# Comparison of pressure-driven membrane processes and traditional processes for drinking water production in Europe based on specific impact criteria

**B van der Bruggen[1]*, JQJC Verberk[2] and J Verhack[1]**

[1]*University of Leuven, Department of Chemical Engineering, Laboratory for Applied Physical Chemistry and Environmental Technology, W. de Croylaan 46, B – 3001 Heverlee, Belgium*

[2]*Delft University of Technology, Faculty of Civil Engineering and Geosciences, Section Sanitary Engineering, Stevinweg 1, 2628 CN Delft*

## Abstract

Due to the policy of many governments of encouraging the use of alternative water sources instead of groundwater, there is a clear need for enhanced water purification systems such as pressure-driven membrane processes. In this article a comparison is made between drinking water production from surface water using pressure-driven membrane processes and using traditional surface water treatment systems. Three alternatives are considered: Traditional treatment using coagulation/flocculation, sand filtration, physicochemical softening, activated carbon adsorption and disinfection (Process A); spiral-wound nanofiltration with ultrafiltration pretreatment followed by marble filtration and disinfection (Process B); and direct capillary nanofiltration with only a limited pretreatment and post-treatment by marble filtration and disinfection (Process C). An evaluation protocol was used (CRIME-DAV), in which the following impact criteria were taken into account: Quality and public health, operational aspects, the environment; the landscape, the economy, and administrative, legal and societal acceptance. The comparison of these aspects shows that none of the considered alternatives is favourable for all aspects. In practice, weight factors used in the protocol may have to be revised, shifting the optimal solution to one of the three processes. The general comparison is to be considered a rough indication and a template for a more detailed practical study. Process A proved to be advantageous for the aspects 'environment' and 'economy' but performance for 'quality and public health' and 'landscape' was poorer than for alternatives B and C. The latter both had a particularly good performance for 'quality and public health' and "operational aspects". Process C was more advantageous than B for economical aspects and the environment.

**Keywords**: pressure-driven membrane processes; drinking water; microfiltration; ultrafiltration; nanofiltration; reverse osmosis; environmental impact

## Introduction

The breakthrough of pressure-driven membrane processes is essentially related to the shift from groundwater to surface water as an alternative water source for drinking water supply, which is a priority for many European governments, including the Flemish government (Mina Plan 2, 2002). The decrease of the groundwater level and the risk of droughts in natural areas by the extraction of groundwater by drinking water companies, agriculture and industry, and by the decrease of the infiltration volume by urbanization are the main reasons for this policy (Van Dijk, 1992). Quota and taxes on the use of groundwater are two methods for influencing the use of water sources (Van Damme et al., 2001).

Whereas groundwater requires only a limited treatment before it is fit for distribution, surface water and other water sources need an enhanced treatment because of the occurrence, or the risk of occurrence, of a wide range of contaminants. An overview of possible contaminants in surface water and in groundwater is given in Table 1 (Degrémont, 1991). Traditional surface water treatment focuses on the removal of contaminants present in groundwater; other contaminants are hardly removed, so that the treatment scheme has to be extended with processes such as adsorption on activated carbon and thorough disinfection.

During the last decade, pressure-driven membrane processes made a major breakthrough in drinking water production (Jacangelo et al., 1997). New plants such as Méry-sur-Oise, France (Gaid et al., 1998; Ventresque et al., 1997) and Heemskerk, the Netherlands (Kamp et al., 2000) often make a clear choice for membrane processes for drinking water production, mainly because of the superior technical performance and because a combined removal of various pollutants can be obtained. The first years of operation already prove that the membrane process is reliable (Ventresque et al., 2000). Other plants such as the integrated membrane treatment process consisting of microfiltration followed by nanofiltration in Barrow, Alaska, which treats surface water with high concentrations of natural organic material including disinfection by-product precursors, and significant concentrations of *Giardia* and *Cryptosporidium* (Lozier et al., 1997) provide a realistic view of possible water production methods in the (near) future. Ranging from microfiltration to reverse osmosis, pressure-driven membrane processes are able to remove nearly all undesired compounds from a given water source (Mulder, 1996; Van der Bruggen et al., 2003). Especially where a wide range of possible contaminants has to be removed, membranes are a safe barrier against contamination of the product water. A fine example is the water treatment plant of Koksijde, Belgium (Van Houtte et al., 1998) where municipal

* To whom all correspondence should be addressed.
☎+32 16 32.23.40; fax:+32 16 32.29.91;
e-mail: bart.vanderbruggen@cit.kuleuven.ac.be
*Received 12 January 2004; accepted in revised form 25 May 2004.*

**TABLE 1**
**Overview of possible contaminants in surface water and groundwater**

| Possible pollutants in surface water | | | |
|---|---|---|---|
| **Biological** | **Mineral** | | **Organic** |
| | **Without significant healtheffects** | **With significant health effects** | |
| - Bacteria and viruses<br>- Phyto- and zooplankton | - Turbidity<br>- Colour (suspended solids, humic acids) | - Metals (Cd, Cr, Pb, Hg, Se, As, ...)<br>- Nitrates<br>- Asbestos<br>- Hardness<br>- Fluor | - Pesticides and plant growth regulators<br>- Organic halogen compounds<br>- Chlorinated solvents<br>- Phenols and phenol derivates<br>- Saturated and unsaturated hydrocarbons<br>- Polycyclic aromatic hydrocarbons<br>- Polychlorobiphenyls<br>- Detergents |
| **Possible pollutants in groundwater** | | | |
| **Biological** | **Mineral** | | **Organic** |
| | **Without significant health effects** | **With significant health effects** | |
| - Usually none | - Colour (Fe, …)<br>- Metals (Fe, Mn, …)<br>- Dissolved gases ($H_2S$,...)<br>- Ammonium | - Nitrates<br>- Hardness | Usually none but any accidental pollution lasts a very long time |

wastewater is fed to a microfiltration unit followed by a reverse osmosis unit; the final permeate is recharged in the dunes. The purpose of the membrane operation is the simultaneous removal of all contaminants that might be present in the raw water, which includes ions, pharmaceuticals, pesticides and micro-organisms. Thus, pressure-driven membrane processes are capable of replacing a large number of treatment processes such as surface water pretreatment (coagulation, flocculation and filtration), adsorption on activated carbon or ion exchange. However, pressure-driven membrane processes may also have a significant environmental impact. This aspect is often overlooked, but could influence the comparison between traditional water treatment systems and treatment systems making use of pressure-driven membrane processes. Other aspects such as acceptance of the final product by the end-user are also often neglected and lead to the failure of important projects such as the wastewater reuse project in San Diego, California (Oleszkiewicz and Sullivan, 2002). In this project, tertiary wastewater treatment was planned to provide drinking water for San Diego. However, the customers refused to accept the toilet-to-tap circuit, even though the water quality met all relevant standards.

Drinking water companies and decision makers are required to make a choice between traditional water treatment and a membrane-based water treatment scheme when faced with the need for new investments. This article evaluates both options, taking all aspects of the implementation into account, and with a special focus on environmental aspects and the application of sustainable development in the production of drinking water. For the membrane-based water treatment scheme, a distinction is made between the use of spiral-wound nanofiltration membranes and of novel capillary nanofiltration membranes. The latter units may further reduce the need for pretreatment, thus decreasing the complexity of the system.

## Materials and methods

A generalised scheme was set up for three proposed water treatment methods:

- Traditional treatment using classical techniques such as coagulation/flocculation, sand filtration, physicochemical softening, activated carbon adsorption and disinfection
- Spiral-wound nanofiltration with ultrafiltration pretreatment followed by marble filtration and disinfection
- Direct capillary nanofiltration with only a limited pretreatment and post-treatment by marble filtration and disinfection.

For the evaluation of the impact of the water treatment processes considered, the CRIME-DAV protocol was used (Van Nieuwenhuyze and Van Rotterdam, 1996). This protocol is essentially a list of criteria and subcriteria that have to be taken into account when the interaction between the process and its environment have to be estimated, together with a number of tools or suggestions for quantification of the different criteria. In the comparison, only listed criteria suggested in CRIME-DAV are used. The list of criteria is subject to further evolution, and it is possible to merge different criteria or to omit unimportant aspects. The different criteria used in this study are:

- Quality and public health
- Aspects of operation
- Environment
- Landscape
- Economy
- Acceptance by administration, legal and societal acceptance.

All criteria are divided into different subcriteria. Table 2 summarises the criteria, together with the subcriteria used.

The evaluation is made based on process specifications and on literature data for existing plants or processes; a qualitative appreciation is used (++: very good, +: good, 0: acceptable, -: bad, --: very bad) in view of conformity and because not all aspects can be quantified. Therefore, the evaluation is, to a certain extent, subjective; the weight factors allocated to each (sub)criterion depend on local priorities or preferences. The weight factors used in this study, taken from Sombekke et al., 1997, are indicated in Table 2. Because of this uncertainty, the method should rather be seen as a semi-quantitative tool that helps to define future strategies in drinking water production.

**TABLE 2**
**CRIME-DAV criteria and subcriteria used in the evaluation of water treatment processes**

| | |
|---|---|
| **1. Quality and public health – 0.39** | **4. Landscape – 0.03** |
| 1.1 compliance with current standards (0.47)<br>1.2 introduction of new compounds (0.17)<br>1.3 user appreciation (0.36) | 4.1 compatibility (0.45)<br>4.2 need of space (0.55) |
| **2. Aspects of operation – 0.14** | **5. Economy – 0.10** |
| 2.1 complexity (0.46)<br>2.2 reliability (0.38)<br>2.3 flexibility (0.16) | 5.1 investment costs (0.27)<br>5.2 exploitation costs (0.73) |
| **3. Environment – 0.11** | **6. Acceptance by administration, legal and societal acceptance – 0.23** |
| 3.1 energy consumption (0.21)<br>3.2 production non-reusable waste (0.16)<br>3.3 production hazardous waste (0.17)<br>3.4 materials consumption (0.30)<br>3.5 influence on environmental compartments (0.16) | 6.1 acceptance by administration (0.45)<br>6.2 legal acceptance (0.25)<br>6.3 societal acceptance (0.30) |

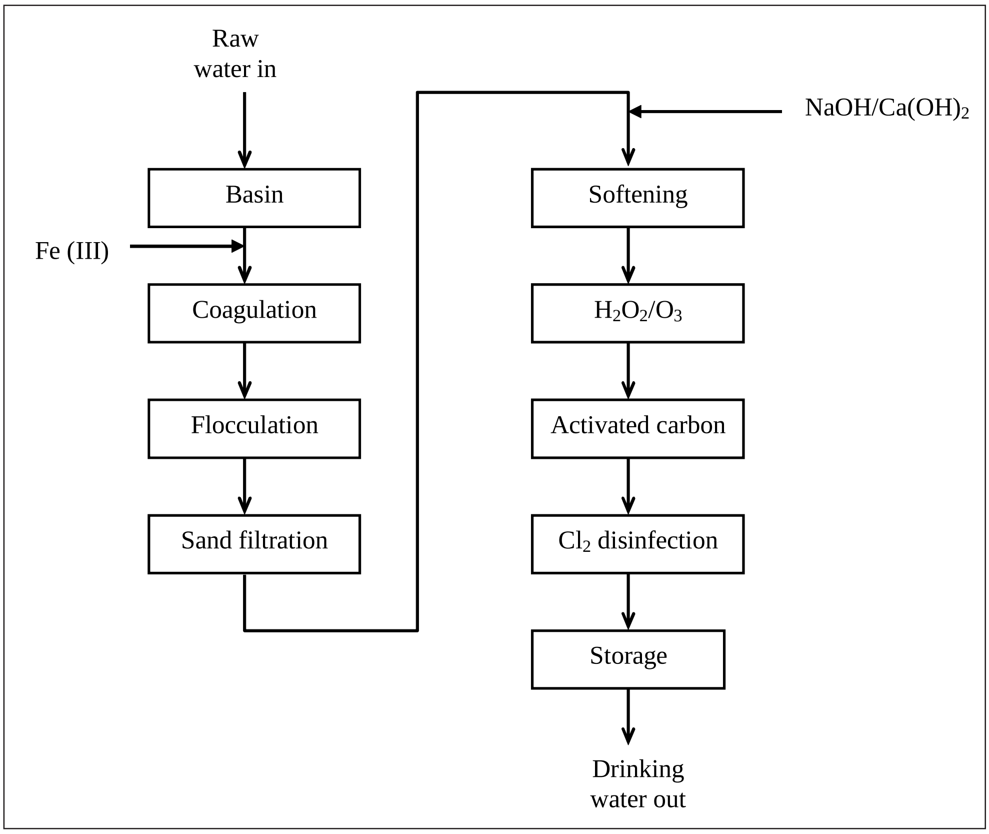


***Figure 1***
*Schematic representation of a traditional drinking water production facility*

## Results and discussion

The scheme that emerged as a typical traditional surface water treatment for the production of drinking water is schematically given in Fig. 1. This scheme (denoted as Process A) uses traditional techniques, but is suitable for the removal of all pollutants indicated in Table 1 from surface water. A possible addition to this scheme is pre-ozonation for the destabilisation of humic acids (Bonnet et al., 1992), which results in a significant removal during flocculation and a lower (20 to 40%) flocculant dosage. This micro flocculation effect seems to be related to surface charges present in humic colloids. Pre-ozonation is not considered further in this study.

Another important issue is the disinfection method. World-

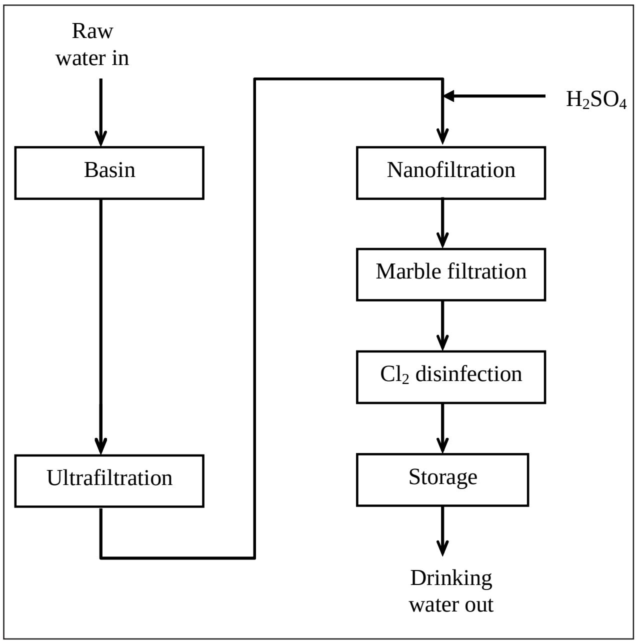


***Figure 2***
*Schematic representation of a drinking water production facility using spiral-wound nanofiltration*

wide chlorine disinfection is still the reference method; however, it is questionable whether this will remain so in the future, given the attention that has been paid during the last decade to the formation of disinfection by-products (DBPs) as a result of chlorine disinfection, and their health effects. Chemical disinfection using chlorine or chloramines is mainly used for the prevention of biological growth in distribution systems (Zhang and DiGiano, 2002), which is not possible with e.g. ozone disinfection. It may be replaced by other processes where AOC (assimilable organic carbon) is almost completely removed, so that no more substrate is left for bacterial growth. Two possibilities for which positive results are claimed are biological activated carbon filters (BACF) (Van der Hoek et al., 1999) and slow-sand filtration (Kruithof et al., 1991).

The scheme for a drinking water facility making use of pressure-driven membrane processes was based on existing facilities described in the literature, as discussed above. A possible scheme, denoted as Process B, is shown in Fig. 2. The conventional coagulation/flocculation and sand filtration are replaced by ultrafiltration (Doyen et al., 2000; Eisnor et al., 2001; Glucina et al., 2000). Nanofiltration is used to replace conventional softening and activated carbon filtration. Sulphuric acid is added in order to prevent membrane scaling (mainly due to $CaCO_3$ precipitation). Post-treatment may comprise filtration over crushed marble for adjustment of the water hardness, followed by chemical disinfection. Again, the disinfection may be replaced by novel methods in which a reduction of AOC should ensure that no bacterial regrowth occurs in distribution systems. The filtration over crushed marble can be replaced by dosed remineralisation when necessary, combined with a pH adjustment. Remineralisation can be important for public health, and to meet legal standards. In Belgium, a minimum total hardness of 60 mgCa/ℓ (15°F) is required after softening; this is not required in all countries but can be taken as a useful guideline. A further possible expansion of the post-treatment is the use of activated carbon adsorption as a clean-up for remaining organic compounds in the NF permeate. The run time of the activated carbon filtration unit increases significantly compared to Process A, because natural organic matter (NOM) and micropollutants are already removed to a great extent in the preceding nanofiltration step. As a consequence, the operating cost for activated carbon adsorption is lower. This step is not further considered here because in most cases it seems to be unnecessary.

A novel drinking water production system using capillary nanofiltration instead of spiral- wound nanofiltration might reduce the need for pretreatment, which can even be by-passed for raw water with sufficiently good quality (Futselaar et al., 2002). The schematic representation of this sequence (denoted as Process C) is given in Fig. 3. The major reason for this is the ease of membrane cleaning and control of membrane fouling for capillary nanofiltration membranes. It may be possible for modules to be backwashed (Frank et al., 2001) and water fluxes can be higher than those obtained with spiral-wound modules, depending on the membrane type used (Van der Bruggen et al., 2003). Moreover, the decrease of the water flux for capillary membranes due to fouling during surface water filtration is similar to the flux decrease for flat sheet membranes with microfiltration pretreatment, which indicates that the concept of using capillary nanofiltration membranes without an extensive feed pretreatment is feasible for surface water treatment. However, this assumption needs to be further evaluated experimentally; if necessary, Fe should be added as a flocculant, followed by sand filtration. Furthermore, the risk of insufficient disinfection due to e.g. broken fibres in the NF module should be decreased by using adequate disinfection in the post-treatment.

The post-treatment suggested here is similar to the one used for the spiral-wound nanofiltration treatment. As for the marble filtration and the disinfection, the same remarks as in Process B apply. The evaluation of the three treatment sequences is given in Table 3. The evaluation is based on the authors' interpretations of literature data and the performance of existing plants, and is therefore subject to discussion. Nanofiltration (Processes B and C) was positively evaluated for the Criterion: Quality and public health, including the Sub-criterion 1.1: Compliance with current standards. If needed, Processes B and C could even be expanded by including adsorption on activated carbon. The superior quality of the produced water is an advantage for Processes B and C (Jacangelo et al., 1997). This aspect will even gain importance in view of the increasing number of possible pollutants in surface water, including e.g. natural organic matter, pesticides and hormones (Schafer et al., 1998; Van der Bruggen et al., 2001), and the sharper standards for drinking water imposed by local, national or international authorities (Sombekke et al., 1997).

For the Subcriterion 1.2: Introduction of new compounds, the formation of DBPs has to be considered. Due to the introduction of membrane processes, the precursors for the formation of DBPs are efficiently removed (Jacangelo et al., 1997; Côté, 1995). Furthermore, the lower re-growth potential (AOC) allows using lower chlorination levels. Processes B and C appear to have a slight advantage over Process A in this area, taking the possibility of adding an adsorption step into account.

The Subcriterion 1.3: User appreciation, may vary significantly among different people, as a function of time and as a function of the amount of available information. The most important factors, however, are the water taste and the absence of contaminants. The latter aspect may be slightly advantageous for Processes B and C.

The application of direct capillary nanofiltration reduces the need for pretreatment, because of the ease of cleaning the membranes. This results in a clear reduction of the complexity of the overall process (2.1). Furthermore, direct capillary nanofiltration is

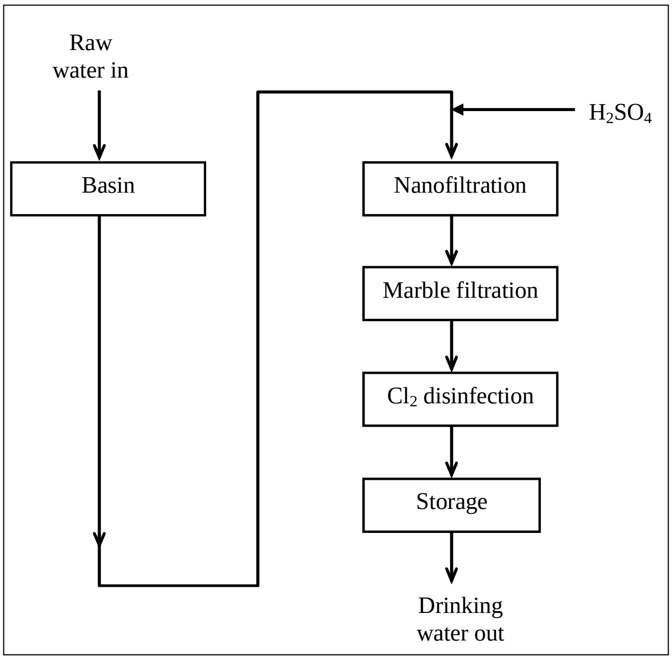


***Figure 3 (right)***
*Schematic representation of a drinking water production facility using capillary nanofiltration with limited pretreatment*

characterised as a robust process with a stable process operation (Futselaar et al., 2002). Spiral-wound nanofiltration also allows the combination of different treatment steps such as NOM and micropollutants removal (activated carbon) and softening (e.g. in a pellet reactor). However, pretreatment is necessary, although less complex than for Process A.

The reliability of the processes is mainly related to the experience with the used techniques. Process A, the traditional treatment scheme, obviously has an advantage for this subcriterion. For capillary nanofiltration, less reliable experience is available. Membrane processes are known to be very flexible, due to the modular approach (Mulder, 1996). Both Processes B and C are positively evaluated for this subcriterion.

Within the Criterion: Environment, Processes B and C are negatively evaluated in the Subcriterion 3.1: Energy consumption, because of the pressures to be applied and the pump energy for cross-flow operation. Process C, however, is an improvement over Process B because of the larger fluxes that can be obtained, in addition to the fact that no UF pretreatment is needed (Futselaar et al., 2002).

Both 3.2 'production non-reusable waste' and 3.3 'production hazardous waste' are negative for all three processes. In Process A, the main waste fraction is the sludge produced in the pretreatment. For Process B, the concentrate from nanofiltration is an additional waste fraction. In Process C, the sludge from the pretreatment can be avoided, but apart from the concentrate, nanofiltration will also generate polluted streams from the membrane cleaning. The difference between both subcriteria depends on, e.g., the composition of the waste fraction: if the concentrate contains hazardous compounds such as pesticides, discharge may not be allowed, even if the pollutants were not added during the process (although they have a higher concentration in the concentrate).

The generation of concentrates also reflects the inefficient use of raw water: the concentrate is a large fraction that has to be considered as waste; the loss of material (raw water) is significantly smaller in Process A. On the other hand, the consumption of chemicals is lower in Process B and even lower in Process C because of the possibility of using cleaning systems with air/water mixtures such as the air-flush system (Bonné et al., 2003).

Criterion 4: Landscape, is advantageous for Process C because the area-intensive pretreatment can be omitted. The advantage for Process B is somewhat smaller, although the membrane operation itself is very compact. This should lead to a good compatibility with the landscape, although

**TABLE 3**
**Evaluation of the three water treatment sequences (A: traditional treatment as shown in Figure 1; B: spiral-wound nanofiltration with pre-treatment, as shown in Fig. 2; C: capillary nanofiltration with limited pre-treatment as shown in Fig. 3)**

| | | Process A | Process B | Process C |
|---|---|---|---|---|
| 1. | **Quality and public health** | | | |
| 1.1 | compliance with current standards | + | + | + |
| 1.2 | introduction of new compounds | - | 0 | 0 |
| 1.3 | user appreciation | + | ++ | ++ |
| 2. | **Aspects of operation** | | | |
| 2.1 | complexity | - | + | ++ |
| 2.2 | reliability | + | + | 0 |
| 2.3 | flexibility | - | ++ | ++ |
| 3. | **Environment** | | | |
| 3.1 | energy consumption | 0 | - | 0 |
| 3.2 | production non-reusable waste | - | -- | - |
| 3.3 | production hazardous waste | - | -- | - |
| 3.4 | materials consumption | - | - | - |
| 3.5 | influence on environmental compartments | 0 | 0 | 0 |
| 4. | **Landscape** | | | |
| 4.1 | compatibility | - | + | + |
| 4.2 | need of space | - | + | + |
| 5. | **Economy** | | | |
| 5.1 | investment costs | - | 0 | 0 |
| 5.2 | exploitation costs | + | - | 0 |
| 6. | **Acceptance by administration, legal and societal acceptance** | | | |
| 6.1 | acceptance by administration | 0 | - | - |
| 6.2 | legal acceptance | 0 | 0 | 0 |
| 6.3 | societal acceptance | 0 | + | + |

this aspect depends largely on local factors.

In general, membrane filtration is characterised by a higher investment cost and exploitation cost than traditional treatment, which results in lower scores for Criterion 5: Economy. The exploitation cost is mainly caused by energy consumption and the need for membrane replacement. However, the higher cost for nanofiltration is counter-balanced by a lower cost of the activated carbon unit or even the absence of this unit. The run time of the activated carbon filter increases dramatically because of the preceding nanofiltration step, so that the frequency of the cost-intensive regeneration of the activated carbon is significantly decreased (Van der Bruggen et al., 2001). This advantage is more pronounced when organic pollution in surface waters becomes more important.

The exploitation cost (5.2) is lower for capillary nanofiltration because of the lower energy consumption and the lower chemicals consumption. Direct capillary nanofiltration will be economically more attractive if the quality of the input water decreases; on the other hand, spiral-wound nanofiltration will be more attractive when a simple pretreatment is sufficient. The investment cost (5.1) is lower for spiral-wound membranes, because of the lower membrane cost. It can be expected that the cost of capillary membranes will decrease when the process develops into a widely applicable technique (Futselaar et al., 2002; Sethi & Wiesner, 2000).

The acceptance by the administration is a complex issue where (inter)national policies are involved, which are highly variable. Legal aspects may involve, e.g., environmental issues such as permits for the discharge of concentrates in surface water or as irrigation water, and possibilities for further treatment of sludge. For both aspects, general conclusions are extremely difficult to make. It is assumed here that there is no significant difference between the three considered processes. Societal acceptance, on the other hand, tends to be supportive for membrane technology, because of the superior product quality and because of the safe operation. Recently, a local drinking water company in Flanders, Belgium, abandoned plans for biological denitrification in favour of membrane processes (electrodialysis or pressure-driven membrane processes) because of protests coming from people living close to the facility. This shows that societal acceptance for membrane technology is growing.

In order to make a comparison between the three processes summarising all aspects in a single number, a weighted average of the qualitative appreciation for all criteria was made (using the weight factors in Table 2). A score of 90 was given for '++', 70 for '+', 50 for '0', 30 for '-' and 10 for '—'. In this way, a total score of 53.4 was obtained for Process A, 58.4 for Process B and 61.3 for Process C. Thus, the Processes B and C, which use membrane processes, seem to be more advantageous than Process A, although the statistical relevance of the differences is doubtful. Furthermore, the use of capillary nanofiltration is a slight improvement over the use of spiral-wound nanofiltration units.

Nevertheless, this final result is a sum of different semi-objective observations, which results in a significant uncertainty on the weighted average. Furthermore, the ranking can be time-dependent. If, for example, societal acceptance for membrane technology (Processes B and C) would disappear ('—'), the weighted average would decrease to 54.3 for Process B, and to 57.1 for Process C. A more conservative evaluation would probably result in a slight advantage for Process A in comparison with B and C. Thus, the comparison does not prove that membrane processes are superior, but that the three processes have a similar overall performance. The choice should depend on a fine-tuning of the weight factors, which reflect local policies towards drinking water production. One could even replace the linear evaluation scale (10 to 90) by a non-linear scale, leaving the possibility of virtually excluding a process on a (sub)criterion that makes its application nearly impossible. A typical example is when a local government refuses to give permission for a given process. In contrast, a more-than-linear mark is necessary when one of the processes reflects an explicit strategy of the authorities.

## Conclusions

None of the alternatives considered here is advantageous for all aspects of the evaluation. The traditional treatment (Process A) may be advantageous for economical aspects, but performance towards quality and public health is poorer than for the membrane operations. Process B, using spiral-wound nanofiltration membranes, is advantageous for quality and public health aspects and societal acceptance, but the cost is generally higher. Process C, where capillary nanofiltration membranes are used, is comparable to Process B insofar as quality and public health aspects and societal acceptance are concerned, but performs better for economical and environmental aspects. However, Processes B and C have a significantly better overall score than Process A, with the weight coefficients used. The use of capillary nanofiltration may be a future trend in drinking water production. On the other hand, the results of this comparison should be considered with caution: they only provide a general comparison, and the results for some aspects depend largely on local conditions. Furthermore, the weight factors may depend on the relative importance that is given to each of the criteria.

## Acknowledgement

B van der Bruggen carried out this study as a post-doctoral researcher of FWO-Vlaanderen and acknowledges their support.

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