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Scaled-up Trials with a gravity-driven ultrafiltration unit in South Africa

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Abstract

The study aims at validating the point-of-use investigations on long-term gravity-driven ultrafiltration for a scaled-up system, which could produce drinking water for a community of 100-200 inhabitants using natural surface water. Eawag, KWB and Opalium conceived a membrane-based small-scale system (SSS) which can operate without crossflow, backflush, aeration or chemical cleaning. Equipped with a biosand filter as pre-treatment (not used in South Africa), it is designed to be robust, energy-sufficient (gravity-driven) and run with restricted chemical intervention (only residual chlorine). The containerised unit (10′) requires to be fed with raw water at a 2 m-height (energy-equivalent to <8 Wh/m^3). As sole operational requirement, the membrane reactor is to be drained (i.e. emptied) on daily to weekly basis to superficially remove the material retained by the membrane and accumulated in the module. Otherwise, the system, which is only driven by a 40 cm differential pressure head (i.e. 40 mbar), is totally self-determined and autonomous.

This report details the validation tests performed at Ogunjini in the region of Durban (South Africa) from February to April 2010: the gravity-driven UF compact unit showed promising results in regards to flux stabilization and flow capacity. The unit was operated in South Africa with Ogunjini surface water and was run with restricted chemical intervention or maintenance (no backflush, no aeration, no crossflow and no chemical). Under South African environmental conditions and with direct filtration of the river water and only one manual drainage of the membrane reactor every weekday, the unit could fulfill the design specification in terms of water production (5 m^3/d) as long as the turbidity of the raw water remained in a reasonable level (up to 160 NTU), with a filtration flux typically around 4 to 6 L/h.m^2 (corrected to 20°C). This value was in the same range as the lab results and was consistent with the first phase results (around 5-7 L/h.m^2 after biosand filtration). However, the flux dropped significantly to a range of 2 to 4 L/h.m^2 after a rain event resulting in a turbidity peak over several days up to > 600 NTU. This demonstrated that for variable raw water types with expected turbidity peaks above 100 NTU, a pre-treatment would be required for the system (biosand filter or other). The performance of microbiological tests confirmed the integrity of the membrane and the ability of the system to achieve complete disinfection.

1 Introduction

As it may be neither economically nor technically viable to set up a reliable water distribution network in developing countries or in rural areas, decentralised water supply stands as one of the greatest challenges in the forthcoming years. In this context membrane processes seem promising as they efficiently remove pathogens and offer a modular design that enables flexibility in terms of flow capacity reduction. In order to fulfil the Millennium Development Goals, novel decentralised water systems should be robust, low-cost and as independent as possible from chemical and energy requirements and they are expected to enter the market within the next years [1].

Within the European project TECHNEAU (www.techneau.eu), a research group aimed to develop a low-energy ultrafiltration (UF) unit for small drinking water applications. The Swiss Federal Institute of Aquatic Science and Technology - Eawag - performed lab work on long-term gravity-driven membrane filtration at a point-of-use (POU) scale [2]. These investigations have enabled to design and build a pilot unit (dimensioned for 5 m^3/d) to be tested in real environments in France and in South Africa.

Based on validation tests performed at Veolia Water Research Center in Annet-sur-Marne (France) from January to August 2009, the gravity-driven UF compact unit showed promising results with regard to flux stabilization and flow capacity [3]. During the first investigations which took place in winter the flux stabilized to a value of around 2.5 $L/h.m^2$, which is below the reference results from the Eawag lab tests performed at room temperature (i.e. 4-10 $L/h.m^2$, at 20 ± 2°C). However, due to manual weekly drainage of the membrane reactor the flux of system could be enhanced to 4-5 $L/h.m^2$, and thereby, the unit could produce more than 4 m^3/d, which was almost consistent with the design target of 5 m^3/d. Moreover, the increase of the drainage frequency (until 3 times/week) along with warmer temperatures – leading to a better membrane permeability and biological activity - contributed to a further enhancement of the system productivity to a value around 5-7 $L/h.m^2$ [3]. This is particularly relevant for South Africa, where the unit was further tested from November 2009 in the region of Durban.

The trials in Annet-sur-Marne highlighted also that the pre-treatment (biosand filter) was the limiting factor in terms of operation and flow as it requested in summer monthly sand scrapping. It was therefore decided in South-Africa to assess the gravity-driven membrane system with direct filtration of the river water. Being aware of the variability of river water quality in the region (high turbidity peaks in case of storm events), it was decided to run the unit with more frequent drainage of the membrane reactor (up to one drainage each weekday).

This study presents the first results of the tests which were performed in Ogunjini, South Africa. These investigations were to demonstrate if gravity driven UF membrane systems alone (i.e. without pre-treatment) can be operated without chemicals and energy, and stand as (cost)-effective options for decentralised water supply. The goal was also to test the pilot unit with the local water

2 Materials and Methods

2.1 Description of the Unit

This small-scale system (SSS) is based on a gravity-driven UF process developed by Eawag, which enables operation without crossflow, backflush, aeration or chemical cleaning [2]. Hence, Eawag, KWB and Opalium (France) conceived a membrane-based SSS, which could treat up to 5 m^3/d of natural surface water – enough to satisfy drinking water needs for a community of 100-200 inhabitants. Considering the fact that the clean water level is placed at a height of around 1 m above ground level, and a required hydrostatic pressure of up to 0.4 m, feed water should be available at an elevation of 1.4 m above ground level (i.e. about only a specific energy demand of about 6 Wh/m^3).

Placed in a 10 feet-long maritime container, the unit is composed of the following components (as shown in Figure 1):

- a submerged flat-sheet UF module (area: 40m^2, Table 1).
- a storage tank for residual chlorination to avoid recontamination of the treated water (not used in those trials).

A slow sand filter was also physically present in the unit and was used in France but was by-passed during the trials in South Africa.

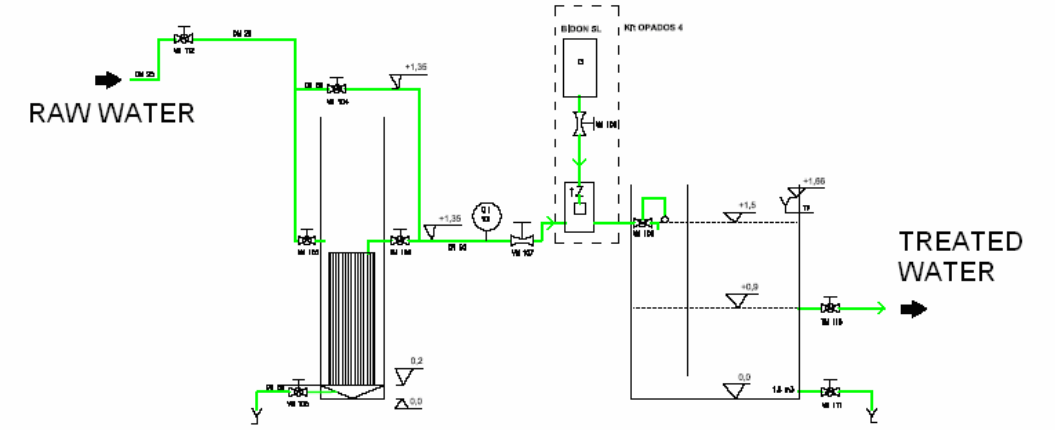

Figure 1 - Process Instrument Diagram of the pilot unit

Table 1 – Membrane characteristics

Membrane Supplier	A3 Water Solutions GmbH, Germany
Nominal MWCO	150 kDa
Membrane material	PES
Gap between membrane sheets	8 mm

As sole operational requirement, the membrane unit is simply drained (i.e. emptied) on a daily to weekly basis to remove the material retained by the membrane and accumulated in the module. Moreover, the operating rate (number of hours of filtration per day) can also vary. Apart from those two control parameters, the system, which is only driven by max. 40 cm differential pressure head (i.e. 40 mbar) in the membrane reactor is totally self-sufficient and independent on energy supply.

2.2 Site for Trials

Trial location and raw water quality

The unit was installed at Ogunjini in South Africa in a rural area at 45 km from Durban (Figure 2). The unit was fed with Ogunjini Waterworks influent (pumped from the river Mdloti). The main water quality parameters of the feed water are presented in Table 2. As shown in this table, the turbidity is slightly higher than the ones observed in Annet-sur-Marne [3] and for lab tests in Eawag (Chriesbach water mixed with wastewater [4]), but it is consistent with regard to NOM content. Therefore, the "scale-up" challenge is relevant and results in South Africa could be comparable with results in France and with Eawag POU investigations (the latter with a membrane area of 25 cm^2).

Figure 2 - The pilot unit at the test location in Ogunjini, South Africa

Table 2 – Ogunjini water, Marne River and Chriesbach water qualities

Ogunjini water Av. Jan.-Ap. 2010 (Min-Max)	Marne River Av. in 2008 (Min-Max)	Chriesbach water mixed with 15% wastewater Min-Max
TOC: 2,0 mg/L (1.6-2.5)* Turbidity: 48 NTU (10-605)	TOC: 2.7 mg/L (0.9 – 7.7) Turbidity: 23 NTU (3 – 258)	DOC: 10-15 mg/L Turbidity: 30 – 40 NTU

*values measured only on water samples with low turbidity (10-15 NTU)

2.3 Operation conditions and monitoring

The present report describes the trials performed in Ogungini from February 2010 to early April 2010. The unit was operated 24 h/d and a manual drainage of the membrane unit was performed every weekday. After 6 weeks of operation, a relaxation (no filtration) of one hour was implemented before each weekday drainage in order to monitor the impact of relaxation time on the filtration performance. No chlorination step was implemented in this study. As the unit is autonomous, the monitoring tasks simply include the general visual control of the unit, the recording of temperature and volumetric flow rate (a mechanical flow meter is included in the unit) and the measurements of the oxygen content (measured in the membrane reactor and in the permeate just after the membrane) and the turbidity in the raw water and UF permeate with portable probes. Data were collected three times every weekday.

The flux and permeability values presented in the study are corrected to 20°C taking into account the permeate viscosity according to the Darcy's law. After stabilization of the flux, weekly analyses for bacterial and viral contamination (Coliforms, E. Coli, CC 37°C, Coliphages), Iron, Manganese and TOC (Total Organic Carbon) were carried out.

2.4 Commissioning and clean water permeability

Some permeability tests with clean water were carried out in order to verify the condition of the pilot unit after the shipment from Europe at the Umgeni Water Centre in Wiggins in November 2009. The results showed a permeability of 330 L/(m^2.h.bar) corrected at 20°C, which corresponds to the specifications of the supplier.

3 Results and Discussion

The main objectives of the study are to demonstrate if gravity driven UF membrane systems alone (without pre-treatment) can be operated without chemicals & energy and stand as (cost)-effective options for decentralised water supply. The goal was also to use the real local and representative surface water.

The investigations were mainly focusing on the flow capacity of the system and on the optimisation of its operating conditions in order to match the target of 5 m^3/d of water produced.

Before looking at the flux stabilisation process itself, the evolution of the water quality during the investigation period (Febuary – April 2010) will be discussed.

3.1 Water Quality

3.1.1 *Results of 4 sampling*

Four sampling rounds were performed in order to characterise the water quality. Microbiological tests as well as TOC, Fe and Mn removal performance were studied. Results are presented in the Table 3.

Table 3 – Water quality (sampling 19-26-31/03/2010, 30/04/2010)

(Min-Max)	TOC (mg/L)	Fe (mg/L)	Mn (mg/L)	Coliforms (/100 mL)	Plate count 37°C (/mL)	Coliphages PFU/10mL	E.Coli (/100 mL)
Raw water	1.7-2.4	0.74-0.89	0.03-0.08	2406-4838	>1000	0-3	44-64
Permeate	1.2-1.3	0.02-0.17	<0.01	0-2	0-448	0	0

About 40% of the total organic carbon could be removed by the combination of active biofilm and UF membrane system. Iron, presumably in a colloidal form, is removed to a large extent (> 75%) and it could be verified that the iron and manganese content in the permeate were below the guidelines for drinking water (Fe <0.3 mg/L; Mn <0.05 mg/L).

Moreover, no pathogenic bacteria were found in the membrane permeate. The existence of non-pathogenic bacteria in the permeate (plate count at 37°C) can probably be attributed to bacterial regrowth. Coliphages analyses were used as an indicator of aquatic viruses removal. Results show that the UF membrane is a good barrier against the Coliphages. The performance of microbiological tests confirmed the integrity of the membrane and the ability of the system to achieve complete disinfection.

Providing the addition of a low residual chlorine dose, the permeate quality corresponded to a drinking water quality.

3.1.2 *Influence of the temperature on the biological activity*

The temperature of the river water during the trials varied between 22 °C and 29 °C. That range of temperatures is suitable for the biological activity which is needed for the process: indeed it was demonstrated that the biofilm that develops at the surface of the membrane acts as a protective layer and stabilises the filtration performances [2]. Figure 3 shows the variations of the oxygen contents in the raw water and the UF membrane permeate. The raw water was generally in condition of oxygen saturation for the temperature range with at least 8 mg/L of oxygen. In the first weeks, a drop of oxygen concentration of about 1 mg/L down to typically 7 to 8 mg/L after membrane filtration is visible. This demonstrates that the biofilm developed at the membrane is active and consumes the oxygen for its growth, but also that under such conditions, oxygen is not a limiting parameter. During the peak of turbidity, the raw water showed lower oxygen concentration (just below 8 mg/L), and the increased biological activity in the biofilm could be observed with the drop of oxygen concentration in the membrane permeate down to 5 mg/L. However, it seems that the oxygen was never a limiting factor to the biology. Later on from the 5/04 to the 10/05, during the period with lower filtration flux, the oxygen consumption increased up to about 1.5 mg/L. This could be accounted for by a thicker biofilm accumulated at the membrane surface, and/or by a longer hydraulic residence time through the biofilm due to lower fluid velocity.

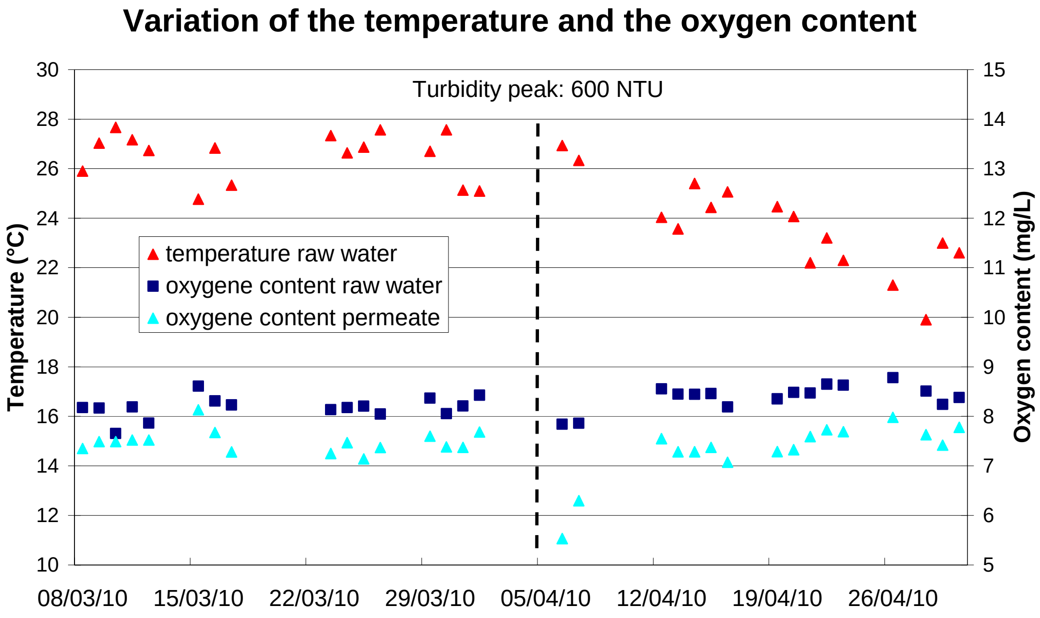

Figure 3 - Effect of temperature on the oxygen content

For each day, the average value of the 3 measurements is presented

3.2 Flux Stabilization

3.2.1 Influence of the intermittent operation and of the turbidity feed

Figure 4 shows the results obtained for the filtration flux against the turbidity. During the first 8 weeks of investigations, the raw water temperature was 22-26 °C and the turbidity remained in the range 10-160 NTU. As long as the turbidity of the raw water remained within this reasonable level, the goal of a drinking water production of 5 m3/d was reached in most days, and the typical filtration flux was stable around 4 to 6 L/(m².h). This value was in the same range as the 4-10 L/h.m² observed at lab scale at 20°C and was consistent with the first phase results with the Marne river (around 5-7 L/h.m² after biosand filtration). The daily drainage seemed to have a positive influence on the long-term stabilisation of the flux, although no flux increase was systematically observed just after a drainage, nor a flux decrease was systematically monitored after few days of operation without drainage (for example over weekends).

However, the flux dropped significantly to a range of 2 to 4 L/h.m² for similar temperature of 22-27°C after a rain event resulting in a turbidity peak over several days up to > 600 NTU (period C in Figure 4). The attempts to recover the (instant) filtration flux while practising 1 hour relaxation (no filtration) before the daily manual drainage enabled to limit the quick flux decline, but did not to recover the flux to much higher values.

Some other observations can be reported from the trials:

- Impact of chlorine cleaning: On 23/02 (pointed A in Figure 4), the system was disinfected with low grade chlorine before starting permeate sampling for microbial analyses. The membrane was soaked into 500 ppm of sodium hypochlorite solution during one day and then rinsed with tap water. An increase of the permeate flux was observed in the following week up to 6 L/h.m². The flux decreased then slowly during the next 3 weeks to reach a permeate flux around 3.5-4 L/h.m².
- Long relaxation: A power failure occurred on 18/03 (pointed B in Figure 4), resulting in 5 days of filtration interruption (the inlet water could not be pumped from the waterworks). A manual drainage was performed to flush the accumulated biological material, and the membrane reactor was filled up with drinking water. Following this forced relaxation of several days, the permeate flux increased over one week of operation up to 6 L/h.m².

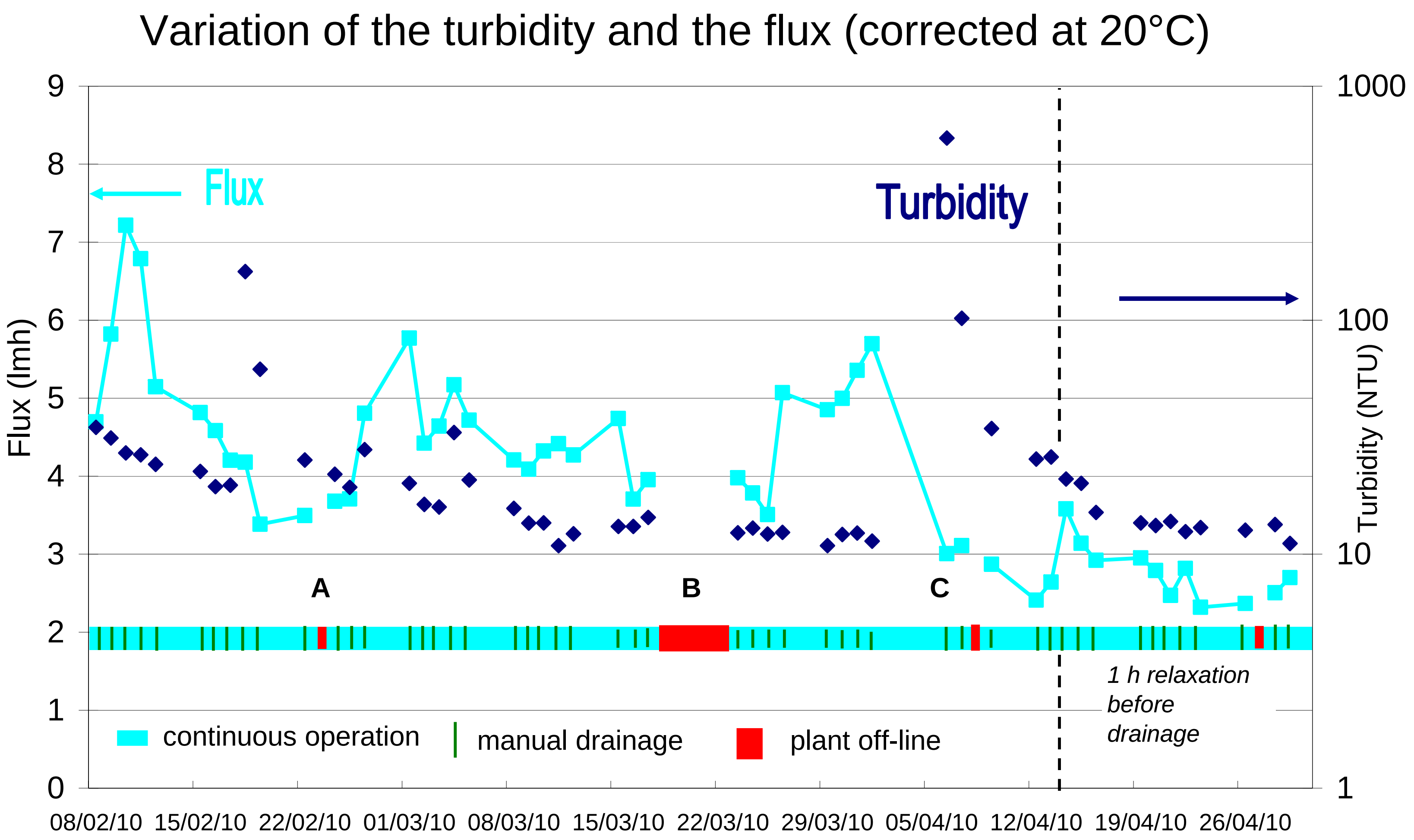

Figure 4 - Flux variation in regards to intermittent operation and turbidity feed (for each day, the average value of the 3 measurements is presented)

3.3 Influence of the pretreatment (sand filter) on the permeate flux

In contrary to the trials in South Africa, the membrane pilot was operated in France with sand filter as pre-treatment (biofiltration). It is therefore of interest to compare the results (obtained during stable operation) to assess the impact of the pre-treatment. The raw water quality of the considered periods is shown in the Table 4.

Table 4 – Raw water quality during the considered period

France	South Africa
• TOC: 2-5 mg/L	• TOC: 1.7-2.4 mg/L (values taken on water with low turbidity range: 10-15 NTU)
• Turbidity: 4-23 NTU	• Turbidity: 10-160 NTU (except peak > 600 NTU)
• Temperature: 17 – 24 °C	• Temperature: 22 – 29 °C

The trials in France and in South Africa were carried out using different drainage schemes as presented in the Table 5.

Table 5 – Comparison of operation conditions in France and in South Africa

	France	South Africa	
Headloss	40 cm	40 cm	
Utilisation rate	24 h/d	24 h/d	23 h/d
Drainage frequency	2-3/w	5/w	

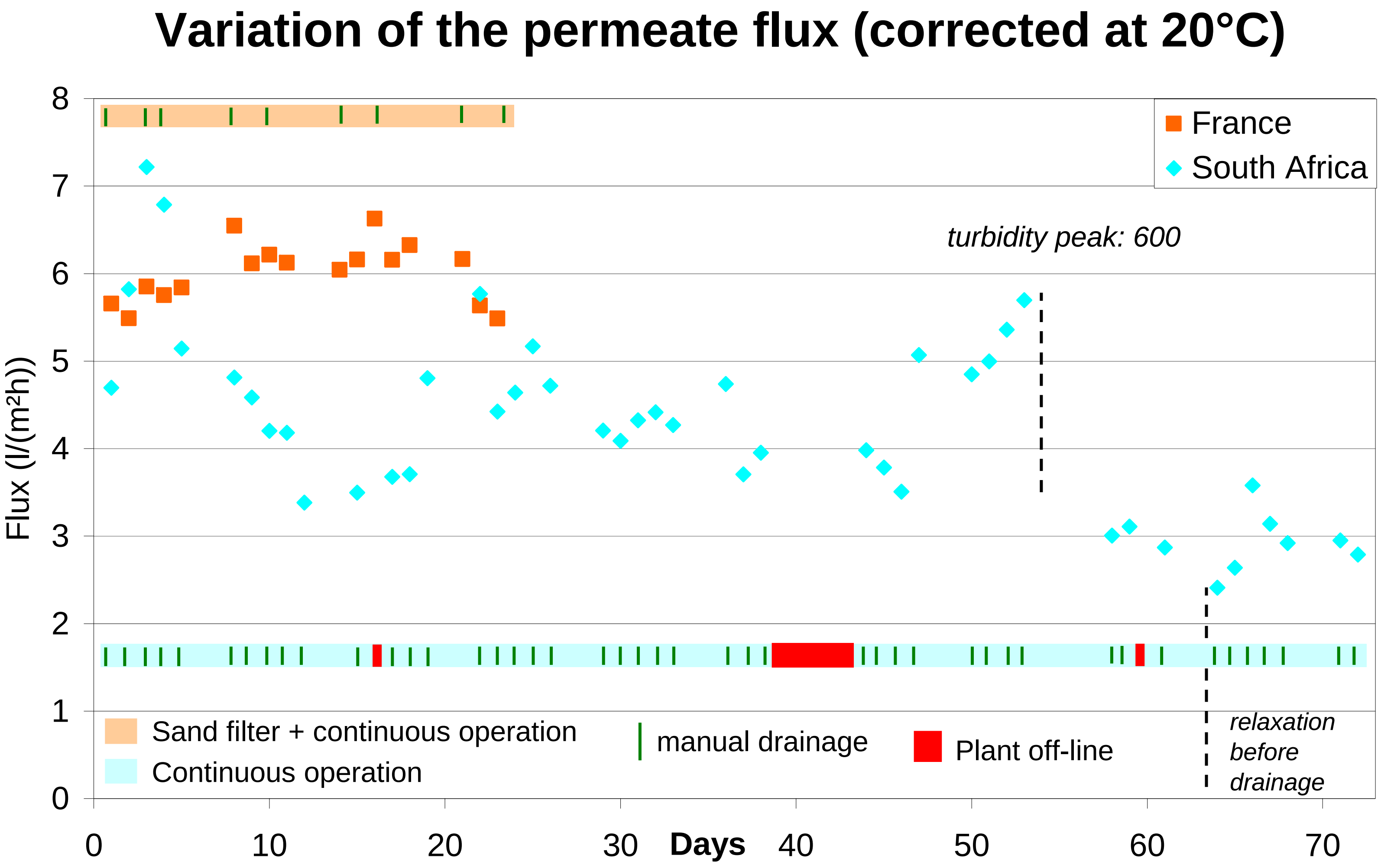

Figure 5 - Effect of pre-treatment (biofilter) on the permeate flux for trials performed in France and South Africa

In France, the permeate flux achieved over 3 weeks was between 5 and 7 L/h.m² thanks to a drainage (2-3 times/week) and the sand filter as pre-treatment.

Although the turbidity was higher in South Africa than in France, a good permeate flux between 4 and 6 L/h.m² was achieved during 55 days without any pre-treatments and with drainage every weekday.

However after a rain event, resulting in a turbidity peak over several days up to >600 NTU, the permeate flux dropped to 3 L/h.m². The manual drainage every weekday and then the relaxation (before each drainage) did not enable to recover the permeability.

From the comparison of the flux curves in Figure 5, it seems that the membrane performance is improved by the pre-treatment, but great care has to be taken in the interpretation of these data, since the water qualities in France and South Africa are quite different. Not only the turbidity, but also differences in composition of NOM can influence the fouling behaviour [5].

4 Design and operation recommendations

Thanks to the investigations in France and in South Africa, it is possible to provide design and operation recommendations for the considered membrane modules 40 m² depending on the expected turbidity range of the raw water (Table 6).

Table 6 – Design and operation recommendations

Turbidity (NTU)	<10	10-100		>100	
Pre-treatment (biofilter)	NO	NO	YES	NO	YES
Membrane drainage frequency	1 / w	5 / w	1 / w	5 / w	2 / w
Biofilter cleaning	-	-	6 / y	-	> 12 / y
Utilisation rate	24 h/d	24 h/d	24 h/d	23 h/d	24 h/d
Filtration flux (L/h.m², 20°C)	5-6	4-5	6-7	2-3	5-6

- With raw water turbidity below 10 NTU, the pilot unit could be operated with direct filtration and as sole operational requirement 1 drainage on a weekly basis to achieve a drinking water production of 5-6 L/h.m², 20°C.
- With raw water turbidity between 10 and 100 NTU, 2 options are possible: used a pre-treatment or not. With no pre-treatment and 5 drainages per week a drinking water production of 4-5 L/h.m², 20°C can be achieved. With a pre-treatment, 1 drainage per week and 6 biofilter cleaning per year (sand scrapping), a drinking water production of 6-7 L/h.m², 20°C can be achieved.
- With raw water turbidity significantly higher than 100 NTU, it is advisable to operate the membrane pilot with pre-treatment (e.g. sand filter, lamella clarifier or other) or to design the pilot unit with a permeate flux of only 2-3 L/h.m² (i.e. at least to double the membrane surface to 80 m²).

It is important to notice that the goal of 5 m³/day is achievable for all types of water providing adequate membrane surface and adequate pre-treatment and operation conditions.

The choice of a pre-treatment step will depend on the cost evaluation of the pilot, the life time of the pilot and the quality of the water and the available man power on site.

5 Cost evaluation

A cost evaluation of the system was performed, taking into account the following hypothesis:

- Specific cost (€/m3) calculated over 25 years Total Life with 2% inflation rate and 3% interest rate
- Calculation were carried out for a flow of 5 m3/d unit (supplying a community of 100-200 inhabitants)
- Filtration flux ranges as in Table 6 are valid for a temperature of 20°C. The flux range will determine a required membrane surface and therefore a cost range.
- Membrane cost: 100 €/m^2, module changed every 5 years (i.e. 5 times over Total Life)
- Capital cost (without membrane module): 6,000€ without pre-treament (no container) and 26,000€ with pre-treatment (price of the prototype pilot plant which can be reduced)
- Energy demand: 6 Wh/m^3 without pre-treatment and 8 Wh/m^3 with pre-treatment. In comparison the specific energy demand for standard UF system producing drinking water is around 100-200 Wh/m^3 [6].
- Cost of the kWh= 0.12 €

Not included in cost evaluation

- man power
- chemicals (residual disinfection and unfrequent membrane cleaning)
- pumping from water source to unit
- taxes

The costs per m^3 of water treated by the gravity driven UF system are calculated in the following table (Table 7) considering all above hypothesis.

Table 7 – Cost per m^3 of the gravity driven UF system depending on the water quality over 25 years

Turbidity	<10	10-100		>100	
Pre-treatment	NO	NO	YES	NO	YES
Capital costs €	6000	6000	26000	6000	26000
Investion costs € (membranes sets)	19184-23024	23024-28776	16443-19184	38368-57557	19184-23024
Operational costs € (energy)	37	37	49	37	49
Total net present value 25 years	25221-29061	29061-34813	42492-45233	44405-63594	45233-49073
Specific cost € / m3	2.8-3.2	3.2-3.8	4.7-5	4.9-7	5-5.4

As expected, the lower is the water quality, the higher are the costs to treat this water. With clean water, it costs roughly 3 euros per m^3 to treat the water with this process but with dirty water (>100 NTU) the price is 50% higher, around 5 euros per m^3.

We can note that the main part of the costs is related to the construction of the unit and the membrane module (capital costs). These costs are estimated for a construction in Europe: they could be lower in case of local construction, serial production, and also potential of flux increase with other membrane types. In addition, the investment costs related to the membrane modules could be much lower if the modules can be operated over a longer period than 5 years. Taking into account these considerations, the capital costs could and treatment costs could potentially be reduced leading to a water price < 1 €/m^3.

As expected, the energy requirement is not significant for the gravity fed system. In case of a conventional UF Plant with a specific energy demand of 100-200 m^3/h, the energy costs for a period of 25 years would be around 620-1230 euros. The energy cost for a conventional UF Plant is higher by a factor of 25 than the energy cost for the gravity fed system.

6 Conclusions

The gravity-driven UF compact unit that was developed by Opalium, Eawag and KWB has shown promising results in regards to flow capacity. The flow capacity was stable despite low operation and maintenance requirements. Although these investigations occurred without pre-treatment, a flux between 4 and 6 L/h.m^2 corrected at 20°C was observed within 60 days. So the goal of producing 5 m^3/d of drinking water was achieved. The pilot system could benefit from a manual drainage of the membrane reactor every weekday and from warm temperature. However, after a turbidity peak at 600 NTU, the flux dropped to a range of 2 to 4 L/h.m^2 and relaxation periods did not lead to better membrane permeability.

Water quality parameters were monitored in order to ensure the bacterial removal and the membrane integrity. Tests confirm the ability of the system to achieve complete disinfection with a residual chlorination to avoid regrowth.

The studies performed in France and in South Africa enabled to provide design and operation recommendations for the system depending on the quality of the considered surface water. For all type of water, the unit is able to provide between 4 and 6 L/m^2.h of treated water. The lower is the water quality, the higher will be the drainage frequency, the pre-teratment need and then the biofilter (pre-treatment) cleaning (See 4. Design and operation recommendations).

The demand of energy of the pilot plant was around 6-8 W/m^3, which corresponds to the energy demand of the pump to elevate the raw water at 1.6 to 2 meters. This amount of energy is similar to the energy demand of a conventional plant and lower than a UF system producing drinking water by a factor of 20.

The cost analyses for the prototype gave a water price between 3 and 5 €/m^3 depending on the water quality. However, a large potential for reducing costs is available if the unit is produced locally and/or on a large scale and/or if higher flux is provided with better membrane, leading to a water price <1 €/m^3.

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8 Dissemination

M. Boulestreau, E. Hoa, M. Peter, W. Pronk, R. Rajagopaul, B. Lesjean (2010). *Operation of a 5 m3/d Gravity-driven Ultrafiltration Unit for Decentralised Water Supply*. Conference Membranes in Drinking and Industrial Water treatment (MDIW 2010), 27-30 June, NTNU-Trondheim, Norway.