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Operation of gravity-driven ultrafiltration prototype for decentralised water supply

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ABSTRACT

The study aims at assessing in long-term trials a gravity-driven ultrafiltration pilot plant designed for a capacity of 5 m^3 d^{-1}. 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 fulfil the design specification in terms of water production (5 m^3 d^{-1}) as long as the turbidity of the raw water remained in a reasonable level (up to 160 NTU), with a filtration flux typically 4–6 l h m^{-2} (corrected at 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^{-1} m^{-2} after biosand filtration). However, the flux dropped significantly to a range of 2–4 l h^{-1} 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 advanced disinfection.

Keywords: Ultrafiltration; Low-energy; Decentralised water supply; Small-scale system (SSS); Gravity-driven; Drinking water

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 [1,2].

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 [3]. These investigations have enabled to design and build a pilot unit (dimensioned

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for 5 $m^3\ d^{-1}$) 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 $l\ h^{-1}\ m^{-2}$, which is below the reference results from the Eawag lab tests performed at room temperature (i.e., 4–10 $l\ h^{-1}\ m^{-2}$, at 20 ± 2°C). However, due to manual weekly drainage of the membrane reactor the flux of system could be enhanced to 4–5 $l\ h^{-1}\ m^{-2}$, and thereby, the unit could produce more than 4 $m^3\ d^{-1}$, which was almost consistent with the design target of 5 $m^3\ d^{-1}$. Moreover, the increase of the drainage frequency (until three times per 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 $l\ h^{-1}\ m^{-2}$ [4]. 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. The focus was on the process features of the unit (flow capacity) as a function of the frequency of mechanical cleaning (manual drainage of the membrane unit). 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. An economic analysis of this process to produce drinking water during 5 y shows a specific cost between 2.8 and 7 € m^{-3} depending on the influent water quality [5]. This was calculated with a high capital cost for the prototype which could be easily lowered.

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 [3]. Hence, Eawag, KWB and Opalium (France) conceived a membrane-based SSS, which could treat up to 5 $m^3\ d^{-1}$ 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 0.006 kWh m^{-3}).

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

- A submerged flat-sheet UF module (area: 40 m^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.

As sole operational requirement, the membrane reactor 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 a max. 40 cm differential pressure head (i.e., 40 mbar) in the

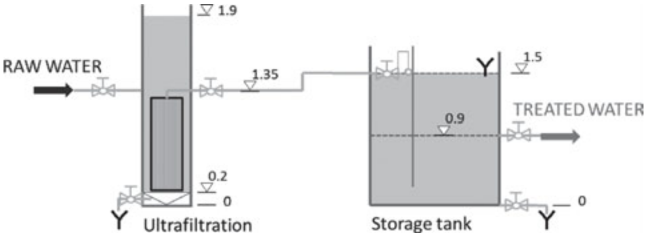

Fig. 1. Process instrument diagram of the pilot unit in South Africa.

Table 1
Membrane characteristics

Module supplier	A3 Water solutions GmbH, Germany
Membrane supplier	Microdyn Nadir
Membrane material and type	Polyethersulfone (PES), Flat sheet
Nominal molecular weight cut-off (MWCO)	150 kDa
Gap between membrane sheets	8 mm

membrane reactor is totally self-sufficient and independent on energy supply.

2.2. Trial location and raw water quality

The unit was installed at Ogunjini in South Africa in a rural area at 45 km from Durban (Fig. 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 Table 2, the turbidity is slightly higher than the ones observed in Annet-sur-Marne [4], but it is consistent with regard to natural organic matter (NOM) content. Therefore, the “scale-up” challenge is relevant and results in South Africa could be comparable with results in France and with Eawag investigations (the latter with a membrane area of 25 cm²) [6].

2.3. Operating conditions and monitoring

The present article reports the trials performed in Ogungini from February 2010 to early April 2010. The unit was operated 24 h d^{-1} and a manual drainage of the membrane unit was performed once a day except the weekend. After a 6 wk-operation, a relaxation (no filtration) of 1 h 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 or calculated in the economic analysis. As the unit was autonomous, the monitoring tasks simply included the general visual control of the unit, the recording of temperature, volumetric flow rate (a mechanical flow meter is included in the unit), the oxygen content (measured in the membrane reactor and in the permeate just after the membrane), the turbidity in the raw water and UF permeate with portable probes. Data were collected three times every weekday.

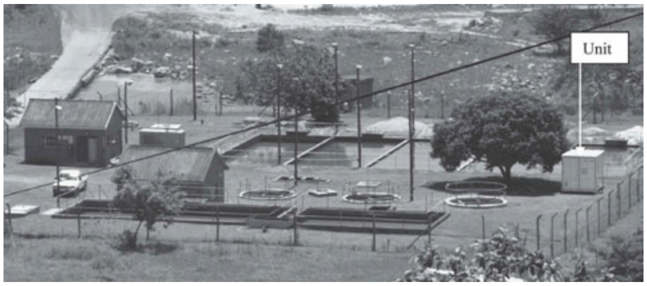

Fig. 2. The pilot unit at the test location in Ogunjini, South Africa.

Table 2
Ogunjini water and Marne river water qualities

Ogunjini water Av. Jan.–Ap. 2010 (min–max)	Marne river Av. in 2008 (min–max)
TOC: 2.0 mg l^{-1} (1.6–2.5)[1]	TOC: 2.7 mg l^{-1} (0.9–7.7)
Turbidity: 48 NTU (10–605)	Turbidity: 23 NTU (3–258)

TOC: Total organic carbon.

[1] Values measured only on water samples with low turbidity (10–15 NTU).

The flux and permeability values presented in the study are corrected to 20°C taking into account the permeate viscosity according to Darcy’s law. After stabilization of the flux, weekly analyses for bacterial and viral contamination (coliforms, coliphages, *E. coli*, colony counts (CC 37°C)), iron, manganese and TOC were carried out.

2.4. Commissioning and identification of hydraulic issues

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^{-1} bar^{-1} corrected at 20°C, which corresponds to the specifications of the supplier.

3. Results and discussion

3.1. Flux stabilization

3.1.1. Influence of the intermittent operation and of the turbidity feed

Fig. 3 shows the results obtained for the filtration flux against the turbidity. During the first 8 wk of investigations, the raw water temperature was 22–26°C and the turbidity remained in the range of 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 m^3 d^{-1} was reached in most days, and the typical

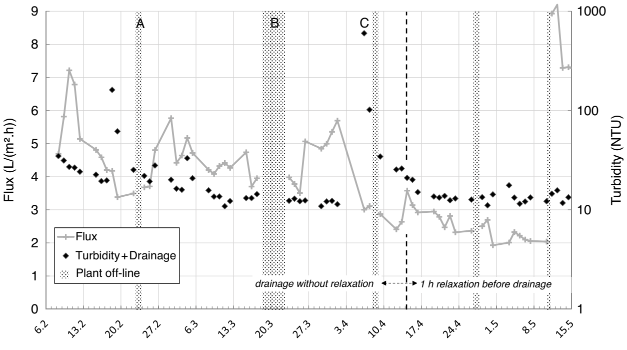

Fig. 3. Flux variations (at 20°C) in regards to intermittent operation and turbidity feed (for each day, the average value of three measurements is presented).

filtration flux was stable around 4–6 l m^{-2} h^{-1}. This value was in the same range as the 4–10 l h^{-1} m^{-2} observed at lab scale at 20°C and was consistent with the first phase results with the Marne river (around 5–7 l h^{-1} m^{-2} 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 (e.g., over weekends).

However, the flux dropped significantly to a range of 2–4 l h^{-1} m^{-2} 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 Fig. 3). The attempts to recover the (instant) filtration flux while practising 1 h 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 Fig. 3), 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 1 d and then rinsed with tap water. An increase of the permeate flux was observed in the following week up to 6 l h^{-1} m^{-2}. The flux decreased then slowly during the next 3 wk to reach a permeate flux around 3.5–4 l h^{-1} m^{-2}.
- Long relaxation: A power failure occurred on 18/03 (pointed B in Fig. 3), resulting in 5 d 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 1 wk of operation up to 6 l$h^{-1}$$m^{-2}$.
- The increase in flux after chlorination or forced relaxation is not immediately but after a few days. It might be due to the fact that the pilot plant needs a few drainages to adapt to the new biofilm properties.

3.1.2. *Influence of the temperature and 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 [3]. Fig. 4 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^{-1} of oxygen. In the first weeks, a drop of oxygen concentration of about 1 mg l^{-1} down to typically 7–8 mg l^{-1} 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^{-1}), 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^{-1}. However, it seems that the oxygen was never a limiting factor to the biology. Later on, during the period with lower filtration flux, the oxygen consumption increased up to about 1.5 mg l^{-1}. 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.

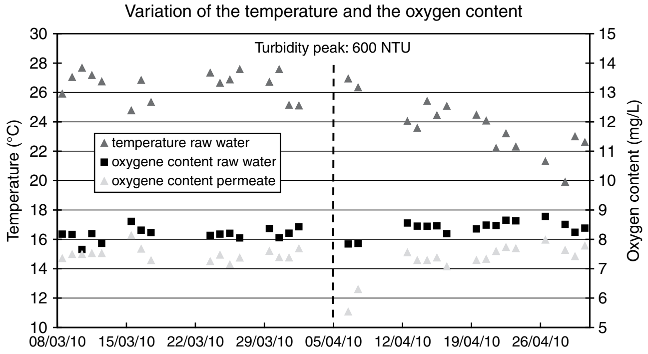

Fig. 4. Effect of temperature on the oxygen content (for each day, the average value of three measurements is presented).

4. Results on the water quality

Four sampling campaigns were performed in order to characterize the water quality. Microbiological tests as well as TOC, iron (Fe) and manganese (Mn) removal performance were studied. Results are presented in the Table 3.

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 or particulate 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 <0.2 mg l^{-1}; Mn <0.05 mg l^{-1}).

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

Table 3
Water quality

	TOC (mg l^{-1})	Fe (mg l^{-1})	Mn (mg l^{-1})	Coliforms (100 ml^{-1})	Plate count 37°C (ml^{-1})	Coliphages PFU/10 ml	*E. coli* (100 ml^{-1})
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
Drinking water standards EU 1998	No abnormal range	0.2	0.05	0	20	0	0
WHO 1993	–	–	0.5	–	–	–	–

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 advanced disinfection.

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

4.1. Influence of the pre-treatment (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). No pre-treatment would mean an installation smaller and cheaper. 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 Table 4.

In France, the permeate flux achieved over 3 wk was between 5 and 7 l h^{-1} m^{-2} with drainage two to three times per 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^{-1} m^{-2} was achieved during 55 d 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^{-1} m^{-2}. The manual drainage every weekday and then the relaxation (before each drainage) did not enable to recover the permeability.

Table 4
Raw water quality during the considered period

France	South Africa
TOC: 2–5 mg l^{-1}	TOC: 2–2.5 mg l^{-1} 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 following design specifications can be drawn for the considered membrane modules:

- With raw water turbidity below 100 NTU, the pilot unit could be operated with direct filtration and regular drainage and achieved a drinking water production of 4–6 m^3 d^{-1}. The specific cost is between 2,8 and 3,8 € m^{-3} without pre-treatment and between 4,7 and 5 € m^{-3} with sand filter as pre-treatment.
- From the comparison of the flux curves in Fig. 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 such as humic acids and biopolymers concentrations can influence the fouling behaviour [7].
- 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, simple sedimentation or other) or to design the pilot unit with a permeate flux of only 2–3 l h^{-1} m^{-2} (i.e., at least to double the membrane surface to 80 m^2). The specific cost is between 4.9 and 7 € m^{-3} without pre-treatment and between 5 and 5.4 € m^{-3} with sand filter as pre-treatment.

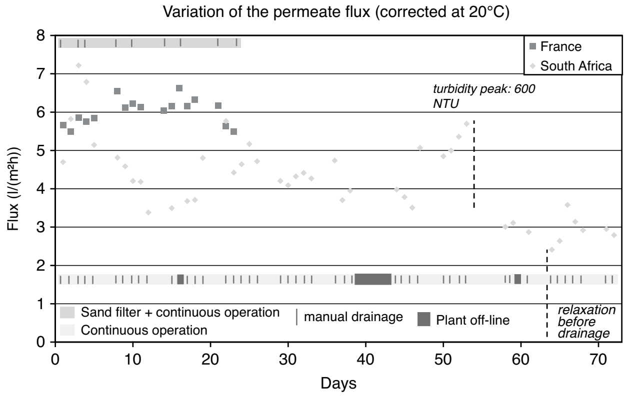

Fig. 5. Effect of pre-treatment (biofilter) on the permeate flux.

5. Conclusions

The gravity-driven UF compact unit has shown promising results with regards to stable flow capacity despite low operation and maintenance requirements. Although these first investigations occurred without pre-treatment, a flux between 4 and 6 l h^{-1} m^{-2} corrected at 20°C was observed within 60 d. The pilot system could benefit from a manual drainage of the membrane reactor every weekday and from warm temperature. The design target of 5 m^3 d^{-1} was achieved. However after a turbidity peak at 600 NTU, the flux dropped to a range of 2–4 l h^{-1} m^{-2} and relaxation periods did not lead to better membrane permeability. The comparison with previous results leads to the conclusion that pre-treatment is not necessary with turbidity below 100 NTU. Above 100 NTU, a pre-treatment (biosand filtration or other) should be set up, or a provision for low flux should be considered.

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