Membrane Water Treatment, *Vol. 7, No. 4 (2016) 313-325*
DOI: http://dx.doi.org/10.12989/mwt.2016.7.4.313

Evaluation of flux stabilisation using Bio-UF membrane filter on KZN Rivers, South Africa

Maipato I. Thoola [*1], Sudesh Rathilal [1a] and Lingam V. Pillay [1,2b]

[1] *Department of Chemical Engineering, Durban University of Technology, P.O. Box 1334, Durban, 4000, South Africa*
[2] *Department of Process Engineering, Stellenbosch University, Private Bag x1, Matieland, 7602, South Africa*

(*Received December 16, 2015, Revised February 06, 2016, Accepted April 02, 2016*)

Abstract. South Africa recognises piped water as the main source of safe drinking water supply. Remote areas do not have access to this resource and they rely solely on surface water for survival, which exposes them to waterborne diseases. Interim point of use solutions are not practiced due to their laboriousness and alteration of the taste. Bio-ultra low pressure driven membrane system has been noted to be able to produce stable fluxes after one week of operation; however, there is limited literature on South African waters. This study was conducted on three rivers namely; Umgeni, Umbilo and Tugela. Three laboratory systems were setup to evaluate the performance of the technology in terms of producing stable fluxes and water that is compliant with the WHO 2008 drinking water guideline with regards to turbidity, total coliforms and E.*coli*. The obtained flux rate trends were similar to those noted in literature where they are referred to as stable fluxes. However, when further comparing the obtained fluxes to the normal dead-end filtration curve, it was noted that both the Umbilo and Tugela Rivers responded similarly to a normal dead-end filtration curve. The Umgeni River was noted to produce flux rates which were higher than those obtainable under normal dead-end. It can be concluded that there was no stabilisation of flux noted. However, feed water with low E.*coli* and turbidity concentrations enhances the flux rates. The technology was noted to produce water of less than 1 NTU and 100% removal efficiency for E.*coli* and total coliforms.

Keywords: flux stabilisation; point of use; surface water treatment; remote rural areas; ultrafiltration membranes; Bio-UF

1. Introduction

South Africa is one of the developing countries that utilises piped water as its main source of safe drinking water supply. The country comprises of three types of communities, urban, informal settlements and rural areas (Buckley 2011). Urban and informal settlements have access to safe water supply; however, a majority of rural areas do not have continued access to piped water due to their poor infrastructure (Donev *et al*. 2012). These communities currently rely on untreated surface water for survival and this in turn makes them susceptible to water-borne diseases (Luyt *et*

*Corresponding author, Ms., E-mail: mthoola@gmail.com
[a] Ph.D., E-mail: rathilals@dut.ac.za
[b] Ph.D., E-mail: pillayvl@sun.ac.za

http://www.techno-press.org/?journal=mwt&subpage=7 ISSN: 2005-8624 (Print), 2092-7037 (Online)

al. 2012). Various POU systems have been evaluated in developing countries and have been implemented as an interim solution. These include, among others, boiling, the use of sodium hypochlorite and solar disinfection. However, these solutions are not practised in high rates as expected, as the users complain that they are laborious, costly and alter the taste and odour of water (Sobsey 2002, Alekal *et al*. 2005, Peletz 2006, Crump *et al*. 2004 and Duke *et al*. 2006).

Membrane technology is highly recommended as an inexpensive water treatment method that does not alter the taste and smell of the treated water (Sutherland 2009 and Adham 2005). The technology comprises of two processes, namely, pressure and electrically driven membrane processes. Pressure driven membrane processes includes microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) in their decreasing order of permeability. The main drawback for the implementation of membrane technologies on a large scale in developing countries has been the technical skills required to handle membrane fouling and the systems energy demands (Pryor *et al*. 1998, Jacobs *et al*. 2005 and Peter-Varbanets *et al*. 2009).

Fouling is brought about by accumulation of matter on the membrane surface during filtration. This accumulated matter can limit the membrane's ability to produce acceptable flux rates through pore blocking, adsorption or the development of a cake layer. This attachment of foulants onto the membrane surface can result in either reversible or irreversible fouling depending on the interfacial characteristics of the membrane and foulants (Qu *et al*. 2012).

The membrane fouling layer that develops when treating surface water is caused by the accumulation of Natural Organic Matter (NOM), inorganic (minerals) and bacterial (such as viruses) content (Hossain and Lowe 2008 and Dong *et al*. 2013). Hence, a system that can overcome or control this fouling is required. Recent developments in decentralised membrane systems have been focused on the different techniques to minimise the operating costs of the systems, as well as the control or minimisation of the fouling layer instead of concentrating on the understanding of the fouling process (Derlon *et al*. 2012).

The Swiss Institute of Aquatic Science and Technology, also known as EAWAG, has developed a Bio-ultra low pressure driven membrane system, which can be used for the production of drinking water from surface water. It offers low acceptable fluxes for extended periods of operation, without the use of chemical treatments or backwashing (Peter-Varbanets *et al*. 2010). The system is gravity driven to eliminate the energy consumption and employs biological filtration for membrane fouling. Peter-Varbanets *et al*. (2010) referred to these acceptable low flux rates as stable fluxes and stated that they were brought about by the formation of a biological layer on the UF membrane surface.

The main contaminants of South African water are eutrophication of surface water, heavy metals, acid mine drainage, salinity increase, increased level of suspended solids, bacterial and viral pathogens, pesticides or insecticides, contaminants with oestrogens and oestrogens-mimicking substances, solid litter, oxygen depletion and radionuclide. However, rural areas are located far away from industrialisation, hence; the main contaminants of their surface water are faecal pollution, colour and stability, salt concentrations, fluoride, sulphate and chlorides and eutrophication (Statistics 2005). Other contaminants which play a role in water pollution in rural areas are pesticides, which are due to agricultural practises (Mohamed *et al*., 2003). These pesticides end up in the water streams during rainy events (Abbaspour 2011).

KwaZulu-Natal is located in the south east region of South Africa, and the main contaminants for water found in these rural areas of the province are faecal pollution, pesticides and colour resulting from dissolved organic matter (Statistics 2005 and Shand *et al*. 2005).

The Bio-ultra-low pressure driven system is a promising technology for eradicating the issues

limiting the implementation of membrane technology in remote areas. It promises the production of stable fluxes for extended periods without any backwashing or chemical cleaning (Peter-Varbanets *et al*. 2010). The technology has been studied in detail on European waters by EAWAG. However, this technology has not yet been studied in-depth on South African surface waters; hence there is a need to evaluate the gravity driven Bio-UF system as an interim water treatment option that will eradicate the laboriousness, cost and alteration of the treated water taste.

2. Materials and methods

2.1 Feed water characteristics

Raw water was collected from several rivers in the KwaZulu Natal province of South Africa and based on the raw water quality and accessibility; Tugela River, Umbilo River and Umgeni River were selected for this study. Each set of experiments were conducted over a minimum duration of three months and each sample collected was analysed for turbidity, total coliforms and E.*coli* within 24 hours of collection. The turbidity was analysed using the HACH (1997) procedure while the total coliforms and E.*coli* tests were conducted as adhering to the IDEXX Laboratories procedures.

The sampling point locations for this study are shown in Table 1.

Table 1 Sampling point locations

River	South co-ordinates	East co-ordinates
Umbilo	29”53’34.50”	30”58’09.63”
Umgeni	29”48’35.53”	31”01’44.65”
Tugela	29”12’35.63”	31”25’10.76”

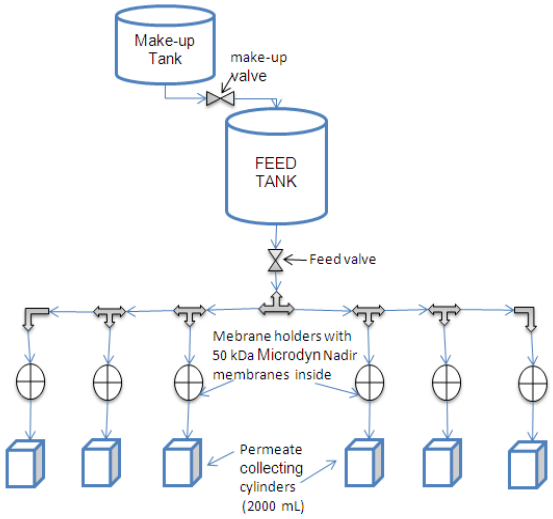


Fig. 1 Schematic process flow diagram for the Bio-UF membrane system

Fig. 2 A photographic image for the laboratory scale set-up for the Bio-UF system during the evaluation of algae growth

2.2 Experimental apparatus

The laboratory systems were set-up to enable parallel investigation of raw water from the three rivers. The set-up for one of the systems is presented in Figs. 1 and 2.

2.2.1 The feed tank, make-up tank and measuring cylinders

Both the feed and make-up tanks were made of plastic, each with a capacity of 32 and 9 litres, respectively. The make-up tank was used for maintaining the level of the system's feed tank. This make-up tank was connected to the system feed tank through a float valve which in turn maintained the level in the feed tank. The feed tank was further connected to the membranes through a ball valve and flexible tubing as shown in Fig. 2. Six measuring cylinders, each with a two litre volume, were used for the collection of permeate as it dropped from the flexible tubing attached to the membrane's permeate side.

2.2.2 Membrane holder

The membrane holders were made of polycarbonate with a diameter of 47 mm purchased from Watman. The holders (shown in Fig. 3) comprised of an assembly ring, a cap, two support grids, a flat gasket, an O-Ring, and the base.

2.2.3 UF membrane

Each experiment was run on a new flat sheet Polyethersulphone (PES) Microdyn Membrane with a nominal molecular cut-off of 50 kDa which was purchased from Memcon (Pty) Ltd.

In order to evaluate the integrity of the membranes, they were initially soaked in deionised water for a period of 24 hours with water being changed initially every hour for four hours, and then left overnight for the removal of conservational agents. After soaking, the clean water permeate was determined by filtering one litre of de-ionised water from each module under gravity while monitoring the time.

Fig. 3 A photographic image showing the different parts of the membrane holder

2.3 Experimental protocol

For the purpose of this study, an optimum operating pressure for the Bio-UF system was determined to be 60 mbar due to operational constraints at higher pressures. This was achieved by evaluating the performance of the Bio-UF under different pressure heads with the aim of obtaining clean water flux of no less than 10 LMH. Unless otherwise stated, this is the pressure that was used throughout the experimentation process.

2.3.1 Experimental procedure

(1) The system shown in Fig. 2 was covered with a foil to hinder the growth of algae.
(2) The feed water from different rivers was collected every second day of the first week and then every week for the duration of the first month. Thereafter, the feed water was collected once in a cycle of two weeks for the rest of the experimental duration.
(3) The collected feed water was analysed for turbidity, total coliforms and E.*coli*.
(4) Thereafter, the raw water was fed into the three separate systems which were set up for analysing the performance of the Bio-UF membrane system using Tugela River, Umbilo River and Umgeni River, respectively.
(5) The feed water was initially poured into the feed tank and then into the make-up tank to maintain the level of the feed tank. The ball valve was opened, and the feed water ran through the flexible piping to the membranes (Fig. 2).
(6) The initial permeate volumes were collected every 10 minutes for the first four hours and thereafter, permeate was collected on an hourly basis during the day for eight hours. The volume collected over night was then measured and divided by the number of hours over which it was collected and the volume of permeate collected every hour was determined with the assumption that the flux was constant.
(7) The quality of the collected permeate from each system was further analysed for turbidity, E.*coli* and total coliforms.

2.4 Performance parameters and analytical methods

2.4.1 Operational Parameters

The main parameter of this study was the permeate flux.

Permeate flux

The permeate flux is a measure of the volume of fluid, which can be produced from the system as a product over a known surface area per time. Since the area of the membrane and the volume of permeate collected per unit time was known, the flux rate could be calculated from the following equation

$$J = \frac{V}{A \times t} \tag{1}$$

Where: J is the flux rate (L/m^2.hr)
A is the area of the membrane (m^2)
V is the volume of permeate collected (L)
t is the time taken to collect the volume (hours)

The collected permeate volume from experimentation was recorded in litres and the time over which that volume was collected was recorded. The only resistance to this system was that of the membrane.

Upon determining the flux rate using Eq. (1), Eq. (2) was used to verify that there was no change in the differential pressure across the membrane

$$J = \frac{\Delta P}{\mu \times R_t} \tag{2}$$

Where: ΔP is the differential pressure across the membrane (Pa)
μ is the viscosity of the fluid being filtered through the membrane (N.s/m^2)
R_t is the total resistance of the filtration process (m^{-1})

2.4.2 Analytical methods

A brief description of the methods used for analysing the water quality is provided in this section.

Turbidity

Turbidity is the optical property of an aqueous suspension that causes light to be scattered rather than being transmitted through the aqueous suspension i.e., a beam of light passes through pure water undisturbed whereas in solutions containing suspended solids, there is a high degree of scattering of the beam of light (HACH, 1997). Hence, a turbidity meter measures the degree of scattering using a photometer and for this study; the HACH 2100P turbidity meter was used. This test comprises of a turbidity meter, calibration standards and a colourless 20mL bottle with a black lid.

Microbiological methods

(a) Total Coliforms and E-coli counts

Coliforms are bacterial species that reside in the intestines of humans as well as animals. These are excreted through the faeces and are transported to the water sources due to poor sanitation and waste-water treatment. When consumed, these coliforms result in waterborne illnesses (IDEXX Laboratories 2010).

For this study, the presence of total coliforms and E.*coli* was determined using the IDEXX Quanti-Trays which are designed to give quantified bacterial counts of 100 mL samples using

IDEXX Defined Substrate Technology reagent products. This Quanti-Tray system comprises of a sealer, colilert-18 medium, a sterile 100 mL container, trays, an incubator and UV light.

Analysis of the biological layer

The presence of a biofilm layer was determined using the optical microscope. The microscopic images were analyses at a magnification of 100x using a Nikon Eclipse 80i camera.

3. Results and discussion

This section shows the results obtained for the evaluation of flux stabilisation from running three types of river samples on the Bio-UF membrane system. For this investigation, a system was regarded stable if it produced a very slow decline in flux rates during the dead-end filtration mode.

3.1 Raw water and permeate quality

The quality of the collected raw water was evaluated in terms of turbidity, E.*coli* and total coliforms contamination. Table 2 presents the raw water characteristics and Table 3 presents the permeate quality range after operating the Bio-UF membrane system for three months.

From Table 2, it was observed that Tugela River had the highest turbidity while Umgeni River had the lowest E.*coli* counts and turbidity. Umgeni River was also noted to have the highest TOC concentration range while Umbilo was noted to have the lowest TOC concentrations.

Table 3 reveals that the Bio-UF membrane system was able to produce water that was microbiologically safe for consumption in terms of E.*coli* and total coliforms concentrations throughout the experimental duration. The system was also noted to be able to yield turbidity of less than 2 NTU within the two hours of operation. Thereafter, the system produced turbidity that that was less than 1 NTU throughout the extended duration of the system's operation without cleaning or backwashing. The system was also noted to be able to removal efficiency of more than 50% for the assessed rivers.

Table 2 Range for raw water quality

River	Coliforms counts (CFU/100 mL)	E.*coli* counts (CFU/100 mL)	Turbidity (NTU)	Total organic carbon (mg/L)
Tugela	1947 – 12033	692 – 3720	18 – above 1000	10 - 29
Umbilo	203 – 17329	10 – 15531	4 – 17.2	2 - 18
Umgeni	248 –24196	80 – 2010	2 - 14	16 - 108

Table 3 Permeate water quality range during three months of the system operation

River	Coliforms counts (CFU/100 mL)	E.*coli* counts (CFU/100 mL)	Turbidity (NTU)	Total organic carbon (mg/L)
Tugela	0	0	0.4 – 1.30	0 – 7.13
Umbilo	0	0	0.58 – 1.45	1.50 – 5.63
Umgeni	0	0	0.50 – 1.50	8.62 – 21.01

3.2 Criteria for the identification of stable fluxes

Peter-Varbanets *et.al*. (2010) states that flux stabilisation is assumed to be related to the development of heterogeneous structures in the fouling layer that is due to biological processes taking place. Peter-Varbanets *et al*. (2011) further states that the stabilisation of flux rates occurs when there is a decrease in resistance due to structural changes in the fouling layer balances or when there is an increase in resistance due to deposits and irreversible fouling. Coulson and Richardson (2003) further add that when a dead-end filtration system is operated under constant pressure, a plot of $\frac{t-t_1}{V-V_1}$ vs $V - V_1$ should yield a linear relationship.

For the study, the trends obtained for the flux rates were compared to those obtained in literature by Peter-Varbanets *et al*. (2010) and regarded stable if a linear relation didn't exist between $\frac{t}{V}$ vs V as described by Coulson and Richardson (2003).

Fig. 4 shows that the initial flux for the Umgeni River was 4.4 LMH followed by a sharp decrease to 2.6 LMH. Another sharp increase in flux to 4.3 LMH was also observed between 100 – 200 hours of operation. Thereafter, the sharp decline continues to 1.9 LMH after 1000 hours. Stabilisation in flux appeared to be occurring at approximately 1.5 LMH during a period of 1200 hours and 2000 hours of operation. The sudden sharp decrease in flux observed for Umgeni River within the first 50 hours of operation, was brought about by the system being air locked.

When looking at Umbilo River, it was noted that the initial flux was approximately 6 LMH followed by a sharp decrease in flux to 2.8 LMH for the first 500 hours. Thereafter, there was a slow decline to approximately 1.7 LMH at 1600 hours. A further slow decline in flux due to membrane fouling was noted to be continuing throughout the experimentation period. For Tugela River, the initial flux was greater than 14 LMH and this river also experiences a sharp decline in flux during the first 500 hours to approximately 2.6 LMH. A very slow decrease to approximately 1.3 LMH at 1400 hours is noted after which there appeared to be stabilisation of flux for the remaining hours of the experimentation.

The observed trends were noted to be similar to those noted by Peter-Varbanets *et al*. (2010) who classified the trends as stable fluxes. However, in order to get a clear understanding of the

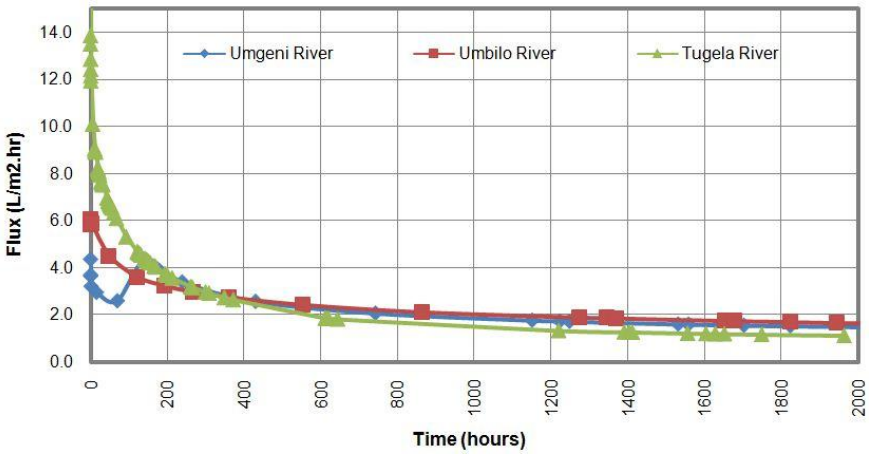
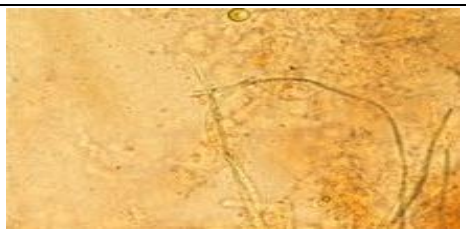
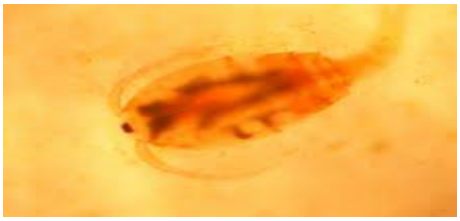
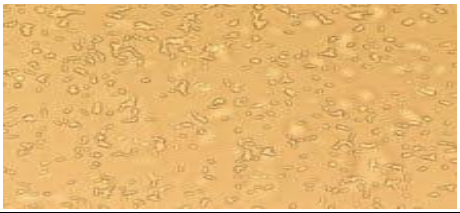


Fig. 4 Flux – Time plots obtained during the evaluation of Bio-UF

Table 4 Microscopic Analysis for the fouling layer formed on the membranes

River	Microscopic analysis
Tugela	
Umbilo	
Umgeni	

formation of the biological layer and flux stabilisation, the membranes were further analysed under a microscope at a magnification of 100x using a Nikon Eclipse 80i camera for the presence of microbiological activity on the membrane surface.

Table 3 reveals that Umbilo River contained protozoa and according to Tortora *et al*. (1995) protozoa feeds on Microorganisms. Umgeni River is noted to be highly concentrated in microorganisms while Tugela River contained suspended matter as well as some traces of filamentous algae. These microorganisms formed a biological layer which Akhondi *et al*. (2015) refers to as a biofilm. Akhondi *et al*. (2015) also states that at temperature above room temperature (i.e., 29℃), the depth of biofilm increases.

From the obtained microscopic analysis, it was noted that the biological layers from the three Rivers were concentrated with different content. Hence, in order to understand the concept of flux stabilisation clearly, the stable trends obtained in Fig. 4 were analysed further by plotting flux rates vs time during the observed stabilisation zone. Fig. 5 presents a closer look at the stabilisation zone for the period of 600 hours to 2000 hours of operation as shown in Fig. 4.

From Fig. 5, it was noted that no stable fluxes were observed from the three rivers which were used in this investigation. However, when looking closely at the three rivers, it was noted that the rate of flux decline for Umgeni River appears to be different to those obtained by Umbilo and Tugela Rivers. This could have been brought about by the membrane clogging due to the high concentrations of microorganisms noted in Table 4 and Total Organic Carbon concentrations noted in Table 2. Hence, it then became necessary to evaluate if the obtained flux rates from the three rivers were of any difference from normal constant pressure dead-end filtration response as presented in Coulson *et al*. 2003.

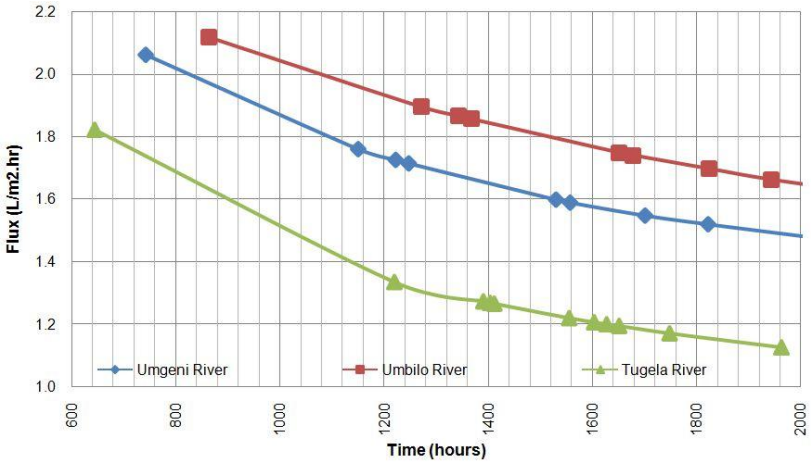
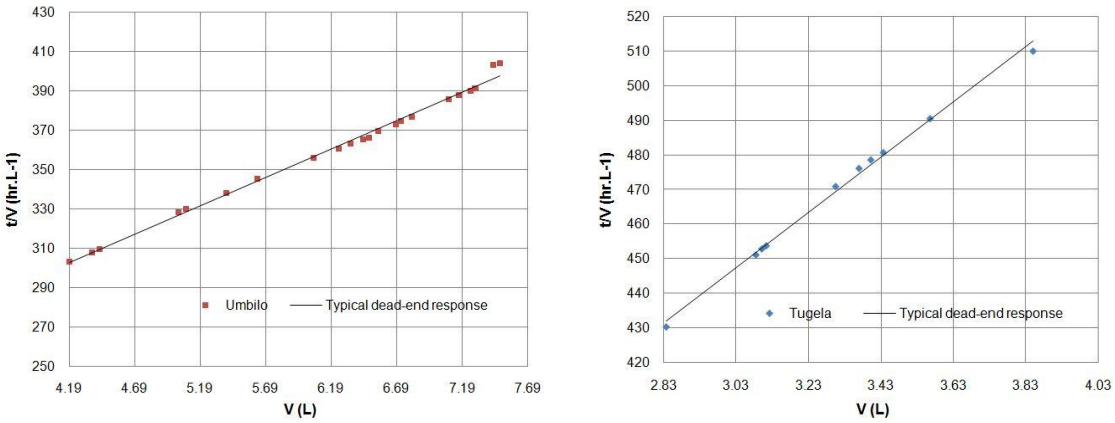


Fig. 5 A closer look on the Flux-Time plots obtained from the three rivers



(a) Reponse of Umbilo River with reference to normal dead-end filtration

(b) Reposne of Tugela River with reference to normal dead-end filtration

Fig. 6 Dead End filtration curve response for Umbilo and Tugela River

Fig. 6 shows the trends obtained when plotting t/V vs V for the period of 1200 hours to 2000 hours of operation.

From Fig. 6, it was noted that both Umbilo River and Tugela River yielded a similar response to the expectant typical response for a dead-end ultrafiltration membrane system operated under constant pressure. This indicates that the 'stable fluxes' observed is due to the inherent nature of a dead-end filtration and not biological fouling on a UF membrane as suggested by Peter-Varbanets *et al*. (2010).

From Fig. 7, it was observed that the response for Umgeni River seems to be deviating from the normal dead-end response in comparison to Tugela and Umbilo River. However, when looking at Table 2, it was noted that Umgeni River had the lowest concentrations for turbidity and E.*coli* counts. This implies that there is a correlation between the quality of the raw water and the flux rates obtainable through the Bio-UF membrane system.

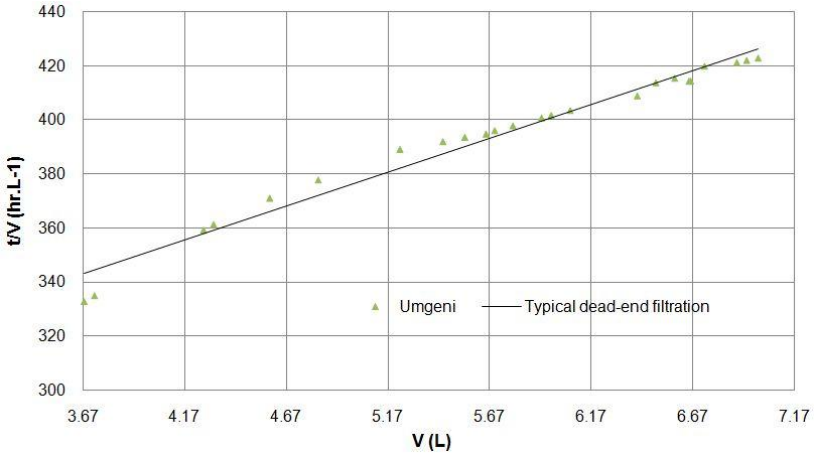


Fig. 7 Dead End filtration curve response for Umgeni River

4. Conclusions

It can be concluded that there is no stabilisation of flux rate obtainable when using the Bio-UF membrane system on the three rivers used for this investigation. It is concluded that the noted stabilisation in Peter-Varbanets *et al*. (2010) is of no difference from normal constant pressure dead-end filtration. However, it can also be concluded that rivers that contain low concentration of E.*coli* and Turbidity are able to achieve enhanced flux rates when compared to normal dead-end filtration.

Acknowledgments

The authors would like to acknowledge Durban University of Technology for financial assistance and Mr Patrick Chamane for all the mechanical support provided during this study.

References

Abbaspour, S. (2011), "Water quality in developing countries, South Asia, South Africa, water quality management and activities that cause water pollution", *Proceedings of the International Conference on Environmental and Agriculture Engineering*, Singapore, July, pp. 94-102.

Adham, S. Ed. (2005), *Development of Microfiltration and Ultrafiltration Knowledge Base*, AWWA Research Foundation.

Akhondi, E., Wu, B., Sun, S., Marxer, B., Lim, W., Gu, J., Liu, L., Burkhardt, M., McDougald, D., Pronk, W. and Fane, A.G. (2015), "Gravity-driven membrane filtration as pretreatment for seawater reverse osmosis: linking biofouling layer morphology with flux stabilization", *Water Res*., **70**, 158-173.

Alekal, P., Baffrey, R., Franz, A., Loux, B., Pihulic, M., Robinson, B. and Young, S. (2005), "Decentralized household water treatment and sanitation systems", Massachusetts Institute of Technology, p. 38.

Buckley, C. (2011), "Sanitation challenges in informal settlements: Applications of DEWATS and Community Ablution Block (CAB) in South Africa", *DEWATS Newsletter*, **4**(1), p. 2.

Coulson, J.M., Harker, J.H., Backhurst, J.R. and Richardson, J.F. (2003), *Chemical Engineering*: *Particle Technology and Separation Processes*, (5th Ed.), Butterworth-Heinemann, Burlington, VT, USA.

Crump, J.A., Otieno, P.O., Slutsker, L., Keswick, B.H., Rosen, D.H., Hoekstra, R.M., Vulule, J.M. and Luby, S.P. (2004), "Household based treatment of drinking water with flocculant-disinfectant for preventing diarrhoea in areas with turbid source water in rural western Kenya: Cluster randomised controlled trial", *British Medical*, **331**(7515), 478-484.

Derlon, N., Peter-Varbanets, M., Scheidegger, A., Pronk, W. and Morgenroth, E. (2012), "Predation influences the structure of biofilm developed on ultrafiltration membranes", *Water Res*., **46**(10), 3323-3333.

Donev, G., van Sark, W.G.H.M., Blok, K. and Dintchev, O. (2012), "Solar water heating potential in South Africa in dynamic energy market conditions", *Renew*. *Sustain*. *Energy Rev*., **16**(5), 3002-3013.

Dong, H.W., Fan, L.Q., Luo, Z., Zhong, J.J., Ryu, D.D. and Bao, J. (2013), "Improvement of ethanol productivity and energy efficiency by degradation of inhibitors using recombinant Zymomonas mobilis", *Biotechnol*. *Bioeng*., **110**(9), 2395-2404.

Duke, W.F., Nordin, R.N., Baker, D. and Mazumder, A. (2006), "The use and performance of Biosand filters in the Artibonite Valley of Haiti: A field study of 107 households", *Rural Remote Health*, **6**(3), p. 570.

HACH (1997), Water Analysis Handbook, (.3rd Ed.), Loveland, CO, USA.

Hossain, Md. M. and Lowe, J. (2008), "Application of ultrafiltration membranes for the removal of humic acid from drinking water", *Desalination*, **218**(1-3), 343-354.

IDEXX Laboratories, I. (2010), Colilert® -18: A new standard in coliform/E. coli detection. Retrieved 10 March, 2010. https://www.idexx.com/water/products/colilert.html

Jacobs, E.P., Bradshaw, S.M., Botes, J.P. and Pillay, V.L. (2005), "Reverse pressure back-flush in pilot scale, dead-end ultrafiltration of surface water", *Membr*. *Sci*., **252**(1-2), 51-63.

Luyt, C.D., Tandlich, R., Muller, J.W. and Wilhelmi, B.S. (2012), "Microbial monitoring of surface water in South Africa: An overview", *Environ*. *Res*. *Public Health*, **9**(8), 2669-2693.

Peletz, R. (2006), *Cross-Sectional Epidemiological Study on Water and Sanitation Practises in the Northern Region*, Master of Technology; Massachusett Institute of Technology, Kenya.

Peter-Varbanets, M., ZurbrÃ gg, C., Swartz, C. and Pronk, W. (2009), "Decentralized systems for potable water and the potential of membrane technology", *Water Res*., **43**(2), 245-265.

Peter-Varbanets, M., Hammes, F., Vital, M. and Pronk, W. (2010), "Stabilization of flux during dead-end ultra-low pressure ultrafiltration", *Water Res*., **44**(12), 3607-3616.

Peter-Varbanets, M., Margot, J., Traber, J. and Pronk, W. (2011), "Mechanisms of membrane fouling during ultra-low pressure ultrafiltration", *J*. *Membr*. *Sci*., **377**(1-2), 42-53.

Pryor, M.J., Jacobs, E.P., Botes, J.P. and Pillay, V.L. (1998), "A low pressure ultrafiltration membrane system for potable water supply to developing communities in South Africa", *Desalination*, **119**(1-3), 103-111.

Qu, F., Liang, H., Wang, Z., Wang, H., Yu, H. and Li, G. (2012), "Ultrafiltration membrane fouling by extracellular organic matters (EOM) of Microcystis aeruginosa in stationary phase: Influences of interfacial characteristics of foulants and fouling mechanisms", *Water Res*., **46**(5), 1490-1500.

Shand, P., Haria, A.H. and Neal, C. (2005), "Hydrochemical heterogeneity in an upland catchment: further characterisation of the spatial, temporal and depth variations in soils, streams and ground waters of the Plynlimon forested catchment, Wales", *Hydrol*. *Earth Syst*. *Sci*., **9**(6), 611-634.

Sobsey, M.D. (2002), "Managing water in the home: Accelerated health gains from improved water supply", *World Health Organization*, pp. 1-70.

Statistics, S.A. (2005), *Water Quality Accounts for South Africa*, Statistics South Africa, Pretoria, South Africa.

Stednick, J.D. (1991), *Wildlands Water Quality Sampling and Analysis*, Academic Press, San Diego, CA, USA.

Sutherland, K. (2009), *Membrane Filtration*: *What*' *New in Membrane Filtration?*", *Filtrat*. *Separ*., **46**(5), 32-35.

Totora, G.J., Funke, B.R. and Case, C.L. (1995), *Microbiology*: *An Introduction*, (5th Edition), The Benjamin / Cummings Publishing Company Inc.: Bridge Parkway.

WHO (2008), Guidelines for drinking water quality: Second Addendum, Volume 1, Recommendations, (3rd Edition), Geneva, Switzerland.

CC