design and operation should be found.

Despite the lack of data from NF plants treating surface water, some knowledge about the costs can be obtained from the studies of the membrane treatment costs at other water treatment applications. Some of the studies are based on data collected from real operating plants [3,4] while the others use empirical cost calculations and pilot-scale operational data [5–8].

The cost of the NF process is largely a function of the membrane flux: higher flux corresponds to higher pressures and higher energy consumption, smaller membrane area, less membrane modules and less associated equipment. Thus, estimates of the process cost require accurate flux estimates for specific application from pilot tests. Both Wiesner et al. [6] and Chellam et al. [8] noticed that the economics of NF was extremely sensitive to the flux, but the recovery had relatively small effect on the cost of NF.

The cost of membrane modules is proportional to the design capacity and flux of the membrane plant, but the data collected from the real operating plants indicate that the other components of investment costs have a significant economy of scale [3,4]. The proportion of the membrane related investment costs are 20–30% of the total investment costs at small plants (plant capacity 4,000–8,000 $m^3$/d), and the proportion increases to near 50% as the plant size increases (plant capacity 53,000–125,000 $m^3$/d) [3,4]. Therefore, the cost of membrane modules become more important factor of cost and smaller economy of scale is realised at larger plants [3,4].

Operation and maintenance (O&M) costs of a membrane plant can be separated into fixed and variable costs [3]. Fixed costs include labour and general maintenance that are not dependent on plant operation, whereas variable costs vary proportionally with plant production and include energy, pre-filter replacements, chemicals and retentate treatment. Membrane replacement, which is generally a major factor in O&M costs [3], can be categorised to fixed costs if the membranes are replaced according to a certain fixed schedule or to variable costs if the membranes are replaced according to need.

In some cases the cost of membrane treatment can be lowered by blending membrane filtered water with less treated water to produce overall product water. The degree of possible blending is controlled by the required quality of product water and the quality of less treated blending water. The plant operation rate also affects the cost of membrane treatment. The operation rate should be as high as possible to minimise the effect of amortised annual investment costs and fixed O&M costs that are not influenced by operation rate.

Several studies indicate that NF may be economically competitive with other treatment options mostly at small water treatment plants [6,8]. The cost estimates of Wiesner et al. [6] suggest that NF is cheaper in enhancing the disinfection-by-product removal after conventional treatment than ozonation and granular activated carbon adsorption, at least at facilities with capacities lower than 80,000 $m^3$/d. The findings of Pianta et al. [9], in turn, indicated that the treatment of karstic spring water with a combination of microfiltration/ultrafiltration and NF costs approximately twice the cost of conventional treatment with ultrafiltration and powdered activated carbon.

Few studies have been carried out to establish the environmental impact of water treatment [10] and desalination plants [11–13], but only one study was found on the environmental impact of NF as water treatment technique [14]. Sombekke et al. [14] found out that from the environmental point of view there was no significant difference between treating groundwater by NF or by pellet softening and granular activated carbon filtration. Despite the lack of previous studies and information, it is essential to take the environmental aspects into consideration when evaluating NF as a water treatment option.

The cost and the environmental impact of NF as a refining treatment after conventional surface water coagulation and sand filtration were calculated and evaluated in this study. The aims of the study were to value the NF process as water treatment technique from the economical and environmental point of view and to find the most efficient ways to minimise both the cost and the environmental impact of the process. The calculations are based on the pilot-scale NF trials carried at a real surface water treatment plant.

## 2. Materials and methods

### *2.1. Cost of NF*

The additional cost caused by the installation of the NF process after the conventional surface water treatment at Espoo City Waterworks (ECW) was calculated at different operational parameters. The production capacity of the designed NF process corresponds to the present production of the ECW plant and was 18,000 $m^3$/d plus an extra capacity of 5% for the use at the plant.

The required membrane area and the consequent membrane related investment costs were calculated from the fluxes extrapolated from the data of the pilot-scale NF studies conducted at ECW. The costs were calculated for NF operation at driving pressures from 4 to 7 bar and at recoveries of 68% or 83%. The design fluxes were temperature normalised to 1ºC according to the membrane manufacturer’s guideline for investment cost calculations to ensure the capacity requirements during cold feed water temperature. In the total membrane module requirement an 20% allowance was reserved for the NF plant maintenance. The expected price of a membrane module (NF255-400) was 780 € and the active membrane surface area of one membrane module was 37 $m^2$.

Based on the literature [3,4] and the manufacturer’s knowledge the membrane modules were expected to cause 40% of the total investment costs. The non-membrane investment costs include all equipment and facilities necessary to support the use of membranes: pressure vessels, pumps, monitoring equipment, pre-filters, membrane cleaning system, process automation, buildings, retentate disposal, etc. No investment costs were reserved for the feed water pre-treatment, since the required pre-treatment capacity is available at the present process of ECW. A 20-year pay-back period and 7% interest rate were used in the investment cost calculations.

The O&M costs of the NF process consist of energy, pre-filter and membrane replacement, chemicals, wastewater discharge and labour.

Energy is required for the pressure increase at the pre-filters and mostly at the NF membranes. The pressure requirement at the pre-filters was expected to be 1 bar. The NF driving pressures varied between the compared options. The expected price of electricity was 7 c/kWh and the expected efficiency of the pumps was 70%.

A 20% yearly replacement of membrane modules was planned according to the supposed module life-time of 5 years. The used membranes are disposed at the refuse dump. The weight of a used membrane module was expected to be 30 kg and the cost of waste disposal 60 €/t. According to the pilot-scale studies and the experiences at three operating NF plants in Finland [15] the cost of pre-filter replacement and disposal was calculated as 20% of the membrane replacement and disposal cost.

The membrane cleaning is performed at intervals realised at the pilot-scale NF studies at ECW. An acidic cleaning solution followed by an alkaline solution and a pure alkaline cleaning solution are used in turns. The acidic cleaning solution contains 0.8% citric acid and 0.1% oxalic acid and the alkaline cleaning solution 0.2% $Na_4EDTA$ and 0.1% $Na_5P_3O_{10}$. The used prices of the cleaning chemicals were as follows: citric acid 1.15 €/kg, oxalic acid 0.92 €/kg, $Na_4EDTA$ 2.50 €/kg and $Na_5P_3O_{10}$ 0.92 €/kg. The cleaning solutions are made of and the membranes are rinsed with the NF permeate. Cleaning solution and rinsing water volumes were expected to be 50 and 500 L per membrane module, respectively.

The retentate stream is discharged by the residual pressure to the nearby river, since the volume and concentrations on the retentate are not higher than would be allowed for the discharge. Hence, the cost of retentate disposal was considered negligible. The membrane cleaning solutions and rinsing waters are neutralised and discharged to the sewage network. The cost of neutralising chemical was considered negligible. The expected price of waste water was 1.21/m$^3$.

The variation in the required working time for O&M of the NF process is mainly seen in the time required for the membrane cleaning and the time for the other O&M is basically fixed. The basis for the required weekly work time was 1 min/membrane module for cleaning at two weeks cleaning interval and 20 h/week for other O&M. The expected cost of work was 30 €/h.

The installation of the NF process after the conventional surface water treatment requires higher feed water intake and higher production capacity of coagulation pre-treatment due to the less than 100% recovery of the NF process. The increased energy consumption, use of coagulation chemical and sludge and sand-filter rinsing water disposal to the sewage in the pre-treatment were included in the O&M cost calculations. Other changes in the O&M costs of the pre-treatment were expected to be negligible. The energy requirement of the pre-treatment process is 0.13 kWh/m$^3$. The used coagulant is polyaluminium chloride at a dosage of 65 g/m$^3$ and the price of the chemical is 0.22 /kg. The wastewater production in the pre-treatment is 0.055 m$^3$/m$^3$. On the other hand, the ozonation that is used for the removal of odour and taste causing small organics is not needed after the installation of NF. The saved energy consumption is 600,000 kWh/a and the total savings 90,000/a. The higher product water quality also allows the chloramine dosage to be lowered by 66% from 0.6 mg $Cl_2$/L to 0.2 mg $Cl_2$/L [16, 17]. The present price of the chloramine disinfection is 0.2 c/m$^3$.

## 2.2. Environmental impact of NF

The environmental impact of using the NF as a refining treatment step in the conventional surface water treatment train was assessed by calculating the inputs and outputs of the NF process described above from the environmental point of view at different operating parameters. Since the goal was to evaluate the effect of adding the NF after the conventional treatment train, only those system inputs and outputs that differ from the conventional treatment were included to the analysis. Only the inputs and outputs related to the O&M of the process were included to the analysis. The data for calculations was derived from the pilot study, from the manufacturers and from the literature.

## 2.3. Pilot-scale study

The cost and environmental impact calculations are based on the pilot-scale study conducted at ECW between December 1999 and February 2000. The two similar NF pilot processes were run in parallel at ECW. A schematic view of the NF pilot plant is presented in Fig. 1. The feed water was filtered by a 5-µm cartridge filter before it entered the pressure vessels. The array of the plant was two-staged, and part of the retentate from the final stage was circulated back to the feed stream to enhance the recovery of the plant.

The pressure vessels in the both stages housed two spiral-wound modules with nominal dimensions of 9.9 cm in diameter and 101 cm in length. The same membranes, Filmtec NF255-400 by DOW, were used in the both pilots during the whole experiment. The membranes were used for 5 months in the same NF pilots at ECW before the study. The active surface of the membranes is

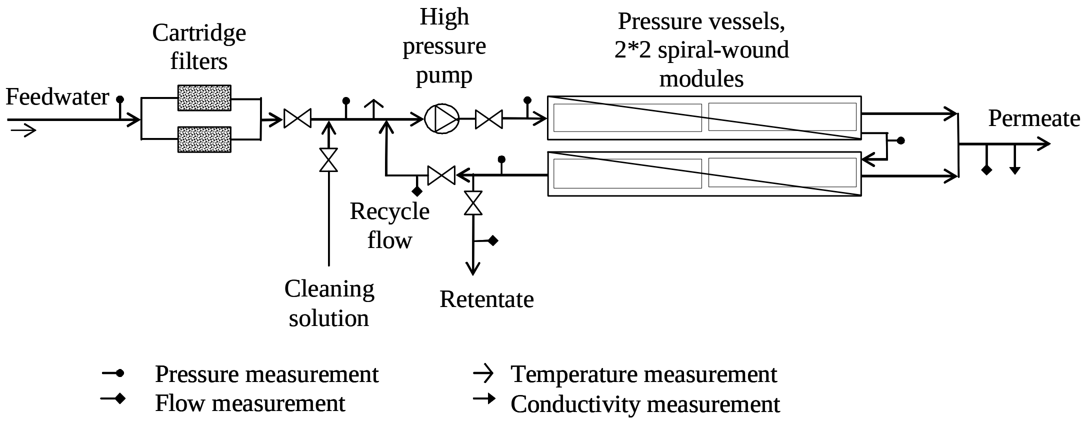

Fig. 1. Schematic view of NF pilot.

made of polypiperazine amide and according to the manufacturer the membrane cut-off is approximately 200–300 g/mol. The total membrane area of each NF pilot plant was 4×7.7 $m^2$.

The pilot processes were fed with the chemically treated and sand-filtered product water of ECW. ECW takes raw water from a small humus-rich lake (average TOC 6.9 mg/L). The process at ECW consisted of periodic ozonation, chemical coagulation with polyaluminium chloride, dissolved air flotation, rapid sand filtration and post-treatment with chloramine and lime during the study. The feed water for the NF pilot was drawn before the post-treatment. Some NF feed water quality parameters during the study are presented in Table 1.

Permeabilities, fluxes, flux declines, required cleaning intervals and retentions of the studied NF membranes at different operating parameters were evaluated. The used driving pressures ranged from 4 to 7 bars at pilot-scale recoveries of 40% and 55% (corresponds to 12% and 18% recoveries per membrane module and to 68% and 83% plant-scale recoveries, respectively) at the parallel NF pilots during cold feed water temperature ($T = 0.5$–1.0ºC). The NF process was run for two-weeks at the driving pressures of 4, 5 and 6 bar and for one-week at the driving pressure of 7 bar.

Between the runs the membranes were cleaned by an acidic cleaning phase followed by an alkaline cleaning solution. The cleaning solutions compositions were the same as designed for the NF plant.

Table 1
Some NF feed water quality parameters during pilot-scale study as average values ± standard deviation

| | |
|---|---|
| pH | 6.3±0.1 |
| Conductivity, mS/m | 13.7±2.5 |
| $UV_{254}$, 1/cm | 0.046±0.007 |
| TOC, mg/L | 2.9±0.1 |

## 3. Results and discussion

### 3.1. Operation of NF pilot at different driving pressures and recoveries

The permeabilities of the NF membranes at the parallel pilots operated at different recoveries with varying driving pressures are presented in Fig. 2. The permeabilities are normalised according to the membrane manufacturer's guidelines to the year-average feed water temperature at ECW ($T$ = 10ºC) to give a reliable picture of the average operation of the NF process. The flux

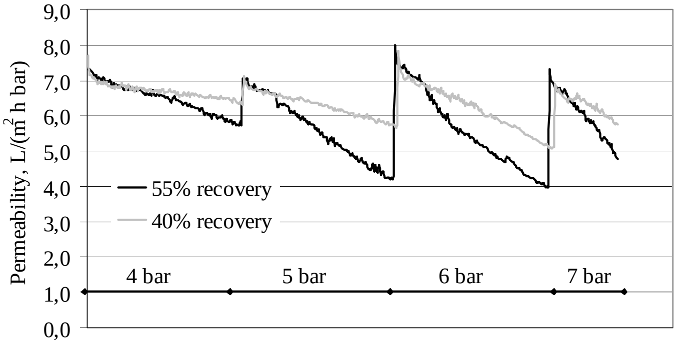

Fig. 2. Temperature normalised ($T$ = 10ºC) permeabilities of membranes at parallel NF pilots operated at different recoveries and driving pressures (operating $T$ = 0.5–1.0ºC, cross flow 0.6 $m^3$/h at 55% recovery and 0.9 $m^3$/h at 40% recovery).

declines were remarkably higher at the 55% recovery than at the 40% recovery.

The normalised permeabilities, required cleaning intervals and retentions of the membranes observed in the study are well in accordance with the performance of the NF-pilot during an all-year experiment at ECW. Thus, despite the temperature effects seen by Sharma and Chellam [18], the results of the study are considered representative of the NF installed after the conventional surface water train at ECW at all temperatures.

At the Méry-sur-Oise NF treatment plant, treating polluted and conventionally pre-treated river water of seasonally varying temperature the average operational permeability is very similar, 6 L/($m^2$ h bar) with the same NF membrane [19]. However, the permeability of the membranes remained stable for longer periods at Méry-sur-Oise.

The design fluxes extrapolated from the pilot-scale studies for the cost calculations of the plant-scale NF process (at feed water temperature of 1ºC) at different operating parameters are presented in Table 2. It is clearly seen that the increase of recovery did not remarkably increase the

Table 2

Fluxes of designed plant-scale NF process at different driving pressures, recoveries and feed water temperatures, driving pressures to produce design flux at 10ºC feed water temperature as well as required cleaning intervals. Extrapolated from pilot-scale NF study

| | Driving pressure | | | |
|---|---|---|---|---|
| | 4 bar | 5 bar | 6 bar | 7 bar |
| Design flux, feed temperature 1ºC | | | | |
| 68% recovery | 16.5 L/($m^2$ h) | 20.4 L/($m^2$ h) | 26.7 L/($m^2$ h) | 29.3 L/($m^2$ h) |
| 83% recovery | 16.6 L/($m^2$ h) | 20.7 L/($m^2$ h) | 27.7 L/($m^2$ h) | 30.2 L/($m^2$ h) |
| Operational flux, feed temperature 10ºC | | | | |
| 68% recovery | 23.4 L/($m^2$ h) | 29.0 L/($m^2$ h) | 37.8 L/($m^2$ h) | 41.6 L/($m^2$ h) |
| 83% recovery | 23.6 L/($m^2$ h) | 29.3 L/($m^2$ h) | 39.3 L/($m^2$ h) | 42.9 L/($m^2$ h) |
| Driving pressure, feed temperature 10ºC | | | | |
| 68% recovery | 3.0 bar | 3.6 bar | 4.5 bar | 4.9 bar |
| 83% recovery | 3.0 bar | 3.6 bar | 4.6 bar | 5.0 bar |
| Cleaning interval | | | | |
| 68% recovery | 2 weeks | 1.4 weeks | 0.6 week | 0.5 week |
| 83% recovery | 1.5 weeks | 0.7 week | 0.5 week | 0.4 week |

average operating flux. This is partly caused by the lower feed water cross flow when operating the NF pilot at higher recovery (0.6 $m^3$/h at 55% and 0.9 $m^3$/h at 40%). However, there is no basis to reliably assess the effect of the difference in the cross flow on flux.

The year-average operating fluxes (normalised to the year-average operating temperature, 10ºC) at different operating parameters are also presented in Table 2. The calculated year-average fluxes were approximately 40% higher than the design fluxes indicating that lower than designed driving pressures can be used during higher temperature season. The required driving pressures to produce the design fluxes at the year-average feed water temperature are presented in Table 2. These values were used when calculating the energy consumption of the NF.

The membrane cleaning is recommended as the operational flux declines 15% from the basic line [20]. The cleaning intervals that are required to comply with the 15% flux decline at different driving pressures and recoveries are presented in Table 2. The results show that as higher driving pressures and recovery caused more intensive membrane flux decline remarkably shorter cleaning intervals are needed. This leads to higher usage of cleaning chemicals, to higher time requirement for cleanings, to quicker membrane wear out and to shorter membrane life-time.

The average retentions of conductivity and organic matter (TOC) at different operating parameters during the pilot-scale NF study are presented in Fig. 3. The permeate quality remained stable and retentions high in terms of organic matter despite the varying driving pressure and recovery of the NF process. On the contrary, the higher driving pressure and the lower recovery increased the conductivity retention due to the membrane compression and the lower concentration gradient. Since the NF was used mainly for the organics removal the operating parameters did not affect the applicability of the process in the terms of product water quality.

### 3.2. Cost of NF

The investment and O&M costs of the designed NF process at the different driving pressures and recoveries are summarised in Fig. 4. The results suggest that at certain operating parameters investment and O&M costs are balanced in an optimal way resulting in the least total cost of NF operation. In this case the optimum operating parameters were 6 bar at 83% recovery. As a whole, the use of higher recovery seemed more economical.

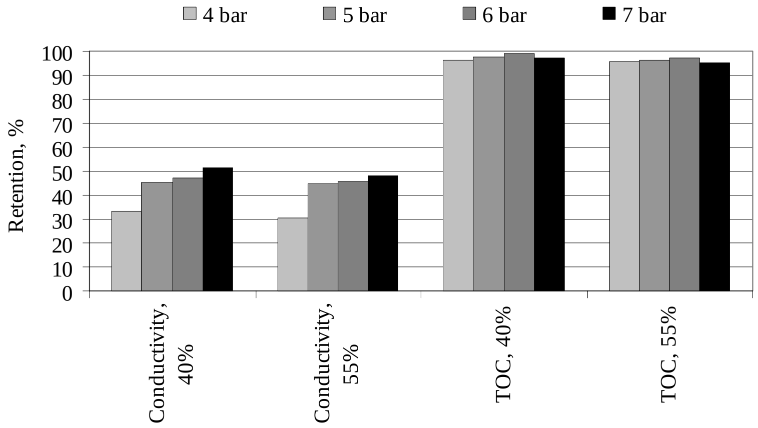

Fig. 3. Average retentions of conductivity and organic matter (TOC) at different driving pressures and recoveries of NF pilot process.

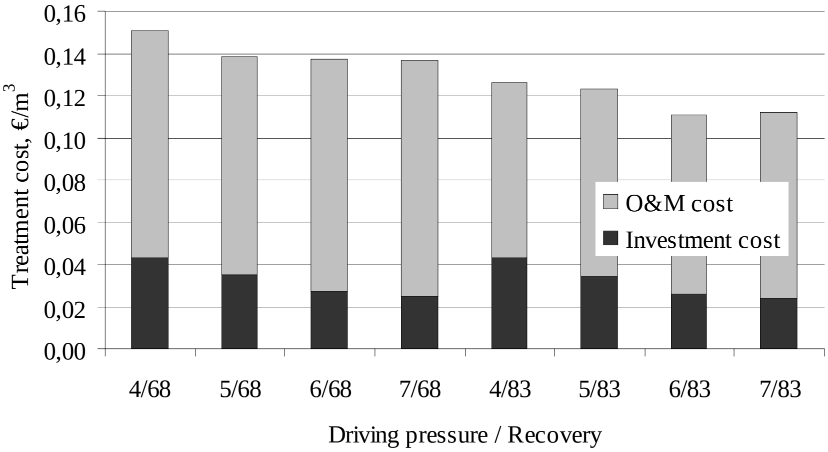

Fig. 4. Investment and O&M costs of NF process at different driving pressures and recoveries.

The calculated investment costs ranged from 0.024 €/m$^3$ at the driving pressure of 7 bar to 0.043 €/m$^3$ at the driving pressure of 4 bar with the both studied process recoveries. Less variance and non-linear relation to driving pressure was seen in the O&M costs, which ranged from 0.103 to 0.112 €/m$^3$ at the recovery of 68% and from 0.083 to 0.089 €/m$^3$ at the recovery of 83%. The total es-timated cost of installing NF at ECW ranged from 0.110 to 0.151 €/m$^3$ at the studied operational para-meters.

The cost of conventional water treatment at ECW is approximately 0.17 €/m$^3$ excluding capital costs. With that respect the addition of NF at ECW process would increase the price of water treatment notably.

It was assumed that the pilot-scale studies give reliable basis to assess the effect of the operating parameters on the performance and the cost of the designed plant-scale NF process when the plant-scale recovery was increased proportionally the pilot-scale study. However, the real performance and cost of the plant-scale NF process would differ from the calculations e.g. due to the fact that the NF pilot corresponds to the performance of the NF process in the beginning of the plant-scale NF process where the operational environment is much easier than in the end of the process. A booster pumping may also be required at the real NF process.

When comparing these treatment costs with other cost data, it should be borne in mind that the system boundaries, the used unit costs and the application sites affect costs and calculations remarkably and may make comparisons impossible. For example, the seasonal variation of the feed water temperature in the Finnish applications requires the NF process to be designed for winter conditions (design flux at feed water temperature of 1ºC). This caused up to 20% higher total cost of NF in comparison to the design at the year average feed water temperature of 10ºC. However, the calculated cost of installing and operating NF at ECW is very similar to the estimated cost caused by NF at the Méry-sur-Oise plant (0.12 €/m$^3$) treating conventionally pre-treated river water [19]. On the other hand, the calculated costs are somewhat lower than the estimated cost of membrane softening in Florida (8% interest rate and 20-year pay-back time): the total cost ranged from 0.15 to 0.27 €/m$^3$ and the O&M cost from 0.11 to 0.18 €/m$^3$ at a plant size similar to the designed NF process [3].

The distribution of O&M costs at the different driving pressures and recoveries are presented in Fig. 5. The results indicate that at the lower driving

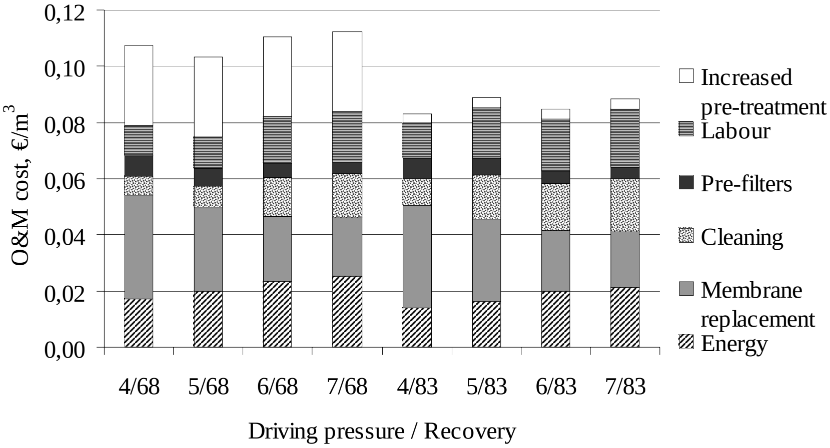

Fig. 5. Distribution of O&M costs of NF process at different driving pressures and recoveries.

pressures the O&M costs are dominated by membrane replacement and at higher driving pressures the shares of energy consumption, membrane replacement and cleaning interval related costs of cleaning and labour become more equal. The other authors have noticed the same dominating cost factors of the membrane O&M, but the shares vary according to the applications and the sites [3,5–7].

Energy consumption and membrane replacement account for 42–61% of the O&M costs at all the studied operational parameters. Accordingly, changes in the prices of electricity and membranes as well as in the energy requirement and the membrane life-time affect the total cost of NF remarkably. For example, a 2 c/kWh increase in the price of electricity (29% addition to present price) would increase the total estimated cost of NF by 4–6%.

The effect of recovery was seen basically in the lower O&M cost of increased pre-treatment at the higher recovery (the cost of increased pre-treatment 0.028 €/m$^3$ at the recovery of 68% and 0.003 €/m$^3$ at the recovery of 83%). No expected decrease was seen in the investment and membrane replacement costs at the higher recovery because the average operational fluxes did not increase remarkably in comparison to the lower recovery.

The differences in the cost of labour are partly theoretical, since the operational personnel can not be hired exactly according to the need calculated based on the requirements of the cleanings. If the NF process would be installed at ECW, the present personnel could operate the NF process and hiring one full-time operator would be needed at each operational option at most. One full-time operator would cause fixed labour related cost of 0.009 €/m$^3$. That would reduce the total costs up to 10% when using the highest driving pressures while no change would be seen at the lowest driving pressures.

Since shorter cleaning intervals are needed at the higher driving pressures and recovery, quicker membrane wear out and shorter membrane life-time can be expected. There is no basis to predict the effect of the shorter cleaning interval on the membrane life-time accurately. Decreasing the expected membrane life-time to 4 years or increasing it to 6 years increased and decreased the calculated membrane replacement costs at maximum by 0.009 €/m$^3$ and 0.006 €/m$^3$, respectively. These caused up to 7% changes in the total costs of NF process.

In some applications it would be possible and economical to treat just a part of the water by the NF and mix less treated water with NF product water as a drinking water [3]. However, in the studied case the whole water stream needs to be treated by NF, because the goal is to enhance organics removal and odour and/or taste forming compounds are involved.

### 3.3. Environmental impact of NF

The treatment steps of the water treatment including NF and the related inputs and outputs caused by the installation of NF are presented in Fig. 6.

The additional inputs caused by the installation of the NF process include extra raw water due to less than 100% recovery of NF, extra energy for pre-treatment of more raw water, energy for prefiltration and NF, extra chemicals for pre-treatment of more raw water, pre-filters, NF membranes and chemicals for membrane cleaning. The additional outputs from the installation of the studied NF process are retentate, used rinsing and cleaning solutions and increased wastewater from pretreatment (emissions into water), emissions into atmosphere and waste products.

The installation of NF at ECW would decrease some inputs and outputs of water treatment due to no need for ozonation, lower required disinfectant dosage and less need for distribution system maintenance. The lower need for disinfection chemical and less distribution network maintenance are related to the lower potential for microbial activity in the higher quality drinking water.

The inventory analysis of the environmental impacts of water treatment after installation of the NF process in the conventional water treatment train at ECW are presented in Table 3. The biggest environmental impact is always seen at the lower recovery. This indicates that from the environmental point of view it is more efficient to use the higher recovery. Otherwise, the least and the most environmental impact is seen either at the lowest or at the highest studied driving pressure.

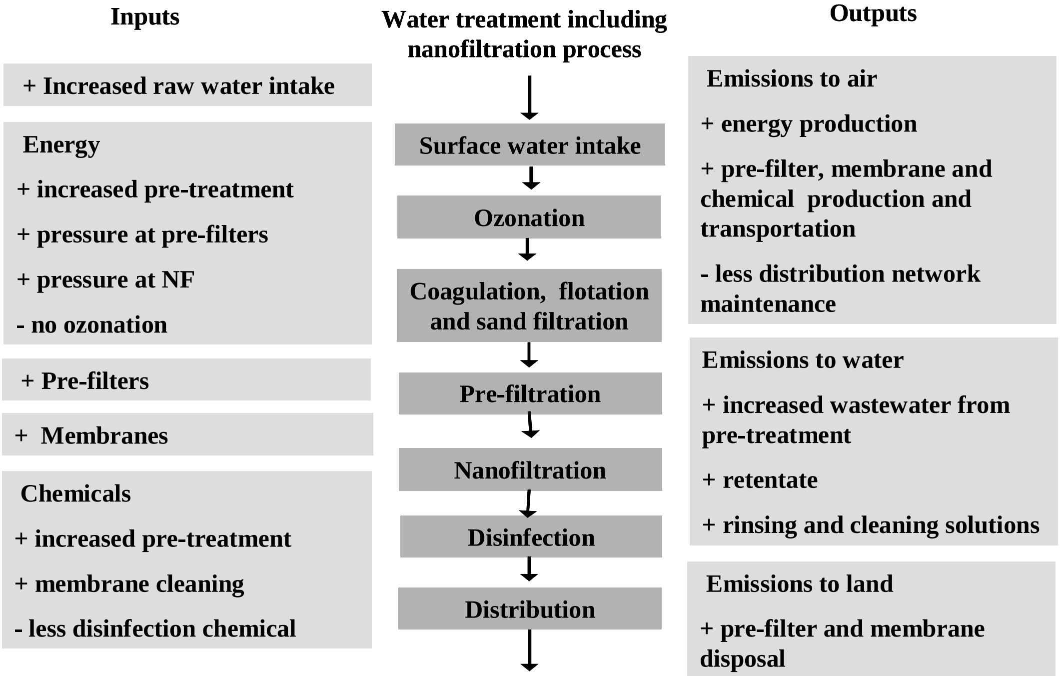

Fig. 6. Changes in O&M inputs and outputs of water treatment after installation of NF.

Table 3
Inventory of environmental impact of NF process O&M at different driving pressures and recoveries. Biggest impact indicated by dark and least impact by light colour

| | Driving pressure | | | |
|---|---|---|---|---|
| | 4 bar | 5 bar | 6 bar | 7 bar |
| Increased raw water intake, $m^3/m^3$ | | | | |
| 68% recovery | 0.54 | 0.54 | 0.54 | 0.54 |
| 83% recovery | 0.27 | 0.27 | 0.27 | 0.27 |
| Energy consumption, $kWh/m^3$ | | | | |
| 68% recovery | 0.22 | 0.26 | 0.32 | 0.34 |
| 83% recovery | 0.14 | 0.17 | 0.22 | 0.24 |
| Membrane replacement, modules/a | | | | |
| 68% recovery | 310 | 250 | 191 | 174 |
| 83% recovery | 308 | 247 | 184 | 169 |
| Chemicals, $g/m^3$ | | | | |
| 68% recovery | 36.7 | 37.0 | 39.1 | 39.5 |
| 83% recovery | 19.3 | 21.5 | 21.7 | 22.5 |
| Wastewater stream, $m^3/m^3$ | | | | |
| 68% recovery | 0.53 | 0.53 | 0.53 | 0.54 |
| 83% recovery | 0.24 | 0.24 | 0.24 | 0.24 |
| Waste disposal, g/m3 | | | | |
| 68% recovery | 0.57 | 0.46 | 0.35 | 0.32 |
| 83% recovery | 0.56 | 0.45 | 0.34 | 0.31 |

Since the NF process increases the energy consumption of the water treatment approximately by 60–150%, efforts should be devoted to decrease energy consumption and environmentally friendly energy production should be favoured. Sombekke et al. [14] found out that the use of green energy was very efficient in improving the environmental impact of NF. At the moment the disadvantage of the green energy is its high price in comparison to the “conventional” energy.

The pressure increase for NF accounts for 58–75% of the energy consumption caused by the NF process, and thus the most efficient option is to reduce the energy consumption of NF. This can be achieved by development and use of more permeable NF membranes requiring less driving pressure or by increasing the membrane area and using lower design fluxes and driving pressures. The latter option causes more membrane related production and transportation effects and bigger waste disposal and optimisation is required to balance the various environmental impacts in an optimal way.

The installation of NF increases the use of chemicals remarkably. The increased chemical use originates mostly (73–94%) from the increased coagulation pre-treatment, suggesting that increasing the recovery of the NF process is the best way to reduce the environmental impact of the chemical use. However, the environmental impact of the used chemicals varies and small output of some chemical may be more harmful than high load of another. The use of different chemicals after installation of NF is listed in Table 4 at different operational parameters of NF.

The application of the higher recovery reduces

Table 4
Changes in chemical use after installation of NF in conventional water treatment

| | Driving pressure | | | |
|---|---|---|---|---|
| | 4 bar | 5 bar | 6 bar | 7 bar |
| Polyaluminiun chloride coagulant, t/a | | | | |
| 68% recovery | 232.4 | 232.4 | 232.4 | 232.4 |
| 83% recovery | 113.2 | 113.2 | 113.2 | 113.2 |
| Cleaning chemical $Na_4EDTA$, t/a | | | | |
| 68% recovery | 2.0 | 2.3 | 4.1 | 4.5 |
| 83% recovery | 2.7 | 4.6 | 4.8 | 5.5 |
| Cleaning chemical $Na_5P_3O_{10}$, t/a | | | | |
| 68% recovery | 4.0 | 4.7 | 8.3 | 9.1 |
| 83% recovery | 5.3 | 9.2 | 9.6 | 11.0 |
| Cleaning chemical citric acid, t/a | | | | |
| 68% recovery | 8.0 | 9.3 | 16.6 | 18.1 |
| 83% recovery | 10.7 | 18.3 | 19.2 | 22.0 |
| Cleaning chemical oxalic acid, t/a | | | | |
| 68% recovery | 1.0 | 1.2 | 2.1 | 2.3 |
| 83% recovery | 1.3 | 2.3 | 2.4 | 2.7 |
| Decrease in disinfection, t/a | | | | |
| 68% recovery | 6.5 | 6.5 | 6.5 | 6.5 |
| 83% recovery | 6.5 | 6.5 | 6.5 | 6.5 |

also efficiently the need for raw water intake, retentate discharge and production of wastewater in pre-treatment. The application of the higher recovery reduces the volume of the retentate stream more than 50%, but also increases the concentrations in the retentate remarkably. The effect of the retentate stream on the receiving river should be studied carefully when considering the discharge permission.

Generally the small footprint is mentioned as an advantage of membrane processes, but in the evaluated case the installation of NF would remarkably increase the footprint of water treatment. However, with proper mitigation measures the adverse environmental impacts of the NF process can be minimised. These measures include optimisation of pre-treatment process or even application of other pre-treatment technique, operational optimisation of the NF process, use of less energy requiring membranes, use of green energy, use of environmentally friendly cleaning chemicals or cleaning chemical reuse and retentate utilisation.

## 4. Conclusions

The installation of NF after the conventional surface water train at ECW was estimated to cause at minimum 0.11 €/m$^3$ increase in the cost of treated water. At this cost a very reliable and easy to operate treatment process, remarkable increase in the quality and stability of treated water and hence, a better customer acceptance would be gained. However, the environmental impact of the water treatment also increases remarkably after the installation of NF and improvements should be done to minimise these effects. The main ways to minimise the cost of NF are related to recovery of the process, energy consumption, membrane life-time and membrane cleaning, whereas the environmental impact minimisation is mostly related to recovery of the process and energy consumption.

Generally both the lower cost and the least adverse environmental impact were gained at the higher recovery (83%) of NF. The investment and O&M costs of NF were, in turn, balanced to the minimum total cost at a certain driving pressure, while the environmental impact either increased or decreased linearly with driving pressure. As a conclusion, the operating parameters minimising the cost of NF seemed to also balance the total environmental impact of NF quite well.

The presented costs are calculated estimates and when analysing the data, one should bear in mind the generalisations made in the calculations. However, the results indicate reliably the effect of the operating parameters on the cost and the environmental impact of NF when installed after the conventional surface water treatment train at ECW. The estimates also give useful information about the scale of NF costs.

According to these cost calculations NF can be considered as a potential treatment option also in the surface water applications when evaluating the construction of new or upgraded facilities especially when an efficient water treatment is required. The results also emphasise the importance of the process optimisation in minimising both the economical and environmental effects of NF.

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