PERFORMANCE CHARACTERISTICS OF BIO-ULTRAFILTRATION ON LOCAL SURFACE WATERS

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AUTHOR'S DECLARATION

I declare that I am the sole author of this dissertation except where indicated and that all references, to the best of my knowledge are accurately reported. This is a true copy of the dissertation, including any required final revisions, as accepted by examiners.

I understand that my dissertation may be made electronically available to the public.

Research Student	Signature	Date
Supervisor	Signature	Date

THIS DISSERTATION

IS

DEDICATED TO THE

THOOLA AND NTHOBA FAMILIES

(with Special mention of my sisters : Mokhali and Refiloe)

ABSTRACT

Access to safe drinking water supply is still a major problem especially in remote rural areas of developing countries. These communities rely solely on untreated surface and ground waters for survival due to the lack of financial resources to provide access to piped water. The consumption of this water in turn makes them easily susceptible to water related diseases. Hence, there is a need for an interim solution while the government is still sourcing funds for the distribution of water to these communities. Membrane filtration is a promising technology for the treatment of surface water as it does not alter the taste or smell of the end product. The main limitation for the implementation of membrane technology in rural areas is still energy demand, fouling and the skills required for membrane cleaning.

Biological ultrafiltration is an emerging technology that produces water of high quality in terms of turbidity, organics and bacteria removal. The technology has been evaluated using a gravity driven dead-end mode on European waters and it offered acceptable stabilisation of fluxes for extended periods without any chemical cleaning or backwashing. This is a promising technology which can be implemented to act as an interim solution for the treatment of surface water in remote rural areas prior to consumption.

This study concerns the evaluation of a biological ultrafiltration membrane system on local three South African rivers, namely, Tugela River, Umbilo River and Umgeni River. A laboratory systems comprising of a feed tank and six membrane modules connected in parallel was set up to assess the performance of a bio-UF membrane on a range of surface waters. The performance was assessed on the system's ability to produce stable fluxes from the three rivers, the system ability to produce water with acceptable quality in terms of SANS 241:2011 for turbidity, TOC, total coliforms and E-coli. The membranes were initial cleaned and the flux rates for ultra-pure water were determined for each membrane prior to being exposed to raw water. Raw water samples were collected from three rivers with varying turbidity, total coliforms and organics. The concentrations of these contaminants were tested prior to running the raw water through the system. Thereafter, permeate was collected with time and its quality was evaluated in terms of turbidity, TOC

and coliforms. The impacts of algae on flux stabilisation were evaluated by allowing the bio-UF system to run for a minimum of 3 months with and without algae growth.

The system was found to be able to produce water that is compliant with the SANS 241:2011 standard in terms of turbidity, total coliforms, E-coli and TOC concentration. The system was also found to be unable to produce stable fluxes for all three rivers. The observed responses were noted to be similar to normal dead-end response, however, a slow declining flux rates was observed for Umgeni River. The presence of algae during the operation was a bio-UF membrane system was noted to further decrease the rate of flux decline. There appears to be a correlation between the raw water quality and the rate of flux decline. A further investigation was carried out aimed at assessing the relationship between the concentration of bacterial counts, TOC and turbidity. From the obtained results, it was noted that feed water with low turbidity (≤ 5 NTU), high bacterial count (≥30 000) and high total organic carbon (≥70 mg/L) is able to reduce the rate of flux decline.

Hence, it can be concluded that a dead-end gravity driven Bio-UF membrane system can be used for the treatment of surface water in remote where the most main contaminants are from natural organic matter, micro-organisms and turbidity. Furthermore, it is able to produce slower declining flux rates which will increase the filter run time.

It is recommended that the impacts of algae, type of bacteria and organics that enable slow decline in flux rates during the operation of Bio-UF should be investigated in order to identify means of enhancing the flux rates. Microfiltration membranes are available on the local markets hence it is also recommended that the performance of Bio-UF should be evaluated in comparison to Bio-MF.

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LIST OF ABBREVIATIONS

Bio-UF	Biological Ultrafitration.
Bio-fouling	Biological fouling
COD	Chemical Oxygen Demand.
DP	Differential pressure.
EPS	Extracellular polymeric substances.
EAWAG	Eidgenössische Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz (currently known as Swiss Federal Institute of Aquatic Science and Technology).
E-coli	Escherichia coli.
hr.	hour
LMH	Litres per area per hour.
L/day	Litres per day
MBR	Membrane Bio-reactor.
MDG	Millennium Development Goals.
MF	Microfiltration.
MWCO	Molecular Weight Cutt-off.
RO	Reverse Osmosis.
SANS 241	South African National Standards 241 drinking water.
SMP	Soluble EPS.
SSS	Small Scale Systems.
TOC	Total Organic content.
TSS	Total suspended solids.
UF	Ultrafiltration.
UNICEF	United Nations Children's Fund.
WFMF	Woven Fibre Microfiltration.
WHO	World Health Organisation.

NOMENCLATURE

SYMBOL	DEFINITION	UNITS
A	Area of the membrane	m^2
J	Flux rate	$L / (m^2.hr)$
ΔP	Trans-membrane pressure difference	Pa
R_t	Total resistance to the filtration process	m^{-1}
R_m	Membrane resistance	m^{-1}
R_r	Resistance due to reversible fouling	m^{-1}
R_{irr}	Resistance due to irreversible fouling	m^{-1}
r	is a constant for incompressible cakes and for compressible cakes it is depended on the voidage and specific surface areas of the particles forming the cake	m^{-2}
t	Time taken to collect the volume	hr
μ	Viscosity of the fluid being filtered through the membrane	N.s/ m2
V	Volume of permeate collected	L
υ	Volume of cake that has been deposited on the membrane for every volume of filtrate	m^3

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND PROBLEM STATEMENT

South Africa is a developing country which comprises of three types of communities namely; urban, rural areas and informal settlements. The country solely recognises piped water as the main safe water supply for its communities. However, the communities that seem to benefit from these systems are urban areas which are inhibited by medium to high income earners. The people who do not have means to build or buy their own private water treatment systems are low income earners and this class of people is dense in rural areas (Donev et al., 2012) as well as in the informal settlements (also known as under privileged urban areas). At present, these communities are relying on untreated ground and surface water for survival which in turn makes them vulnerable to waterborne diseases such as diarrhoea, giardiasis, cholera, hypothesis and typhoid fever (Luyt et al., 2012). The poor infrastructure of these areas makes it costly to connect piped water from water treatment plants as well as to build local water treatment systems due to the lack of technical skills. According to Ms Buyelwa Sonjica's Morning Live interview on the 22 July 2010, the government was sourcing funds to build local treatment systems and train people who can maintain the plants once they are built.

Various research studies have been conducted for the development of an interim solution for safe water supply for rural and underprivileged urban areas (Table 2.1). These developed interim solutions comprises of, among others, decentralized point of use systems such as boiling, solar water disinfection, slow sand filtration, ceramic filters, cloth filtration, LifeStraw and chemical disinfection with flocculation (Sobsey, 2002; Alekal, 2005; Peletz, 2006; Crump et al., 2004 and Duke et al., 2006). However, these methods of treatment are not implemented in high rates as expected in low income families due to the costs involved in their operation; such as the buying of wood, flocculants; their laboriousness and the time required for effective treatment. The community members on whom some of these technologies were tested have also complained that the systems altered the smell and taste of the water thus they discontinued practising them (Crump et al., 2004). Hence a treatment system is required that will not alter the taste or smell of the water; not be laborious or time

consuming and yet be economical, user-friendly, and produce safe consumable water according to South African National Standards for Drinking Water (SANS 241:2011) and World Health Organisation (WHO) guidelines.

Membrane Technology is a promising technology and is significantly growing on a worldwide scale for water and wastewater treatment (Le Clech et al., 2006). It comes highly recommended as an inexpensive method (Sutherland, 2009) of water treatment when compared to conventional methods because it requires a small floor spacing (footprint) (Waite et al., 2001) and limited usage of chemicals for treatment, which in turn eliminates the alteration of taste and smell of permeate (Adham, 2005). There are two types of membrane processes namely: pressure driven and electrically driven processes. Pressure driven membrane processes comprise of microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO), in their decreasing order of permeability. The main drawback that still limits the implementation of membrane systems on a large scale is fouling and energy requirements (Pryor et al., 1998; Jacobs et al., 2005). A further constraint for the implementation of these systems in remote rural areas as well as in under privileged urban areas is the technical skills required for cleaning the membranes.

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) while reducing the energy consumption and membrane fouling. These acceptable low flux rates are referred to as stable fluxes and they are brought about by the formation of a biological layer on the UF membrane surface and the use of gravity as a driving force for the technology, which eradicates the energy demands associated with membrane operations.

Biological filtration, also referred to as bio-filtration, has gained much attention in the recent years for the treatment of wastewater. However, very little focus has been placed on drinking water treatment (Fonseca et al., 2001). Bio-filtration is a process which involves the use of naturally occurring micro-organisms in surface water for the breaking down of materials found in the water (Evans, 2005). This, therefore, result in the

production of improved water quality in terms of turbidity, colour and dissolved organic carbon as the micro-organisms feed on the dissolved organic compounds. In order for bio-filtration to occur, a medium or surface on which the micro-organisms can adhere to is required. When this occurs in membrane filtration it is referred to as biological fouling.

Biological ultrafiltration, mostly referred to as Bio-UF, is an emerging technology which still needs to be developed further (Jermann et al., 2007). During the filtration process of surface water, the main membrane foulants are organic matter (Dong et al., 2013, Roddick et al., 2012 and Hörsch et al., 2005), thus only fouling through the formation of a biofilm can prevent the complete clogging of the membrane. The micro-organisms found in this water adhere themselves onto the UF membrane surface and feeds on the organic matter found in the feed water resulting in the breaking down of materials and the formation of a porous fouling layer. This then allows for the disinfection of drinking water without the use of chemicals.

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 water of good quality in terms of WHO guidelines (Peter-Varbanets et al., 2012) and the production of stable fluxes for extended periods without any backwashing or chemical cleaning (Peter-Varbanets et al., 2012). 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 Bio-UF as a water treatment option for the provision of drinking water in areas where piped water is currently unavailable.

1.2 OBJECTIVES

The overall objective of this research was to evaluate a gravity driven biological ultrafiltration membrane system for the treatment of drinking water in remote rural areas of South Africa.

The specific objectives for the research were as follows:

I. To evaluate the performance of Bio-UF membrane on a range of South African surface waters. The performance criteria will be the evaluation of the system's ability for the removal of turbidity, total organic carbon, total coliforms and E-coli.

II. To evaluate the ability of a Bio-UF membrane system to produce stabilisation of flux on a range of South African surface waters.

III. To establish the influence of algae growth on flux. The criteria will be the operation of the gravity driven bio-UF membrane system with and without algae growth.

1.3 APPROACH

A laboratory system comprising of a feed tank and membrane modules connected in parallel to each other, was set up to assess the performance of a Bio-UF membrane on a range of surface waters. Ultra-pure water was initially run through the system to get a clean water curve which was later used as a reference point after cleaning. Raw water samples were collected from three rivers with varying concentrations of turbidity, total coliforms, E-coli and total organics. The turbidity, TOC and coliforms of the raw water were tested prior to running the raw water through the system. Thereafter, permeate was collected with time and its quality was evaluated in terms of turbidity, TOC and coliforms. The systems were allowed to run for a minimum of three months with and without light exclusion in order to evaluate the impact of algae on the technology.

1.4 THESIS OUTLINE

Chapter 2	This chapter provides a detailed background on the challenges of water supply faced by remote rural areas, the literature reviewed on the current available POU systems and theoretical framework of fouling during Bio-UF.
Chapter 3	A brief introduction to the laboratory scale set-up is given and a general methodology used for the experimentation, data collection and analysis is presented.
Chapter 4	This chapter presents the results obtained from the evaluation of the performance of the Bio-UF membrane system as a means of treating surface water in remote rural areas. The results obtained when evaluating the impact of algae on the performance of the Bio-UF membrane system are also presented.
Chapter 5	This chapter presents the results obtained from an evaluation carried to investigate the correlation between feed water quality and flux rates.
Chapter 6	The conclusions made from this study and recommendations for future work are presented in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter presents the literature reviewed on ultrafiltration (UF) in conjunction with biological filtration as a means of treating surface water in remote rural areas. This chapter is outlined as follows:

Section 2.2 outlines the challenges of water supply in developing countries; section 2.3 outlines the currently available practises for decentralised water treatment systems in rural areas; section 2.4 outlines ultrafiltration as a means of treating surface water to acceptable standard for turbidity, E-coli and total coliforms in terms of WHO (2008) and South African National Standards, referred to as SANS, 241: 2011; section 2.5 outlines the background on biological ultrafiltration membrane systems as a means of treating surface water in remote rural areas and section 2.6 outlines the acceptable water quality for consumption in terms of WHO guidelines, SANS 241:2011 standard and the status of water quality in rural areas of South Africa.

2.2 CHALLENGES OF WATER SUPPLY IN DEVELOPING COUNTRIES

According to global statistics, about 1.1 billion people in the world were without microbiologically safe sources of drinking water at the end of 2000 (Mara, 2003). Target 10 of the 7th Millennium development goal (MDG), set by WHO and the United Nations Children Fund, known as UNICEF, in 2002 aims to reduce the number of people without access to safe drinking water by half in 2015 (UNICEF, 2000). In industrialised and transitional countries, target 10 of the 7th MDG, can be easily achieved due to freely available financial resources. However, in developing continents such as Africa and Asia, the rapid growth in population poses a threat to its achievement (Peter-Varbanets et al., 2009).

South Africa is one of the developing countries in which 38.3% of its population resides in remote rural areas and still lacks access to safe drinking water sources (Statistics, 2010). Currently, the country only recognises piped water as the only means of safe

water supply and due to the costs involved in building water treatment plants; a large portion of these communities are still without piped water.

Urban areas are often industrialised and comprise of a majority of people who have migrated from rural areas during the urbanization in the second half of the 20th century (Peter-Varbanets et al., 2009). These communities are in the centre of all services, hence they have reliable centralized water supply and treatment systems that are managed and controlled by municipalities.

On the other hand, informal settlements are also closely located to water supply and treatment facilities as most of these are found in neighbouring urban areas. The members of informal settlements are from rural areas and they reside here in order to be close to the urban area in which they are working. However, due to the poor infrastructure of these informal settlements; it becomes difficult to distribute water and proper sanitation facilities, resulting in these communities lacking access to safe drinking water. In most parts of the country, interim solutions have been provided such as the ablution blocks or containers which are connected to the municipal main lines. These ablution blocks supply both safe sanitation and drinking water to the people residing in these communities (Buckley, 2011).

Rural areas are located far from any form of urbanisation and mostly still lack basic services such as proper sanitation and infrastructure for safe water supply. The households in these areas are widely dispersed and it becomes a financial constraint to supply piped water from cities to these communities. According to Mara (2003), these communities have to travel long distances to access untreated surface and ground water for survival which in turn poses a health risk of infection with waterborne diseases and illnesses; this was also cited by Snow (1855). There is a need to provide as source of safe water supply to these communities and the department of water affairs is currently providing financial assistance with the implementation of decentralised systems such as rainwater harvesting in these areas (Kahinda et al., 2007).

2.3 DECENTRALISED WATER SYSTEMS FOR RURAL AREAS

2.3.1 Overview

Decentralised water supply seems to be a relevant interim solution to be implemented in order to overcome both water quantity and quality in remote rural areas. These systems comprise of rainwater harvesting and point of use, point of entry and small-scale systems, respectively.

2.3.2 Rainwater Harvesting

Rainwater harvesting is one of the most commonly used methods and has been practised over many decades (Worm, 2006). It refers to the capturing of rain as it falls, through the capturing of a run-off from a roof or local catchment, ground catchment, rock catchment and seasonal floodwater from local streams as well as the conservation of water through the watershed management (Lee et al., 2010). This collected water can in turn be used for providing water to the people, livestock and crops as well as for groundwater recharging and the reduction of urban floods (Domenech and Sauri 2011; Biazin et al., 2012). Even though rain harvesting has many health benefits such as lowering the risk of back injuries (Mbugua, 1995) and time consumption from the collection of water (Kahinda et al., 2007), there are a number of quality concerns which have been raised over the years. These include the contamination of the rainwater by airborne pathogens, the material of the roof and the storage tank. However, the probability of finding airborne pathogens is low, thus they can be negligible (Mbugua, 1995; IRC, 2002 and Dunstan et al., 2009). The contamination from the roof and storage tank is highly dependable on the material used, paint or substances that have accumulated on the roof or gutters such as dust and leaves. These contaminants alter the taste and smell of the water as well as pose health risks upon consumption. The main drawback of this technology is that the rainfall is seasonal and not guaranteed. Furthermore, there is a high possibility of contamination and re-growth of bacteria while

water is in the storage tank (Dunstan et al., 2009). Rain harvesting is however, still used for overcoming the issue of water quantity with a further treatment step being implemented to overcome the water quality concerns. These treatment steps include, but not limited to, the utilisation of detergents such as sodium hypochlorite.

2.3.3 Point of Use (POU), Point of Entry (POE) and Small Scale Systems (SSS)

Water quality is still a major issue which needs to be addressed and decentralised water supply systems such as Point of Use (POU), Point of Entry (POE) and Small Scale Systems (SSS) have been used to overcome this issue. These systems are used in places where water treatment systems are unavailable or malfunctioning (Sobsey et al., 2008).

POE systems are used in households that already have a piped water distribution whose quality is not acceptable in terms of WHO guidelines. This technology is used at the point of entry of water to the house and for the treatment of water prior to the distribution to different areas of the household (Sobsey et al., 2008)

Small Scale Systems, on the other hand, are meant for the treatment of community water and can supply small communities with up to 10 000 L/day (IRC, 2002, Elfil et al., 2006 and Peter-Varbanets et al., 2009). This technology is effective for households that are closely gathered and require technical skills for operation (Peter-Varbanets et al., 2009).

Point of use, as the name implies, is the type of treatment that is mainly practised in households for the removal of impurities prior to consumption where water is collected in buckets from the water source or storage facility. POU is the most suitable decentralised system applicable to communities whose households are widely dispensed for thetreatment of surface and ground water for prior to consumption (Peter-Varbanets et al., 2009; Pikwa et al., 2009 and Dankovich, 2014).

Various research studies have been conducted on POU systems as a means of supplying safe water to rural areas (Table 2.1) with much focus being placed on

developing countries. The aim of these studies was to determine means of treating ground and surface water prior to consumption by the communities.

TABLE 2. 1: Evaluated POU system in remote areas and emergency situations.

TECHNOLOGY	RESEARCHER	REGION APPLIED	SUCCESS RATE	LEASON LEARNED	SHORTCOMINGS
BOILING	Sobsey 1989	Vietnam	The system gave a reduction of 97% in geometric mean for thermotolerant coliforms. Out of all the water samples that were stored by self-boilers after boiling them, 37% were found to met the WHO standards and 38.3% to fall within the low risk category according to WHO standards.	Boiling is effective in the inactivation of all bacteria, viruses and protozoa that can result in diarrheal disseases however there was a lack of safe handling of the purified water after boiling in some households such that recontamination occurred. The water had to be consumed within 24hrs of boiling.	This technology is considered to be unrealistic and inaccessible to the poorest community due to the scarcity and high cost of fuels.
CERAMIC FILTER	Clasen et al 2004	Bolivia	The community was divided into two groups, one using the filters and the other not. Out of 96 samples that were collected from each group, the filtrate coming from the group using the ceramic filters was found to be 100% free of thermotolerant coliforms compared to 15% for the group not using the technology.	The technology has the ability to lower diarrhoea disease by 70% compared to the households not using it. Care needs to be taken when cleaning the system to prevent damaging of the filter.	The systems are operated through depth filtration which means that a breakthrough of bacteria can occur after operating the system for a long period.
CHEMICAL DISINFECTION with flocculation.	Crump et al 2004	Kenya	The community was divided into two groups: one having a disinfection with flocculation and one with disinfection only. The group having flocculation with disinfection was found to have a decrease of 19% in diarrhoea cases while the group that disinfected had a 26% dearhoea cases. Water samples were obtained from the 2 groups and from the none users of the technology. The results showed that 40% of the samples obtained from the none users had <1 CFU/100mL compared to 82% for flocculation with disinfection group and 78% for group that were only disinfecting.	There was a decrease in the death rate of people in groups that were using the intervention compared to those who were not using it.	The cost of the disinfectants and flocculants may prevent the low income families from using this system. The users also complained that the disinfectant altered with the taste and odour of the water.
CLOTH FILTERS	Peletz 2006	Ghana	The cloth filter takes less than one minute to filter a standard 44L bucket.	It was highly acceptable to the low income communities as it was given out for free by the government and it had no limit to the volume of water to be treated. People had a mentality that the water is only harmful when the turbidities are high and stopped using the filters when they percierved the water to be clear.	The cloth has a tendency of tearing off and often requires a replacement. The cloth is purchased from South African distributors who gets the cloth from the manufacturer in India.
LIFESTRAW	Vestergaard Frandsen	University of Arizona	According to the US Environmental Protection Agency (EPA) guidelines. This technology removes at least 99.9999% of all bacteria, 99.99% of all viruses and 99.9 % of parasites.	It can produce at least 10l/hr of purified water.	The system is only limited to emergency situation and it cannot sustain as a long-term solution. It also does not have the ability to remove Giardia.
SLOW BIOSAND FILTRATION	Duke et al 2006 and Kaiser et al 2002	Haiti	The system had the ability to remove 98.5% of Bacteria and reduced turbidity from 6.2 to 0.9 NTU. The system can also remove protozoa by 99.98-100%.	High precaution needs to be taken when sharing filtered water as recontamination can occur from lack of safe storage. 13% of the filters where found to have significantly dropped in filtrate flowrate due to clogging.	It was noted that the system can not handle waters with high turbidity and has very limited virus removal efficiency.
SOLAR WATER DISINFECTION	Alekal 2005	Schools in Napal	The system had the ability to remove faecal coliforms and the reported cases of diarrhoea were found to have reduced by 20-30%.	Schools were noted to be the ideal entry for POU systems because students can have the ability to reach 5 family members and some community members.	On cloudy days, the system require 48hrs or more for proper disinfection to occur. The system has also been rated as a laborious process due to needed frequent cleaning of the containers.

From Table 2.1, it was noted that most of the systems had shortcomings such as an altered taste and smell of the end product, technology unaffordability to low income earners, laborious to use and unreliable (Sobsey, 2002; Kaiser et al., 2002; Clasen et al., 2004. ; Crump et al., 2004; Duke et al., 2006). A POU system that is able to overcome the outlined shortcomings and can be easily implemented in these communities is still needed. Membrane technology is a promising technology to be used as it does not alter the smell or taste of the water, and based on recent developments in membrane design and configurations, the cost of membranes have significantly decreased (Peter-Varbanets et al., 2009; Sutherland, 2009).

2.4 INTRODUCTION TO MEMBRANE TECHNOLOGY

A membrane is a material through which one type of substance can pass more readily than others, thus presenting the basis of a separation process (Mbulawa 2005). The driving force can be through a concentration difference, pressure difference, temperature difference or electrical potential (Mulder, 1996; Wang and Zhou, 2013). The most commonly used membrane processes in water treatment are pressure driven processes which can be operated either by gravity or electric power supply. These pressure driven membrane processes are referred to as membrane filtration processes and are further divided into four processes which are: Microfiltration (MF), Ultrafiltration (UF), Nanofiltration (NF) and Reverse Osmosis (RO) respectively in the order of their descending pore size (Guo et al., 2009) , Figure 2.1.

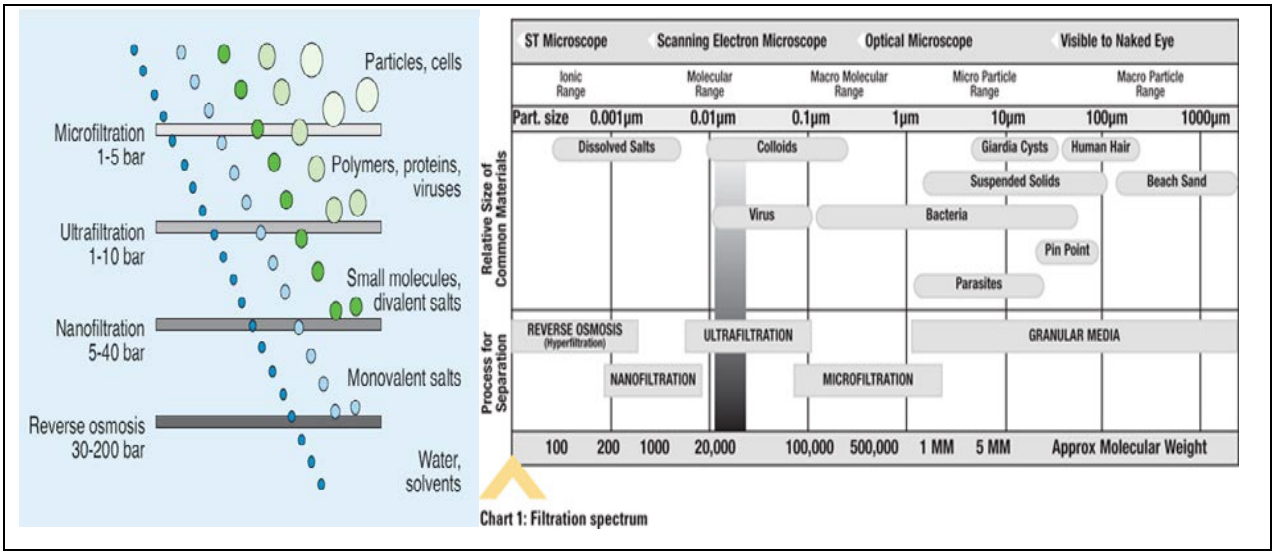


FIGURE 2. 1: Membrane processes in the descending order of their pore sizes [Buteyn, 2010].

MF membranes are membranes that have the largest pore sizes and require the lowest pressure for operation. They are classified according to the pore size range and are able to retain colloidal particles and cells while allowing dissolved substances and water to pass through its wall (Suarez, 2013).

UF membranes on the other hand are classified according to the Molecular Weight Cut-Off (MWCO) hence their ability to retain substances with the smallest molecular weight. These membranes are able to retain all the substances retained by MF together with viruses and macromolecules such as proteins (Suarez, 2013).

NF is a membrane filtration processes that is used for the separation of all substances retained by UF as well as small molecules and divalent salts (Izadpanah and Javidnia, 2012; Suarez, 2013). It is also classified according to MWCO and acts as a mixture of UF and RO i.e. it can remove most of the contaminants that an RO removes.

RO is a membrane filtration process that is used mainly for the removal of monovalent salts i.e. it can remove all of the above stated contaminants in Figure 2.1. However RO membrane system requires the highest pressure for operation (Suarez, 2013).

For the purpose of this study, the review will focus mainly on UF membrane systems.

2.5 ULTRAFILTRATION PROCESS AS A WATER TREATMENT SYSTEM

2.5.1 History of Ultrafiltration membranes

Ultrafiltration membranes use finely porous membranes to separate water and micro-solutes from macro-solutes and colloids. It is a pressure-driven membrane separation process with pore sizes ranging around 0.01 - 0.1µm. These pore size ranges have made UF to be the preferable process in the water treatment due to its ability to improve water quality with regards to the removal of organics and microbial contaminants.

The first synthetic UF membranes were prepared by Bechhold from collodion (Baker, 2004). This was done by measuring the bubble points and terming the unit ultrafilter. There were many early studies carried out on the ultrafilter and by mid-1920's, collodion (also known as cellulosic polymer) ultrafiltration and microfiltration membranes were widely used in laboratory studies but no industrial applications existed until 1960s. The crucial breakthrough was the development of the anisotropic cellulose acetate membrane by Loeb and Sourirajan in 1963 (Baker, 2004). The main goal of Sourirajan and Loeb was to produce a high flux RO membrane, but others, particularly Micheal et al., (1965), produced UF membranes from cellulose acetate and many other polymers including polyacrylonitrile copolymers, aromatic polyamides, polysulfone and polyvinylidene fluoride. Even today, polymers and cellulose acetate are still used for the fabrication of UF membranes (Pearce, 2007 and Sutherland, 2009).

In 1969, Abcor (which is now a division of Koch Industries) installed the first commercially successful industrial UF system equipped with tubular membrane modules to recover electrocoat paint from automobile paint shop rinse water. The economics were compelling and within a few years similar systems were installed. In 1970, the first cheese whey UF system was installed and within a decade, 100 similar systems had been installed worldwide (Cheryan, 1986; Pouliot, 2008; Pearce, 2008 and Noor et al., 2012).

In 1973, Romicon sold the first hollow fibre capillary and spiral wound modules. During 1979 – 1980, Abcor adapted the membranes to UF applications. Over the past 20 years, the UF industry has grown steadily, however, the main problems that plagued the

applications of these membranes were fouling, poor cleanability of some early developed modules and restricted operating conditions (Baker, 2004). However, most of these problems have been overcome through the development of superior membrane materials and improved module design. Fouling on the other hand cannot be completely eliminated. It can however be controlled by techniques such as backwashing and regular cleaning protocols.

Recently, several companies have developed ceramic based membranes as an alternative to polymeric membranes. This is due to the fact that ceramic membranes have low membrane resistance while producing high permeate rates. However, it should be taken into account that these membranes are more expensive than polymeric membranes (Booker, 2010).

2.5.2 Operational Aspects

One of the major limitations associated with the operation of membrane filtration plants is an increase in the operation cost for the recovery of permeate flux which declines due to membrane fouling (Wang, 2008).

2.5.2.1 Fouling and the necessity for frequent cleaning

Fouling is a major constraint for the implementation and efficient performance of ultrafiltration membranes more specifically in the production of drinking water (Peiris et al., 2010). During the operation of membrane processes, the permeate flux is dependent on the trans-membrane pressure and total filtration resistance. This relationship is given by equation (2.1) which is based on Darcy's law for describing the flow of a fluid through a porous medium:

$$J = \frac{\Delta P}{\mu R_t} \qquad \textbf{[2. 1]}$$

Where: J is the permeate flux in L / (m^2.hr.).

ΔP is the trans-membrane pressure difference in Pa.

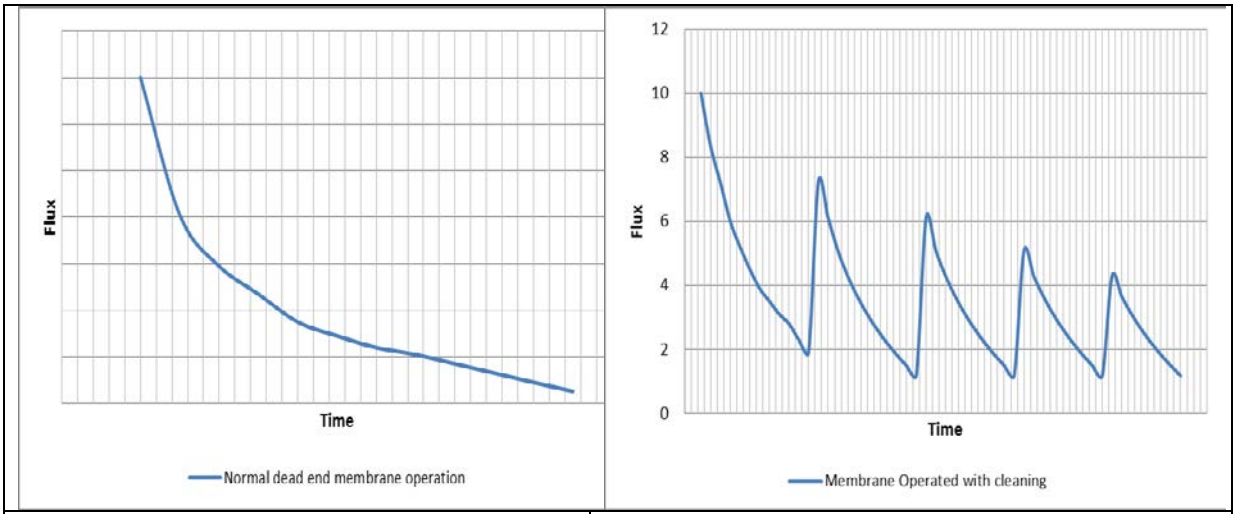
μ is the viscosity of the fluid being filtered through the membrane in N.s/m^2.

R_t is the total resistance to the filtration process in m^{-1}.

The total resistance to the filtration process is the sum of membrane resistance (R_m), reversible fouling (R_r) and irreversible fouling (R_{irr}) (Kimura et al., 2004). Hence Equation 2.1 becomes:

$$J = \frac{\Delta P}{\mu(R_m + R_r + R_{irr})} \qquad \textbf{[2. 2(a)]}$$

Membrane fouling is brought about by the attachment of foulants onto the membrane through pore plugging or narrowing due to adsorption and through the formation of a cake or gel layer on the membrane surface. 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, 2012), (Figure 2.2 (a)).



(a) Normal dead-end membrane filtration without cleaning

(b) Dead-end membrane filtration with cleaning

FIGURE 2. 2: A presentation of membrane fouling without cleaning (a) and membrane fouling with cleaning (b).

Reversible fouling occurs through the loose attachment of particulates onto the membrane to form a cake layer and this is easily controlled by backwashing (Kimura et

al., 2004; Huang et al., 2007; Tian et al., 2013). Backwashing is associated with the reduction of the amount of particulates accumulated on and in the membrane pores consequently increasing the permeate flux (Susanto et al., 2008). However, permeate flux decline will still be observed, (Figure 2.2 (b)), with operations over extended periods and this will consequently result in an increased cost of operation.

Irreversible fouling, on the other hand, is associated with membrane fouling due to the formation of a gel layer on the membrane surface due to the excretion of extracellular polymeric substances (known as EPS) by the micro-organisms. This type of fouling can be controlled by chemical cleaning, however continued use of this method of cleaning can affect the life span of the membrane and the discarding of the chemical after use poses another problem (Kimura et al., 2004).

2.5.3 Process Options

2.5.3.1 Modes of operation for pressure-driven membrane processes

UF membrane processes can be operated in two modes i.e. crossflow or dead-end (Figure 2.3).

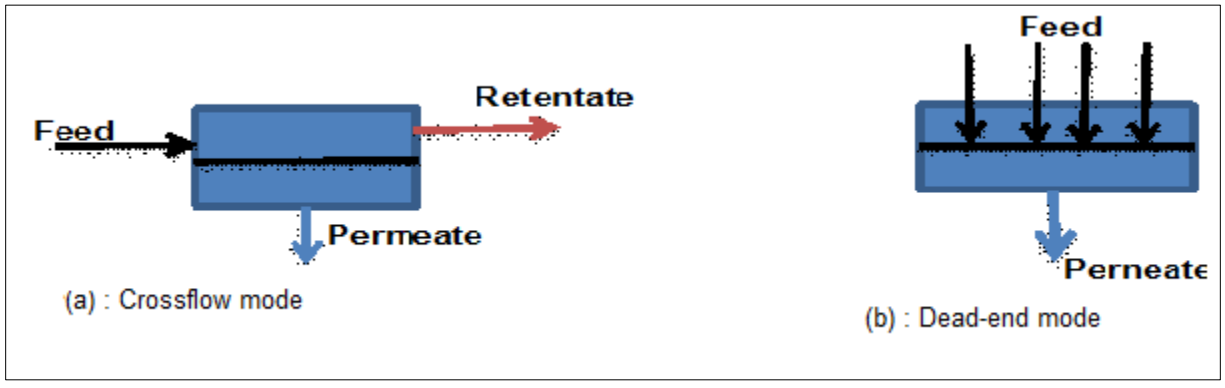


FIGURE 2. 3: Types of filtration modes for pressure driven membranes, crossflow (a) and dead-end mode (b) respectively [Beier 2007].

The crossflow mode of operation occurs when the feed is pumped across the membrane at high velocities with a retentate stream leaving as depicted in Figure 2.3 (a). This mode requires high energy for pumping the feed across the membrane as well as for the recycle pump and consequently has high operational costs. It is the most widely used mode as it has the ability to produce high flux rates (Beier, 2007).

Dead-end on the other hand is a mode of operation which occurs when the feed is pumped vertically onto the membrane without a retentate stream, as shown in Figure 2.3 (b). This is the most favourable mode of operation when the main aim is cost minimisation as it does not require a high amount of energy for pump operations. However when high fluxes are required, it is less favourable as periodic backwashes will be required due to the concentrate build-up on the membrane feed side (Beier, 2007).

Depending on the requirements of the output, UF membranes can also be operated either under constant flux or constant pressure (Freeman et al., 2014). During constant flux operation, the rate of permeate is controlled by using either a constant flow valve or by a positive displacement pump. The differential pressure, ΔP, across the membrane increases with an increase in fouling rate to an extent when chemical cleaning has to be implemented (Choi and Dempsey, 2005; Beier and Jonsson, 2010) . For constant pressure operation, the ΔP across the membrane is kept constant through the use of the pressure control valve on either the retentate stream or just after the feed pump. During this operation, the permeate flux decreases with time and the fouling layer increases until such a point that the achieved flux is unacceptable and membrane cleaning has to be implemented (Freeman et al., 2014).

2.5.3.2 Types of available UF modules

The high need for controlling membrane fouling appears to have dominated the design of UF modules. The first UF systems to be commercialized were based on tubular and plate–and-frame module designs but over the years low cost systems had to be developed (Baker, 2004). Currently there are four types of modules used by industries for UF systems, these include, tubular, plate-and-frame, spiral wound and hollow fibre

modules (Sagle and Freeman, 2004). Figure 2.4 shows a schematic presentation of these different modules.

Tubular modules, Figure 2.4 (b), were the first UF modules to be designed for industrial scale using synthetic membranes. They are normally used for highly fouled solutions such as electrocoat paint due to their large diameter such as inner diameters >10mm (Cheryan, 1986). However, the treatment or cleaning of these modules outweighs their cost and they also consume high energy for operation (Schwinge et al. 2004). For example, a feed to a tubular UF system has to be circulated through the module arrays at a velocity range of 2 – 6 m/s and this high circulation velocity in turn drops the pressure of the system resulting in poor performance (Baker, 2004). Larger pumps are required to retain the system at its optimum operating point however the use of large pumps results in high consumption of energy and an increased operating cost.

Plate-and-frame modules, Figure 2.4 (a), were also developed during the same time as tubular modules. These modules do not have high fouling resistance as tubular modules and are more affordable. Each of these modules consists of two membrane flat sheets with a rubber gasket on the outer edges and a spacer between the sheets (Ndinisa 2006; Li and Tung, 2011). These modules are packed to form a stack referred to as a rig. These plate-and-frame modules can be operated at pressures as high as 10 bar which is higher than that allowed for tubular modules, and their compact design together with the absence of stagnant area allows for easy sterilization. In a plate-and-frame system it is easy to identify and replace a faulty module, to analyse the performance of individual modules and to detect any leakages.

Capillary hollow fibre modules, Figure 2.4 (d), were first introduced by Amicon and Romicon during the early 1970's (Cheryan, 1986). These modules are manufactured from non-cellulosic material and they form a self-supporting tube with a dense skin layer on the inside of the tube. A typical capillary module will contain 500 – 2000 fibres with diameters ranging from 0.5 – 1.0 mm housed in a cartridge that is 762mm in length and 76.2 mm in diameter (Baker, 2004). Each cartridge has an inlet for the feed, an outlet for the reject and two permeate outlets located on each side of the cartridge (Glucina et al., 2009).

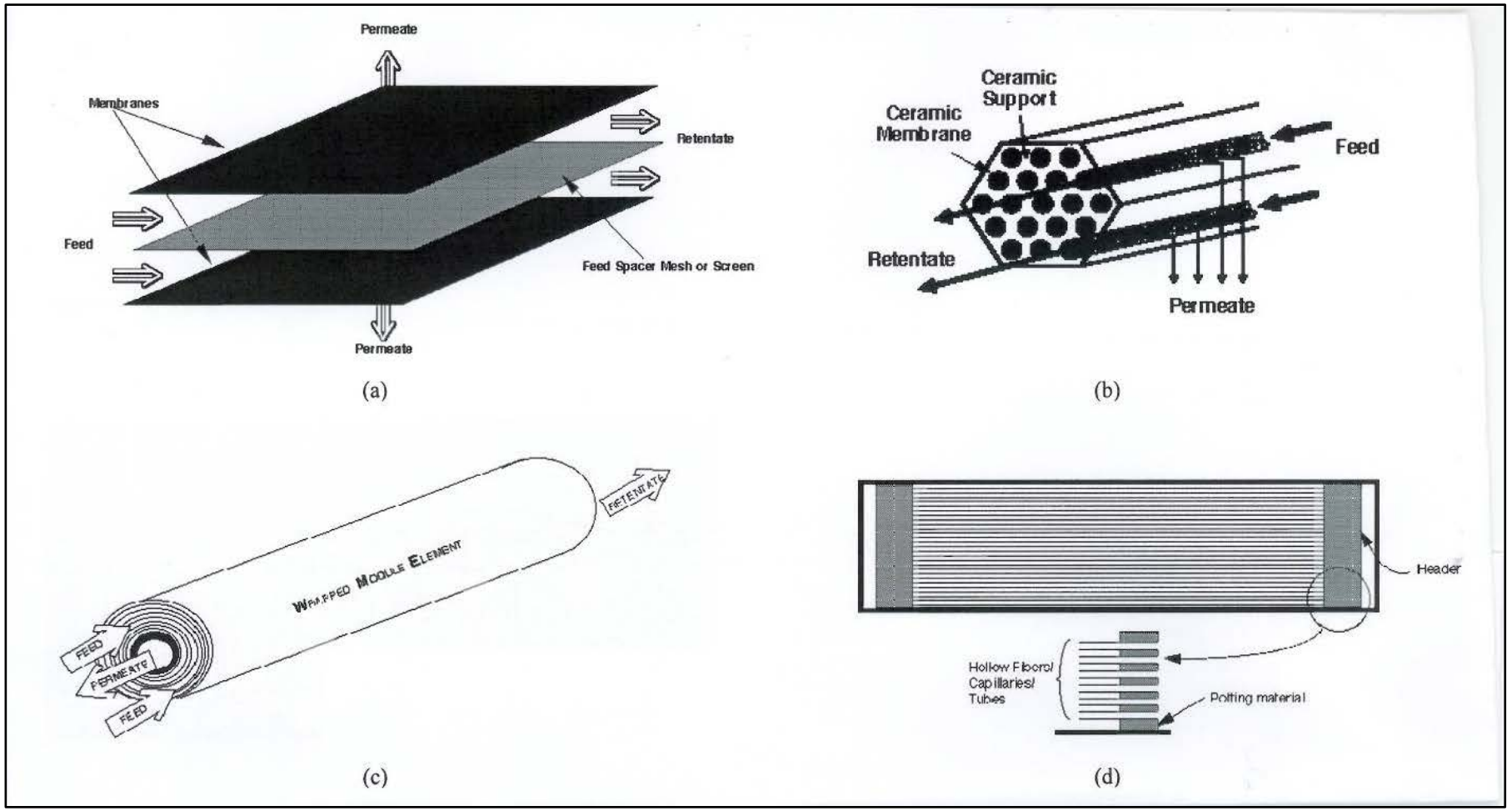


FIGURE 2. 4: Schematic presentation of (a) plate and frame, (b) tubular, (c) spiral wound and (d) hallow fibre module. [Sagle and Freeman, 2004].

Capillary hollow fibre membranes can be operated at a maximum pressure of up to 1.824 bars and they require pre-filtration in order to remove all particulates that are larger than one-tenth of the fibres inside diameter to avoid blinding/plugging at the cartridge entrance which can result in system blockage (Baker, 2004). The main advantage of hollow fibre membranes is that they can be easily cleaned through backwashing by simply closing the permeate outlets for a short period during operation while the disadvantage is that even if only one fibre is damaged or at fault, the whole cartridge has to be replaced

Spiral wound modules, Figure 2.4 (c), are one of the most inexpensive and compact designs available for UF membranes. Similar to plate-and-frame modules, spiral wound modules are also made from flat sheets i.e. two flat sheets are placed together with their active sides facing away from each other and they are separated by a thin mesh like spacer. These sheets together with the spacer are glued on three sides and the fourth open side is fixed around the perforated centre of the tube. An extra spacer, with the required thickness, is placed on one side of the envelope and the whole assembly is rolled around the centre of the tube to form a spiral configuration (Cheryan, 1986; Schwinge et al. 2004; Li and Tung, 2008). The feed is pumped length wise along the pipe (UF unit) while permeate is forced through the membrane sheets into the permeate channel forming spirals towards the perforated centre of the collecting tube. The advantages of the spiral wound modules include its narrow channel heights as this allows for the availability of more membrane area whilst reducing the surface area-to-volume ratio, minimizing pressure drops and reducing channel plugging resulting in low operational costs. One of the disadvantages of spiral wound modules is the mesh spacers used as they tend to create some dead spots behind the mesh in the direction of flow. These spots may cause particles to hang in the mesh network resulting in cleaning problems and limiting the modules for use with relatively clean feeds (Cheryan, 1986).

When focusing on drinking water production, it is important to take into consideration that the membrane filtration process to be used must have the ability to remove microbiological and chemical contaminants which when consumed can result in diseases or illnesses. When referring to Figure 2.1, it can be clearly noted that all mentioned membrane processes are able to remove microbiological contaminants such

as bacteria and viruses; however, a disinfection step is required in the case of microfiltration. Ultrafiltration membrane processes are a promising technology for water treatment due to their pore sizes which are adequate for the removal of both bacteria and viruses.

. 2.5.4 Applications of ultrafiltration membranes

In the early 1960's when industrial UF membranes were introduced, it was believed that they would be widely used for the treatment of industrial wastewater for the removal of microbiological contaminats (Farahbakhsh and Smith, 2004; Sano et al., 2006). However, due to the high cost involved with the use of membranes, they were mainly used for the treatment of small and concentrated waste streams from particular sources prior to mixing with general sewer streams. The application of UF membranes has now widened to include diverse fieldssuch as for the pre-treatment step during desalination (Pearce, 2008); for the removal of spores from cheese milk and whey (Pouliot, 2008); microbial cell harvesting and design of high-performance continuous fermentos (Cheryan, 1986); separation of oil-water emulsion (Yi et al, 2013) and treatment of wastewater with the aim of recycling for agricultural purposes (Falsanisi et al., 2010).

2.5.5 Applications of ultrafiltration membranes in water treatment

Conventional methods of treating water has been applied in many countries for decades however due to the high population growth and demand for safe water quality, the water treatment works are simply not coping (Chen et al., 2013). There is insufficient information available on the performance of conventional methods such as the dissolved air flotation (DAF) unit for the removal of micro-biological contaminants (Koivunen, 2007). However, on a laboratory scale, a DAF unit has the ability for 1.7 log removal for cryptosporidium (Edzwald et al., 2001). Hence there is a need for a system that can cater for the growing population without compromising the quality of the water.

UF membranes have been applied quite broadly in the treatment of water from domestic, industrial as well as in the production of drinking water (Berube, 2009; Chen

et al., 2013; Noor et al., 2012; and Yang et al., 2006). Lowe and Hossain (2008) also state that UF membranes are effective in the removal of humic acids.

A number companies focusing on the design of UF membrane system for the purpose of water treatment have been established. These include the UF plant by Technomax, the UF water treatment plant by H_2O International located in East London, UF system by Aquamarine water treatment and UF water system developed by Haideneng. UF membranes has the ability to cut down the cost associated with the coagulation and flocculation steps used during conventional processes as well as the footprint required for plant operation (Waite et al., 2001 and Sutherland, 2009). However, membrane systems require high energy for pumping the fluid across the membrane. This high energy demand is associated to high operation cost of a UF membrane system and consequently makes these systems less favourable in developing countries (Peter-Varbanets et al., 2009).

2.5.6 Limitation in applying UF membranes in rural areas

The main drawback for the application of membranes on a large scale in developing countries specifically in rural areas is the fouling layer and cost of operation (Pikwa et al., 2009). More so, due to lack of the availability of technical skills in rural areas, it becomes difficult to implement membrane systems as they require regular back-flushing, disinfection, chemical cleaning, a pre-treatment system as well as high pressure regardless of the scale of operation (Peter-Varbanets et al., 2011).

Hence, there is still a need to develop a system that can be able to produce safe water according to WHO guidelines without any pre-treatment as well as being independent of electricity and pressure supplied by tap water (Pikwa et al., 2009). As already known, when operating a membrane system under gravity without any pre-treatment, fouling occurs (Choi and Dempsey; 2005; Beier, 2007; Beier and Jonsson, 2010) and when including the pre-treatment step, the operation cost increases (Peter-Varbanets et al., 2009). These problems make the membrane systems less favourable in rural areas due to the lack of finances.

2.5.6.1 Energy demand

The amount of energy required for the operation of a membrane system is directly linked to the type of operation mode used i.e. dead-end is known to require low amounts of energy when compared to crossflow (Beier, 2007). However, due to the rapid backwash and chemical cleaning required for controlling the effects of fouling, crossflow is normally used regardless of the high energy demand (Choi and Dempsey, 2005). Hence dead-end mode of operation is mainly used in association with a pre-treatment step in cases of highly contaminated feed (Peter-Varbanets et al., 2009 and Chen et al., 2013). In order to eradicate the energy demand during the use of membranes in remote rural areas, a measure of minimizing the fouling layer needs to be implemented.

2.5.6.2 Fouling

Even though membranes appear to be a promising technology, membrane fouling is still the main drawback that limits their implementation in large scale (Le Clech et al., 2006). Fouling can occur through biological fouling from the growth of biological species on the membrane surface, colloidal fouling, organic fouling due to the deposit of organic matter on the membrane surface and scaling from the formation of mineral deposits on the membrane surface due to the precipitation of the feed (Durancear, 2001).

The type of fouling which occurs on the membrane can either be reversible or irreversible depending on the type of foulants found in the feed. Removable fouling can be easily removed by physical cleaning while irremovable fouling is controlled by chemical cleaning (Kimura et al., 2004, Huang et al., 2007, Meng et al., 2009). Irreversible fouling, also referred to as biological fouling, cannot be removed by backwashing as it is brought about by the excretion of EPS by the micro-organisms freely available in the water. Hence it is important to be able to control irreversible fouling for the efficient and long term use of the membrane (Kimura et al., 2004).

When dealing with surface water, the fouling layer experienced is mainly due to Natural Organic Matter known as NOM, inorganic (minerals) and bacterial (viruses etc) content (Lowe and Hossain, 2008; 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 minimize 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).

NOM membrane fouling is highly dependent on the interaction between the inorganic and organic contents of the feed with the membrane surface itself. This type of fouling normally occur due to the deposition of biopolymers such as proteins and polysaccharides (Meng et al., 2009) and is known to be the main source of irreversible fouling (Kimura et al., 2004) which is associated with the presence of bacterial content.

Inorganic matter on the other hand, is associated with the presence of minerals in the water. Most of the research available is on the studies of inorganic fouling with organic fouling and limited studies have been conducted on this type of fouling alone. However, inorganic fouling on an inorganic membrane results in irreversible fouling (Kang et al., 2002; Ognier et al., 2002).

The bacteria content fouls the membrane by the excretion of EPS. This EPS can either be in a bound or soluble form. Bound EPS comprises of proteins, polysaccharides, nucleic acids, humic acids, and lipids which are located on the outside of the cell surface, while soluble EPS comprises of a pool of organic compounds that are released into a solution from substrate metabolism (Meng et al., 2009).

For the control or prevention of membrane fouling, it has become necessary to initially understand the factors affecting membrane fouling. These factors include the membrane material, biomass characteristics, feed water characteristics and operating conditions (Le Clech et al., 2006; Meng et al., 2009; Nguyeni, 2010).

2.6 BIOLOGICAL ULTRAFILTRATION

2.6.1 History

In most membrane processes, the word “fouling” is associated with flux decline hence regarded as an undesirable process during membrane filtration. However, very little focus has been placed on understanding the fouling type and process. Much focus was on understanding the behaviour of membrane adsorption, pore blocking and the development of the cake layer. Preventive and corrective methods for fouling through these processes have been studied and are currently implemented in various operations (Field et al., 1995; Kimura, et al., 2004; Peter-Varbanets et al., 2010). As already mentioned in section 2.5.2.1, these corrective and preventive measures for fouling are not suitable for rural areas of developing countries due to the costs involved for their implementation. Hence, the use of biological filtration in conjunction with ultrafiltration seems to be a promising technology for these areas.

Biological filtration is the process of water purification through the use of readily available micro-organisms in water. This process requires a surface onto which the micro-organisms can adhere through the excretion of EPS and forms a biological layer normally referred to as a biofilm. These micro-organisms in the biofilm consume the organic matter and the film removes iron, manganese as well as ammonia through the production of microbiologically stable water (Ronald, 1997). The use of biological filtration in conjunction with membrane processes is a standard procedure especially in wastewater treatment for the removal of nitrates and phosphorus through the use of membrane bioreactors (MBR) (Le Clech et al., 2006; Ramesh et al., 2007; Meng et al., 2009). Recently this interest has spread into drinking water treatment more specifically into surface water treatment (Kimura et al., 2004; Peter-Varbanets et al., 2011).

The biological ultrafiltration membrane process, well known as Bio-UF, is an emerging technology for the treatment of surface water hence, it is still under development. As the name suggests, this is a process of water purification which encourages the microbial growth on the membrane to enhance the performance of a UF membrane. The technology promises permeate of high quality in terms of colloidal, bacterial, organic

and inorganic matter removals while being operated under the gravitational force in dead-end mode. Instead of expected flux decline to undesirable rates after operating for extended periods, bio-UF offers acceptable fluxes for extended periods (Peter-Varbanets et al., 2010). The stabilisation of flux is associated with the biological processes which were occurring on the membrane surface as well as the presence of NOM in feed water (Kimura et al., 2004). According to the study conducted by Peter-Varbanets et al. (2011), flux stabilisation during bio-UF 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.

2.6.2 Performance characteristics

Dead-end filtration is a membrane process whereby the water flows perpendicular to the membrane without a retentate stream (Figure 2.5). This then results in a cake build-up on the membrane surface and consequently decreases the flux rate (Figure 2.6).

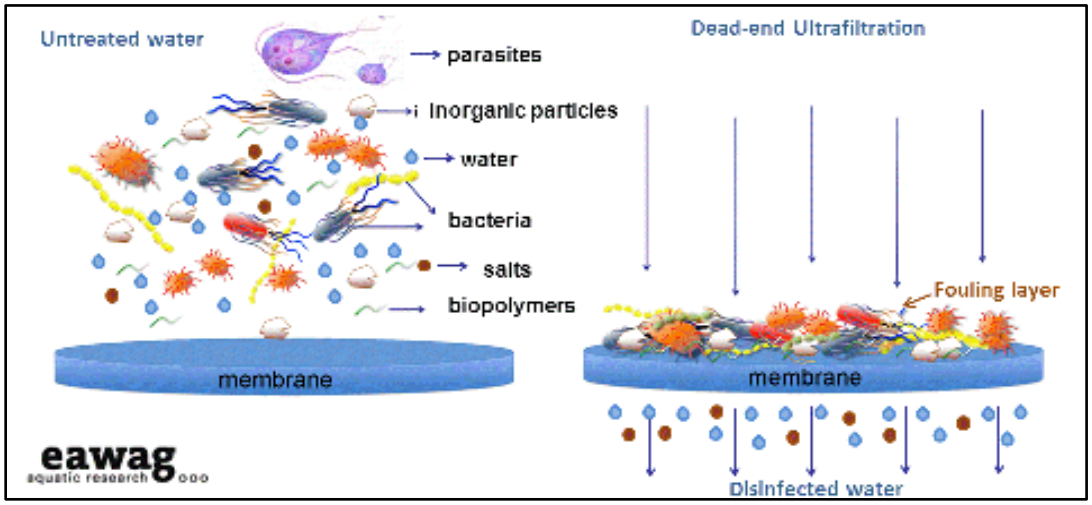


FIGURE 2.5: Fouling of a UF membrane during dead-end operation (EAWAG, 2011).

The filtration process can be employed under constant pressure or constant flux mode. When operated in constant flux mode, the pressure drop across the membrane increases requiring more pressure to push the water through the cake build up (Coulson and Richardson, 2003). This mode is selected when a positive displacement pump is to

be used for achieving the desired flux rate. In cases whereby gravity is to be used as the driving force, the mode that is implemented is constant pressure. During this mode, the filtration rate decreases with an increase in the cake build up on the membrane surface (Figure 2.6).

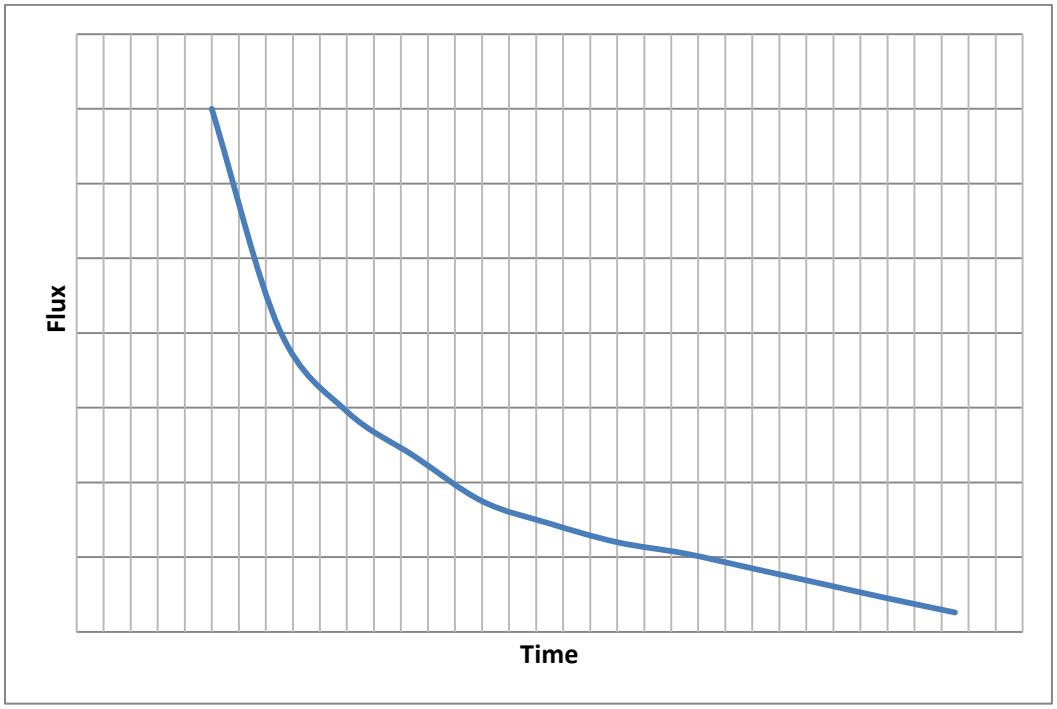


FIGURE 2. 6: Flux-Profile for a normal dead-end ultrafiltration system without chemical cleaning or backflushing.

According to Darcy's law, when pure water is forced to flow through a porous ultrafiltration membrane, the flux rate through the accumulation of the concentrate on the membrane surface is directly proportional to the pressure drop across the membrane. This relationship is given by:

$$J = \frac{V}{A \times t} \qquad \textbf{[2. 2]}$$

Where: A is the area of the membrane through which filtration occurs.

J is the permeate flux in L / (m^2.hr.).

t is the duration of the filtration process.

V is the volume of permeate collect during the filtration process.

But we also know that from Equation 2.1(a) states that:

$$\boldsymbol{J = \frac{\Delta P}{\mu(R_m + R_r + R_{irr})}} \qquad \text{[2. 1(a)]}$$

Assuming that the resistance to flux rate is brought about by the membrane thickness and the cake formed, Equation 2.2 becomes:

$$J = \frac{1}{A}\frac{dV}{dt} = \frac{\Delta P}{\mu(R_m + R_r)} \qquad \textbf{[2. 3]}$$

Taking into account that the resistance of the cake build up on the membrane is directly linked to the thickness of the cake (l), the specific surface area of the particle (S), the voidage (e), the integration of Equation 2.3 for constant pressure operation yields:

$$\frac{t - t_1}{V - V_1} = \frac{r \times \mu \times v}{2 \times A^2(-\Delta P)}(V - V_1) + \frac{r \times \mu \times v}{A^2(-\Delta P)} \qquad \textbf{[2. 4]}$$

Where: $v = \frac{l \times A}{V}$ and is described as the volume of cake that has been deposited on the membrane per unit volume of filtrate.

$r = \frac{5(1-e)^2 S^2}{e^3}$ and is regarded to be a constant for incompressible cakes and is dependent on the voidage and specific surface areas of the particles forming the cake.

According to Coulson and Richardson (2003), a plot of $\frac{t - t_1}{V - V_1}$ vs $(V - V_1)$ should yield a linear relationship.

On the other hand, when biological fouling occurs on a UF membrane system, a bacterium attaches itself on the membrane surface and excretes a gel layer known as EPS. Fouling occurs through the formation of the gel layer covering the membrane surface, as shown in Figure 2.7, and this consequently prevents membrane fouling due to pore blocking.

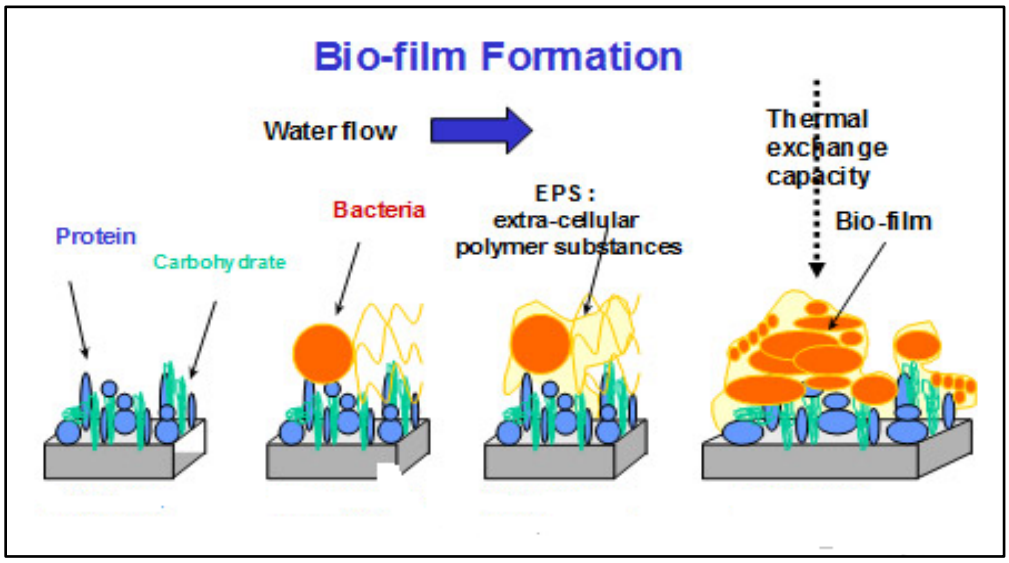


FIGURE 2. 7: Formation of a bio-fouling layer (Mexel energy, 2012).

Flux decline during bio-UF occurs due to the formation of a heterogeneous structure within the fouling layer which is brought about by the presence of biological activities (Derlon *et al.,* 2012). When this occurs, the flux profile outlined in Figure 2.8 is observed.

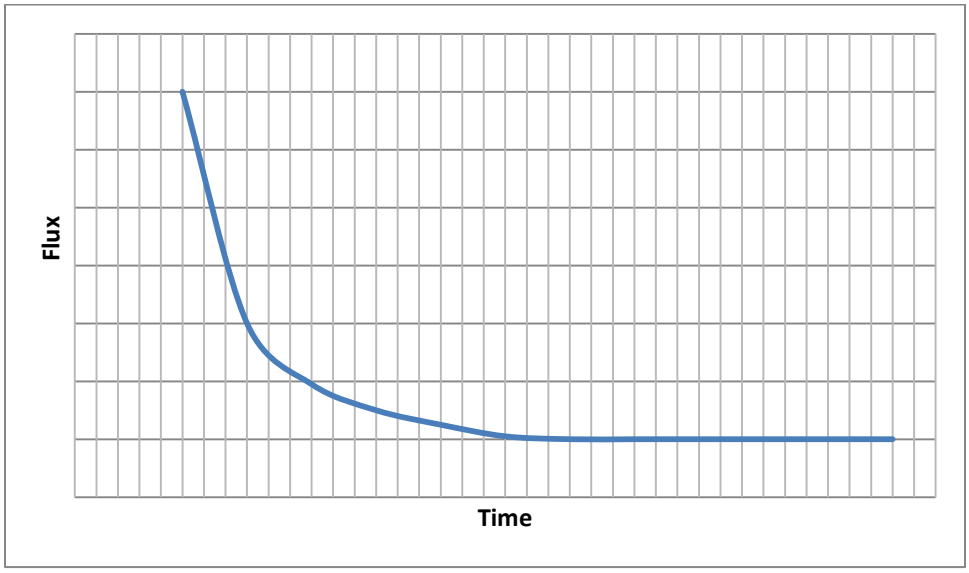


FIGURE 2. 8: Flux-profile for a bio-UF membrane system operated in dead-end mode without chemical cleaning or backwashing.

This stabilisation of flux occurs when the biological processes leading to increase of flux are in equilibrium with the processes leading to decrease of flux (Peter-Varbanets et al., 2010).

2.6.3 Gravity driven membrane processes

Gravity driven membrane processes occur when one substance passes through the membrane due to the pressure exerted on the membrane by the head of the solution being separated.

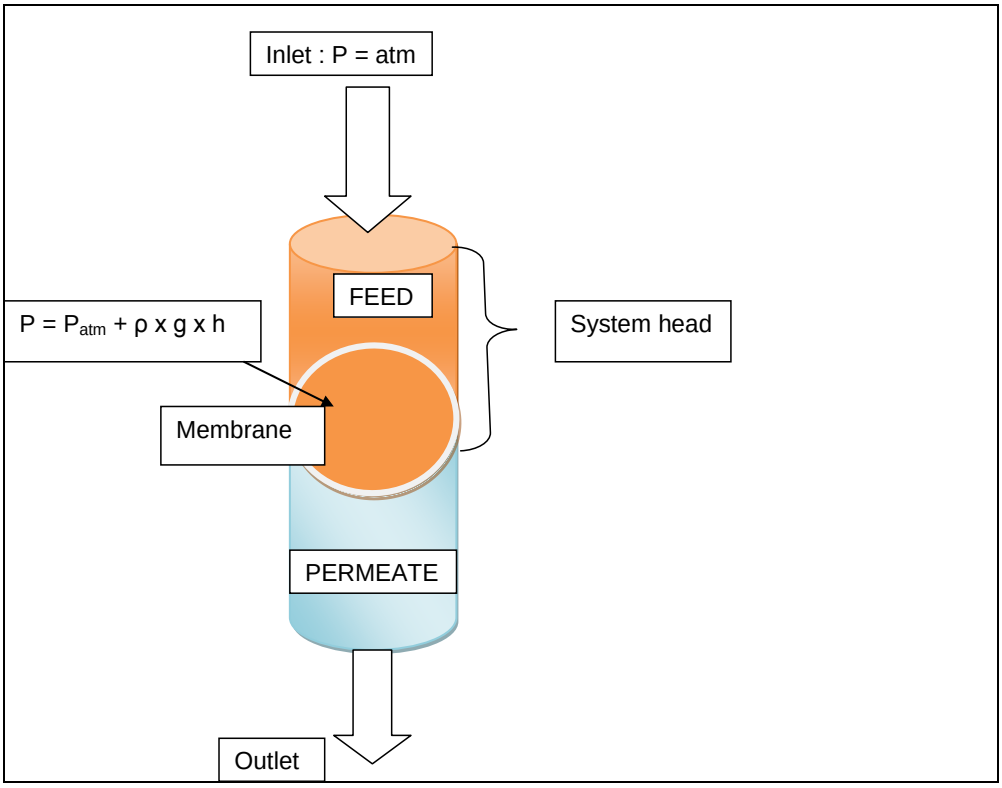


FIGURE 2. 9: A typical gravity driven membrane system.

As shown in the Figure 2.9, the main driving force of the process is the pressure supplied by the feed on the membrane since the pressure on the system inlet is equal to that on the system outlet. Gravity driven systems require no energy for operation however constant cleaning is required to minimise complete clogging of the membrane.

2.6.4 Potential advantages for rural areas and current status of the technology

Ultra-low pressure driven Bio-UF is a promising new technology that has been developed by EAWAG for the production of safe drinking water in developing areas as well as in an emergency situation. The technology promotes the growth of the biological layer on the membrane and allows for the operation of the system in a dead-end mode without any energy requirements. There is also requirement for backwashing or chemical usages for the treatment of the fouling layer. The process is able to control hygienic hazards and produces a flux of 4 – 10 LMH while operated in dead-end mode for extended hours without any backwash or chemical treatment (Peter-Varbanets et al., 2010).

This technology can be implemented in South Africa to eradicate the problems currently encountered with the supply of safe water in remote rural areas. The technology is not intended to take over from the municipal supply of water but rather to act as an interim solution for the minimisation of waterborne diseases. However, prior to the implementation of this technology, it is necessary to evaluate its ability to produce safe drinking water from available surface waters of South Africa.

2.7 WATER QUALITY

For water to be safe for usage i.e. either for consumption or other household usages, it has to meet some standards which are normally set on a national level and those standards have to fall within the World Health Organisation guidelines. These standards set by the country should also take into account the short-term and long-term effects of exposure to human health, which in some cases may result in chronic illnesses such as diarrhoea, typhoid, fevers, acute hepatitis A, E and F, intestinal helminth infection and paratyphoid. Hence it becomes necessary to set some standards based on the chemical, physical and biological properties of water in order to eliminate the spread of these diseases. Table 2.2 presents the drinking water guidelines developed by the World Health Organisation as well as the South African national standard limits for drinking water.

TABLE 2. 2: Physical, chemical and biological guidelines for drinking water (WHO, 2008 and SANS 241:2011).

Properties	Parameter	Units	WHO 2008 Guideline	SANS 241:2011 standards
Physical	Colour	mg/L (Pt-Co)	≤ 15	≤ 15
	Turbidity	NTU	< 5	≤ 1
Chemical	Ph		6.5 – 8.5	≥ 5 to ≤ 9.7
	TDS	mg/L	< 1000	≤ 1200
	Manganese (Mn)	mg/L	0.5	≤ 0.5
	Fluoride (F^-)	mg/L	1.5	≤ 1.5
	Chloride (Cl^-)	mg/L	250	≤ 300
	Sulphate (SO_4^{-2})	mg/L	250	≤ 500
	Nitrate (NO_3)	mg/L	50	≤ 11
	Nitrite (NO_2)	mg/L	3	≤ 0.9
	Aluminium (Al)	mg/L	0.2	≤ 0.3
	Lead (Pb)	mg/L	0.01	≤ 0.01
	Mercury (Hg)	mg/L	0.001	≤ 0.006
	Arsenic (As)	mg/L	0.01	≤ 0.01
	Chromium (Cr VI)	mg/L	0.05	
	Chromium (Cr)	mg/L		≤ 0.05
	Antimony (Sb)	mg/L	0.02	≤ 0.02
	Selenium (Se)	mg/L	0.01	≤ 0.01
	Cyanide (CN)	mg/L	0.07	≤ 0.01
	Cadmium (Cd)	mg/L	0.003	≤ 0.03
	Zinc (Zn)	mg/L	3.0	≤ 5
	Copper (Cu)	mg/L	2.0	≤ 2
	Total organic carbon	mg/L		≤ 10
	Phenols	mg/L	0.002	≤ 0.01
Biological	Total coliforms	MPN/100mL	Must not be detectable in a 100mL sample.	≤ 10
	E-coli and Thermotolerant coliform bacteria	MPN/100mL		Must not be detectable in a 100mL sample.

As already explained, each country is expected to develop its own standards which must fall within the WHO guideline, hence appendix D outlines the South African water standards as stipulated in SANS 241: 2011.

2.7.1 Water quality in rural areas of South Africa

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/insecticides, contaminants with oestrogens and oestrogens-mimicking substances, solid litter, oxygen depletion and radionuclide (Chamber, 2009). However, rural areas are located far away from industrialisation; hence the main contaminants of their surface water are faecal pollution, colour and stability, salts 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 when it rains (Abbaspour, 2011).

The eutrophication is brought about by high levels of algae and tends to alter the taste as well as the smell of the water. In fresh water sources, this contaminant creates an environment which favours the growth of toxin-producing cyanobacteria which is one of the causes of waterborne diseases (Chorus and Bartram, 1999). This contaminant can be treated by powdered activated carbon or dissolved air floatation. However, in areas where such plants cannot be implemented, a further treatment option is still required.

Faecal pollution is associated with poor sanitation and hygiene practises. It is the main factor of pollution in remote rural areas as they still practice open defecation and lack knowledge of the importance of hygiene practises (WHO, 2004).

Fluoride contaminants are mainly found in the coal bearing areas which are in the central and western regions of South Africa (Statistics, 2005).

The regions located in the northern and eastern parts of the country are known to have acceptable salt concentrations while interior regions have surface water with high TDS concentration due to the presence of sulphates and chlorides. The cost for the removal of these contaminants is high, hence they are not considered to be viable (Statistics, 2005).

Colour and stability of surface water is due to the presence of organic matter mainly in the form of acids. This type of contaminant is found along the southern coastline of the country (Statistics, 2005).

Therefore, in accordance with dealing or treating the above mentioned contaminants, an affordable system that can be easily operated whilst being able to eradicate the impacts of eutrophication, faecal pollution, colour and stability contamination on surface water is still required.

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CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter outlines the studies which were conducted at the Durban University of Technology for the evaluation of the performance of a Bio-UF membrane system for the treatment of drinking water in rural areas. Three rivers located in KwaZulu Natal, South Africa were the subject of the study using polyethersulphone (known as PES) membranes supplied by Microdyn Nadir.

The purpose of this study was to evaluate the ability of the Bio-UF membrane system to produce stable flux rates over extended periods without chemical cleaning or backwash; to assess the influences of algae on flux stabilisation during bio-UF as well as the determination of the system's ability to produce drinking water that is compliant with SANS 241: 2011 and WHO guidelines in terms of the concentrations of turbidity, TOC, E-coli and total coliforms in the permeate.

This chapter is outlined as follows: section 3.2 provides the sampling points for the feed water; section 3.3 describes the experimental apparatus; section 3.4 provides a description of the experimental protocol used and section 3.5 outlines the performance parameters together with the analytical methods used.

3.2 FEED WATER

The Bio-UF membrane system is targeted for use by people in remote rural areas. This people currently rely on surface water for survival. Hence, the raw water used in this study was collected from Tugela River, Umbilo River and Umgeni River. These rivers are located in the KwaZulu-Natal province, South Africa and Table 3.1 outlines the co-ordinates for sampling points. The raw water samples were collected from the three rivers and analysed for turbidity, total coliforms, E-coli and Total Organic Carbon within 24 hours of sampling.

TABLE 3. 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”

All precautions required for sample collection were taken as stipulated by Stednick (1991).

3.3 EXPERIMENTAL APPARATUS

The laboratory systems were set-up to enable parallel investigation of the raw water from the three rivers. This set-up is presented in Figure 3.1 and Figure 3.2.

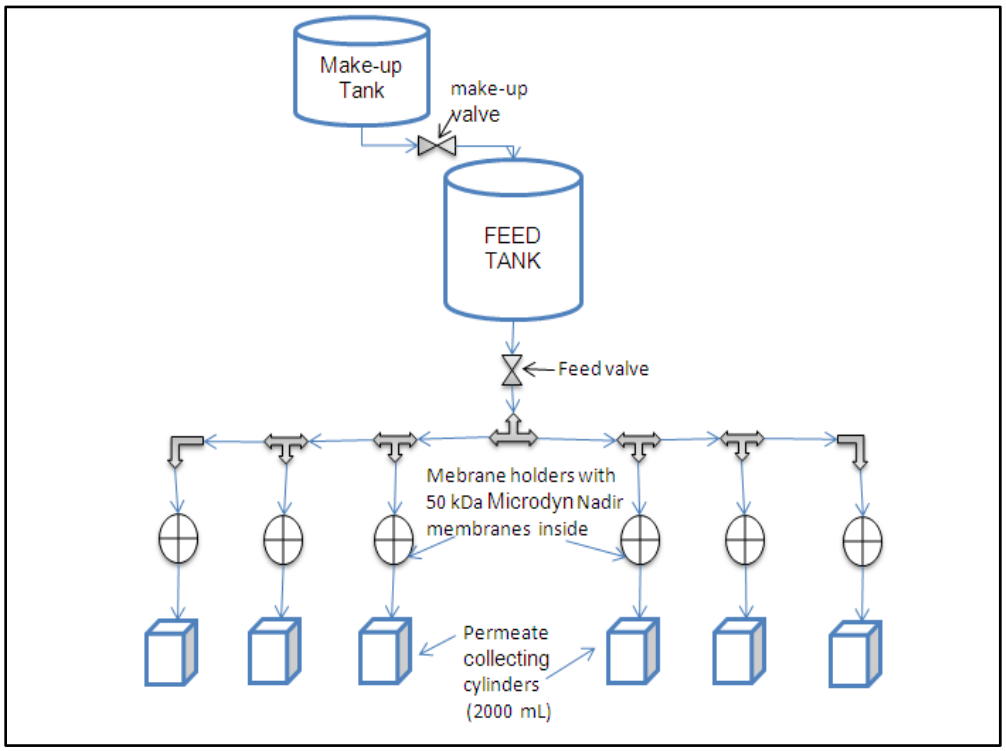


FIGURE 3. 1: Schematic Process Flow Diagram for the Bio-UF membrane system.

FIGURE 3. 2: A photographic image for the layout of the laboratory scale set-up for the Bio-UF system during the evaluation of algae growth

3.3.1 The Feed Tank, the make-up tank and measuring cylinders

The feed tank was a 32L container while the make-up tank was a 9L container. 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 Figure 3.2 above. Six 2L measuring cylinders were used for the collection of permeate as it drops from the flexible tubing attached to the membrane's permeate side.

3.3.2 Membrane Holder

The membrane holders were made of polycarbonate with a diameter of 47mm purchased from Watman. The holders (Figure 3.3) comprised of an assembly ring, a cap, 2 x support grids, a flat gasket, an O-Ring, and the base.

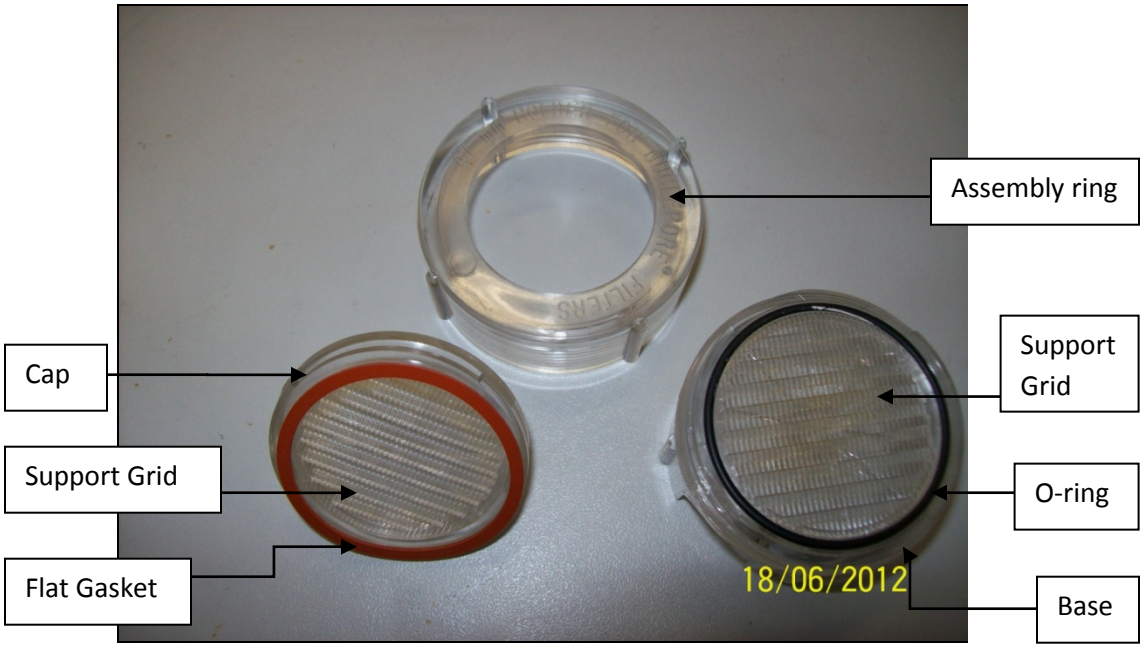


FIGURE 3. 3: A photographic image showing the different parts of the membrane holder.

3.3.3 UF membrane

Each experiment was run on a new flat sheet Polyethersulphone (PES) Microdyn Membrane with a diameter of 47mm, nominal molecular cut-off of 50kDa and a porosity of 0.0026 kg/m.s^2 which was purchased from Memcon (Pty) Ltd.

In order to evaluate the integrity of the membranes, they were initially soaked in de-ionised water for a period of 24 hours with the water being changed initially every hour for 4 hours, and then left overnight for the removal of conservational agents. After soaking, the clean water permeate (flux) was determined by filtering 1Litre of de-ionised water from each module under gravity while monitoring the time. The determined clean

water flux was used as a reference point when to evaluate the effects of the membrane fouling on flux rates.

3.4 EXPERIMENTAL PROTOCOL

For the purpose of this study an optimum pressure head for the operation of Bio-UF was determined to be 60 mbar due to operational constraints at higher pressures. This was done 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.

3.4.1 Experiments with the presence of Algae

a) 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.

b) The collected feed water was analysed for turbidity, total coliforms, E-coli and TOC. Thereafter, the raw water was fed into the three separate systems which were set up for analysing the performance of Bio-UF membrane system using Tugela River, Umbilo River and Umgeni River, respectively.

c) 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 (Figure 3.2).

d) The initial permeate volumes were collected every 10 minutes for the first 4 hours and thereafter, permeate was collected on an hourly basis during the day for 8 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.

e) The quality of the collected permeate from each system was further analysed for turbidity, E-coli, total coliforms and total organic carbon.

f) The experimentation was allowed to run for a minimum of three months for each set of runs. Thereafter, photographic and microscopic images were taken for evaluating the impacts of algae growth on the membrane using a 6 megapixel camera and Nikon Eclipse 80i, respectively.

3.4.2 Experiments without the presence of Algae

In the initial set of experiments, the growth of algae was observed on the system shown in Figure 3.2. Hence, in order to determine the impacts of algae on the performance of Bio-UF membrane system, the system shown in Figure 3.2 was covered with a foil to hinder the growth of algae and the following steps were repeated for a minimum of three months:

a) The feed water from different rivers was collected every two days for the first week and then every week for the duration of the first month after which the feed water was collected once in every two weeks for the rest of the experimental duration.

b) The quality of the collected feed water was analysed as described in section 3.2 prior to being fed into the three separate systems which were set up for analysing Tugela River, Umbilo River and Umgeni River, respectively.

c) 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 (Figure 3.2).

d) The initial permeate volumes were collected every 10 minutes for the first 4 hours and thereafter, permeate was collected on an hourly basis during the day for 8 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.

e) The quality of permeate was determined and the experimentation was allowed to run for a minimum of three months for each set of runs. Thereafter, photographic and microscopic images were taken for evaluating the impacts of algae growth on the membrane using a 6 megapixel camera and Nikon Eclipse 80i, respectively.

3.5 PERFORMANCE PARAMETERS AND ANALYTICAL METHODS

3.5.1 Operational Parameters

The main variable parameter for this study was the permeate flux. Permeate flux varied because of membrane fouling and this consequently reduces the flux rates.

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 and 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:

$$J = \frac{V}{A \times t} \qquad \textbf{[2.2]}$$

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 (hr.)

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

system was that of the membrane. The units for this parameter are litres per hourly area ($L/m^2.hr$).

Upon determining the flux rate using Equation 2.2, Equation 2.1 was used to verify that there was not change in the differential pressure across the membrane.

3.5.2 Analytical Methods

This section provides a brief description of the methods used for analysing the water quality, a detailed step-by-step procedure for each parameter is provided in Annexure A.

3.5.2.1 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. 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. Prior to every test, the meter was calibrated using the calibration procedure provided in Annexure A (HACH, 1997).

3.5.2.2 Chemical Oxygen Demand and Total Organic Carbon (TOC)

According to SANS 241:2011 standard, the most important chemical water quality test to be conducted is a TOC test, however due to lack of finances for purchasing the equipment during the start-up of this research, COD analysis were conducted and the results were then converted to TOC using the relationship between the amount of

oxygen required for the production of one CO_2 molecule as shown in equations (3.1) & (3.2) (Mara and Horan, 2003).

Chemical Oxygen Demand is a measure of the content of organic matter in the sample irrespective of whether the organic matter is biologically degradable or not. The determination of sample COD is based on oxidation of the sample by the digestion of the sample in a sealed tube containing potassium dichromate and sulphuric acid. This test comprises of a HACH COD reactor, 2mL pipette, COD digestion reagent vials, a vial rack and a HACH spectrophotometer (HACH, 1997).

From the obtained COD results, TOC concentration was determined using the ratio of COD to TOC as obtained from Equations 3.2 and Equation 3.2 (a) (Mara and Horan, 2003) :

$$C + O_2 \rightarrow CO_2 \qquad \textbf{[3. 1]}$$

From the above equation it can be noted that one carbon atom reacts with two oxygen atoms to form carbon dioxide. Thus for every 12 grams of carbon used, 32 grams of oxygen is required.

$$\therefore \frac{COD}{TOC} = \frac{32}{12} = 2.666 \qquad \textbf{[3. 2]}$$

And $$TOC = \frac{COD}{2.666} \qquad \textbf{[3.2(a)]}$$

3.5.2.3 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 water treatment. When consumed, these coliforms results in waterborne illnesses.

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 100mL

samples using IDEXX Defined Substrate Technology reagent products. This Quanti-Tray system comprises of a sealer, colilert-18 medium, a sterile 100mL container, trays, an incubator and UV light (IDEXX Laboratories 2013).

b) Bio-layer Analysis

The presence of a biofilm layer was determined using the optical microscope which was operated at the wastewater research laboratories at the Durban University of Technology. The microscopic images were analyses at a magnification of 100x and the images were taken using a Nikon Eclipse 80i camera.

3.6 NON-IDEALITIES

I. The temperature of the laboratory at which the experiments were conducted could not be controlled.

II. The maximum head that could be used in the system was 6 meters since anything above that limited the refilling of the water in the make-up tank.

III. The evaporation of permeate from the collection beaker during the conduction of the experiments could also not be accounted for due to lack of finances to use an online permeate measuring equipment.

IV. The cost involved in the collection of feed water could not be eliminated hence fresh feed could not be available on a daily basis or every two days.

V. The cost involved in conducting full water analysis as per SANS 241:2011 could not be eliminated. Hence only the parameters used for the evaluation of the system's performance were conducted.

VI. The impacts of the system being air locked could not be avoided, since this is only noticeable during a run.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

This chapter presents the results obtained during the investigation. Section 4.2 discusses the performance of the membrane in terms of repeatability; while Section 4.3 presents the performance of Bio-UF on a range of selected waters in terms of turbidity, TOC, total coliforms and E-coli removal; flux stabilisation and the .

4.2 REPEATABILITY OF RESULTS

In order to validate the results that were obtained from the study, raw water from Umgeni River was randomly selected and three runs were conducted. Figure 4.1 shows the repeated measurements for the data collected to determine the membrane flux profile obtain for Umgeni River.

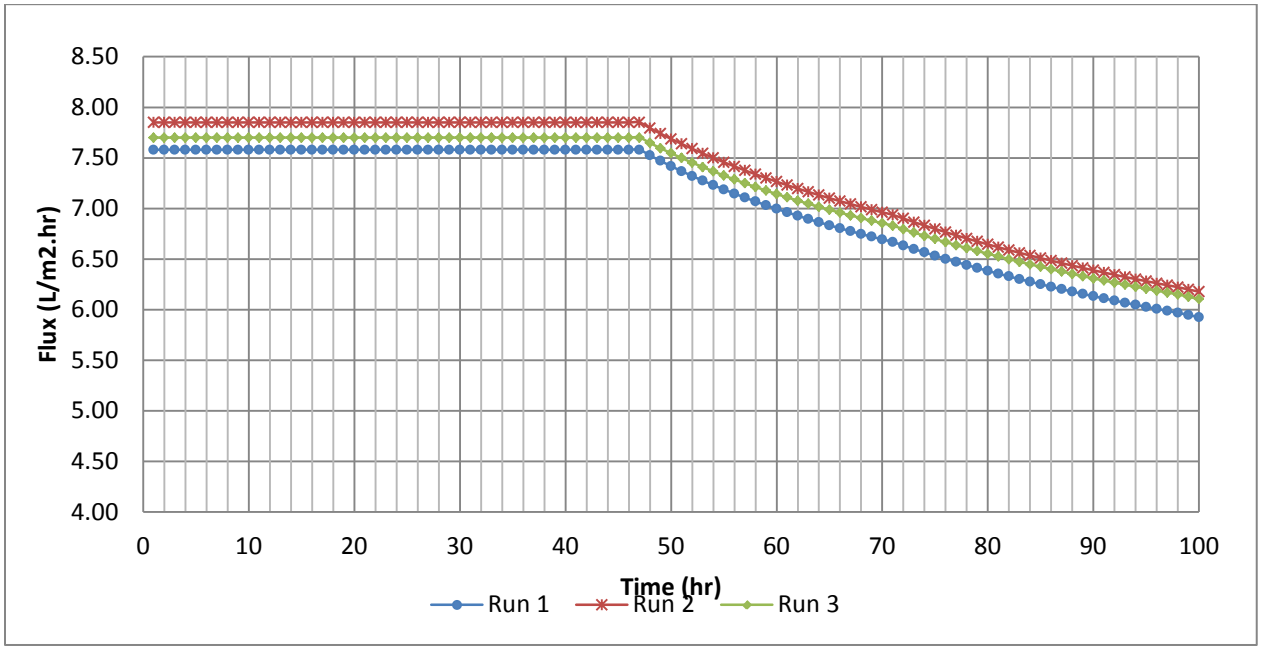


FIGURE 4.1: Flux – Time profile obtained for Umgeni river water after running on a Bio-UF membrane system.

From Figure 4.1, it can be noted that the initial fluxes were in the range of 7.70 and 7.85 LMH for the three runs shown. These fluxes were noted to be stable for the first 46 hours of membrane operation with a slow decline noted thereafter. The observed decline in flux was noted to be due to the occurrence of the fouling layer on the membrane surface. The percentage variance for the data obtained from the three runs was found to be in the range of 4% as shown in Table 4.1:

- Data

TABLE 4. 1: Flux rates for Umgeni River at different hours of operation.

Time	Run 1	Run 2	Run 3
Flux at 40 hours	7.58	7.85	7.70
Flux at 80 hours	6.38	6.65	6.55

- 40 hours of operation: $mean = \frac{7.58 + 7.85 + 7.70}{3} = 7.71$

$$Std..Dev = \sqrt{\frac{(7.58 - 7.71)^2 + (7.85 - 7.71)^2 + (7.70 - 7.71)^2}{2}} = 0.135$$

$$\%\,\text{var}\,ience = \frac{2 \times 0.135}{7.71} \times 100 = 3.5\%$$

- 80 hours of operation: $mean = \frac{7.58 + 7.85 + 7.70}{3} = 7.71$

$$Std..Dev = \sqrt{\frac{(6.38 - 6.52)^2 + (6.65 - 6.52)^2 + (6.55 - 6.52)^2}{2}} = 0.137$$

$$\%\,\text{var}\,ience = \frac{2 \times 0.137}{6.52} \times 100 = 4.2\%$$

Hence it can be concluded that the flux repeatability was good based on the percentage of variance being below 5%.

4.3 THE EVALUATION OF THE PERFORMANCE OF BIO-UF MEMBRANE PROCESS ON A RANGE OF SOUTH AFRICAN SURFACE WATER

The performance of the Bio-UF membrane system was evaluated based on the permeate quality as well as the ability of the membrane to form stable fluxes.

The performance of Bio-UF system in terms of the water quality was evaluated based on the system's ability to produce water that has turbidity, total organic carbon (TOC), Total coliforms and E-coli concentrations that are acceptable according to SANS 241:2011.

For the evaluation of the system’s ability to produce stable fluxes, the performance of the system on three rivers with different water quality was evaluated. For each river, three sets of experimental runs were conducted and the displayed results are average results obtained from the three runs.

The performance of the Bio-UF membrane system in the presence of algae growth was also investigated. This was conducted by performing three sets of experiments for each of the rivers under direct sunlight which induces the algae growth. However, the displayed figures for impacts of algae on flux stabilisation in Section 4.4.3 are for the average fluxes obtained from those three runs.

4.3.1 Raw water quality

Table 4.2 presents the raw water quality range in terms of concentrations for total coliforms, E-Coli, total organic carbon and turbidity.

TABLE 4. 2: Raw water quality range for the different rivers used.

RIVER	COLIFORMS COUNTS (CFU/100mL)	E-COLI COUNTS (CFU/100mL)	TOC (mg/L)	TURBIDITY (NTU)
Tugela	1947 – 12033 above 24196 (once)	692 – 3720 above 24196 (once)	10 - 29	18 – above 1000
Umbilo	203 – 17329	10 – 15531	2 - 18	4 – 17.2
Umgeni	248 – above 24196	80 – 2010	16 - 108	2 - 14

It can be noted that Tugela River had the highest turbidity when compared to Umgeni River and Tugela River throughout the duration of the experimentation. Umgeni River was noted to be having the highest TOC concentrations when compared to other rivers while Umbilo River had high E-coli concentrations on average.

4.3.2 Product quality

4.3.2.1 Turbidity removal

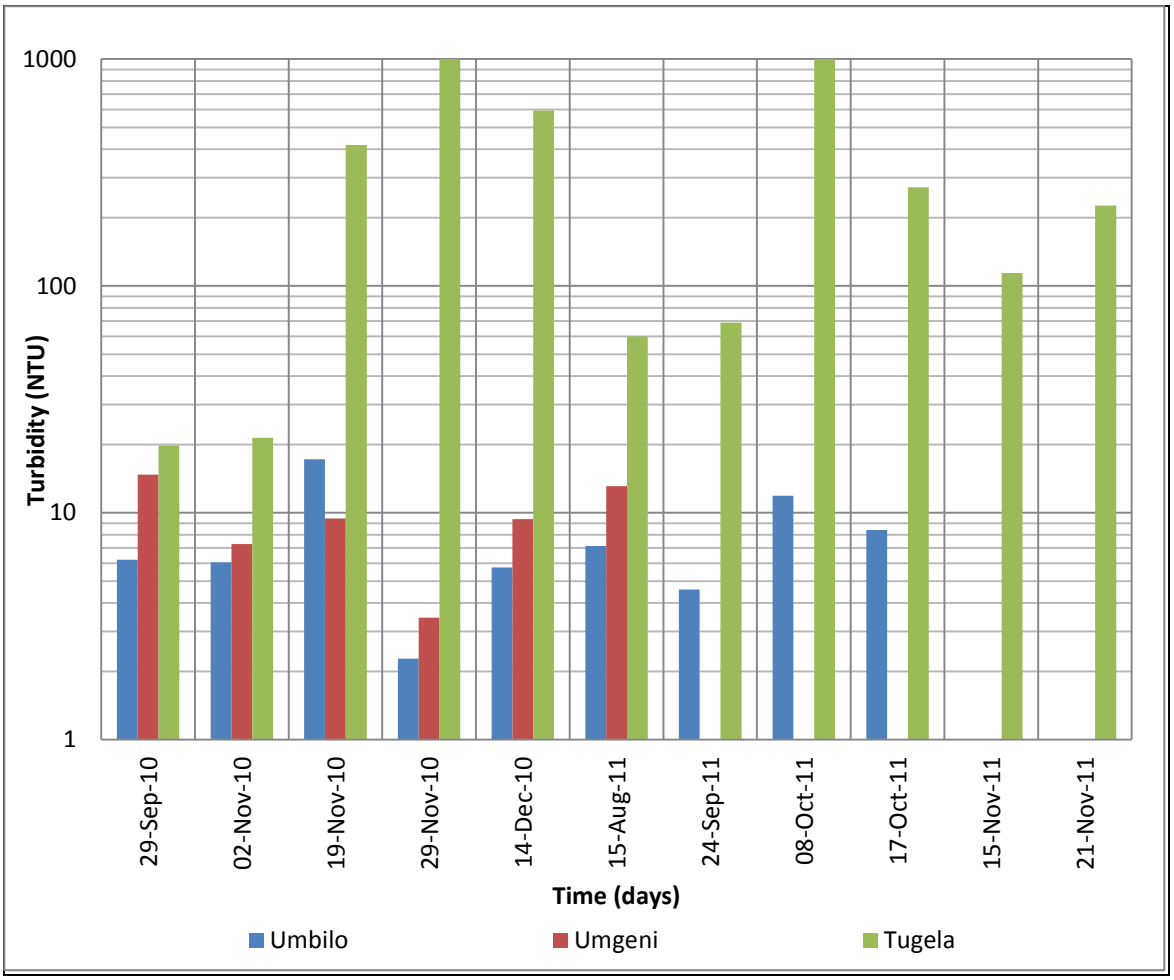


FIGURE 4.2: Raw water Turbidity-Time plot obtained from different river systems

Figure 4.2 shows that Tugela River had the highest turbidity throughout the experimentation period, with turbidity as high as above 1000 NTU and that Umbilo river was the river with the lowest turbidity during most of the experimentation period. Since Tugela River had the highest turbidity it was decided that tests should be conducted for a longer period compared to other rivers with the aim of evaluating the possibilities of final turbidity breakthrough.

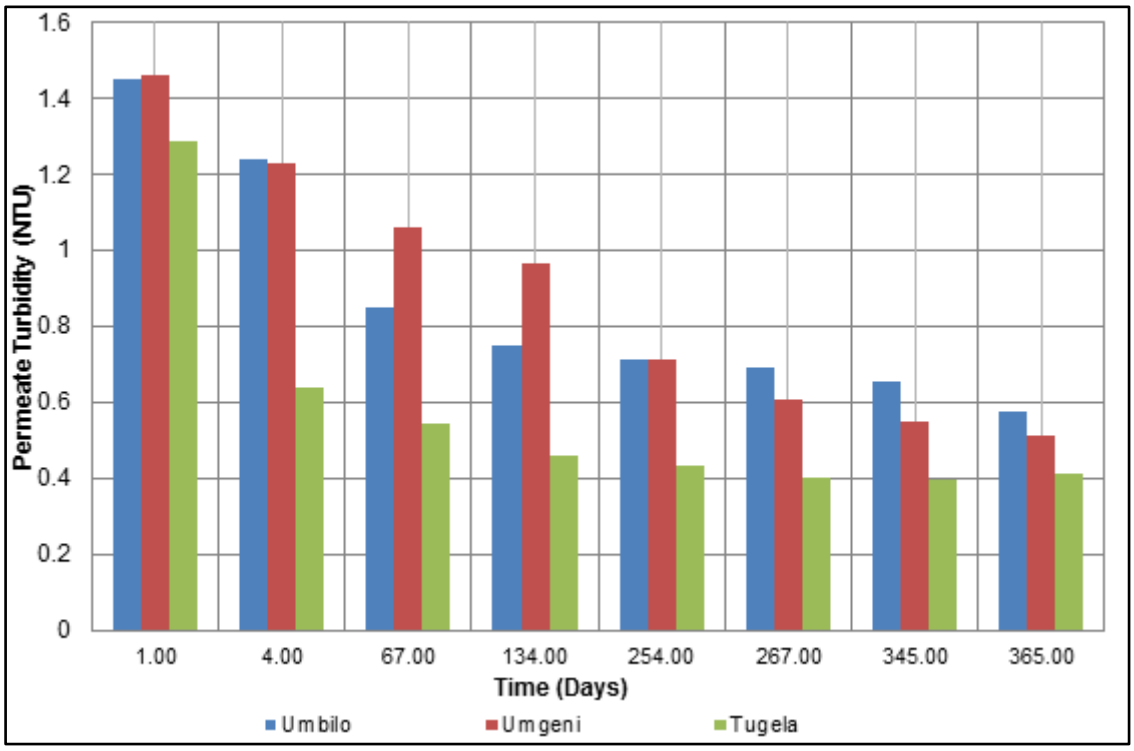


FIGURE 4.3: Permeate Turbidity-Time Plot obtained for the different rivers

Figure 4.3 shows that during the first day of operation, the systems were producing turbidity which ranged between 1.2 and 1.5 NTU even for Tugela River which had an extremely high feed turbidity. A steady continuous decline in turbidity is also observed regardless of the increase in feed turbidity (Figure 4.2). It can also be noted that the system is able to produce turbidity of less than 5 NTU from the first run which is in compliance with the WHO 2008 guidelines. The system is also able to produce turbidity of less than 1 NTU after extended periods of which is in compliance with the SANS 241:2011 standard for turbidity operational limit of no more than 1 NTU.

4.3.2.2 Removal of organics

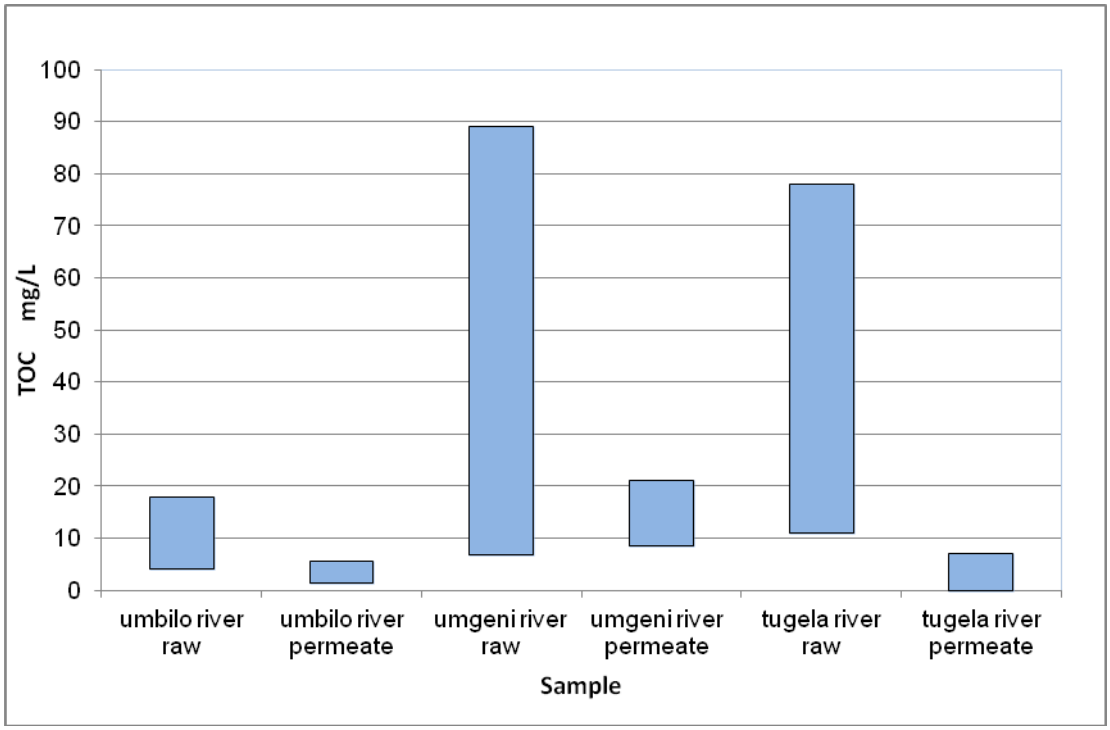


FIGURE 4.4: Raw water and permeate TOC plot for different rivers

Figure 4.4 shows the variation between the minimum and maximum Total Organic Carbon (TOC) concentrations experienced in the feed (noted as raw) and permeate water for the duration of the experiments. The raw water TOC for Umbilo River was noted to be in the range of 4 –18 mg/L while that of Umgeni River was 8 - 89 mg/L and Tugela River had 10 – 79 mg/L. It can also be noted that the feed water from Umgeni River had the highest TOC during most of the experimentation with Umbilo River having the lowest.

The Bio-UF membrane system is noted to be having a good removal for total organic carbon i.e. permeate for Umbilo River and Tugela River were below 10 mg/L throughout the experimentation. This was noted to be in compliance with SANS 241:2011 standard.

It can be noted as well that permeate TOC for Umgeni River was above 10 mg/L for most of the experimentation period. This could have been due to the high concentration of TOC's in the river's raw water.

4.3.2.3 Total coliforms counts in raw water

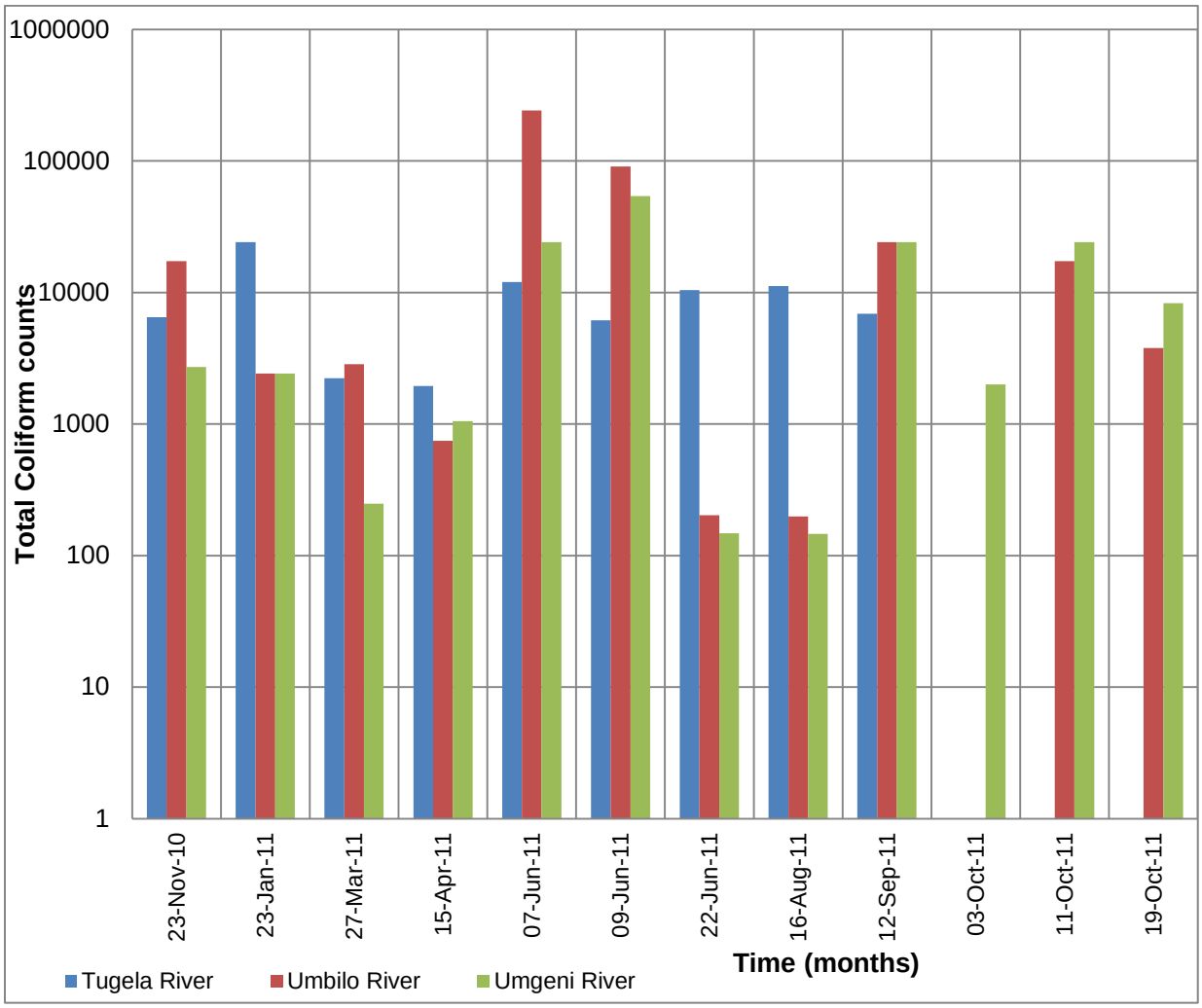


FIGURE 4.5: Raw water total Coliforms-Time plot obtained for different rivers

Figure 4.5 shows that Umbilo River had high concentrations of total coliforms for most of the experimentation period, followed by Umgeni River. Rain was noted to have high impacts on total coliforms as samples taken on and after a rainy day were found to be having high coliform counts, this can be noted from Umbilo River and Umgeni River on samples taken on 07th and 09th of June 2011as rainfall was experienced the 07 June 2011. It should be noted that for Tugela River, the samples for the 07th June 2014 were taken in the morning prior to the start of the rain.

4.3.2.4 Total E-coli counts in raw water

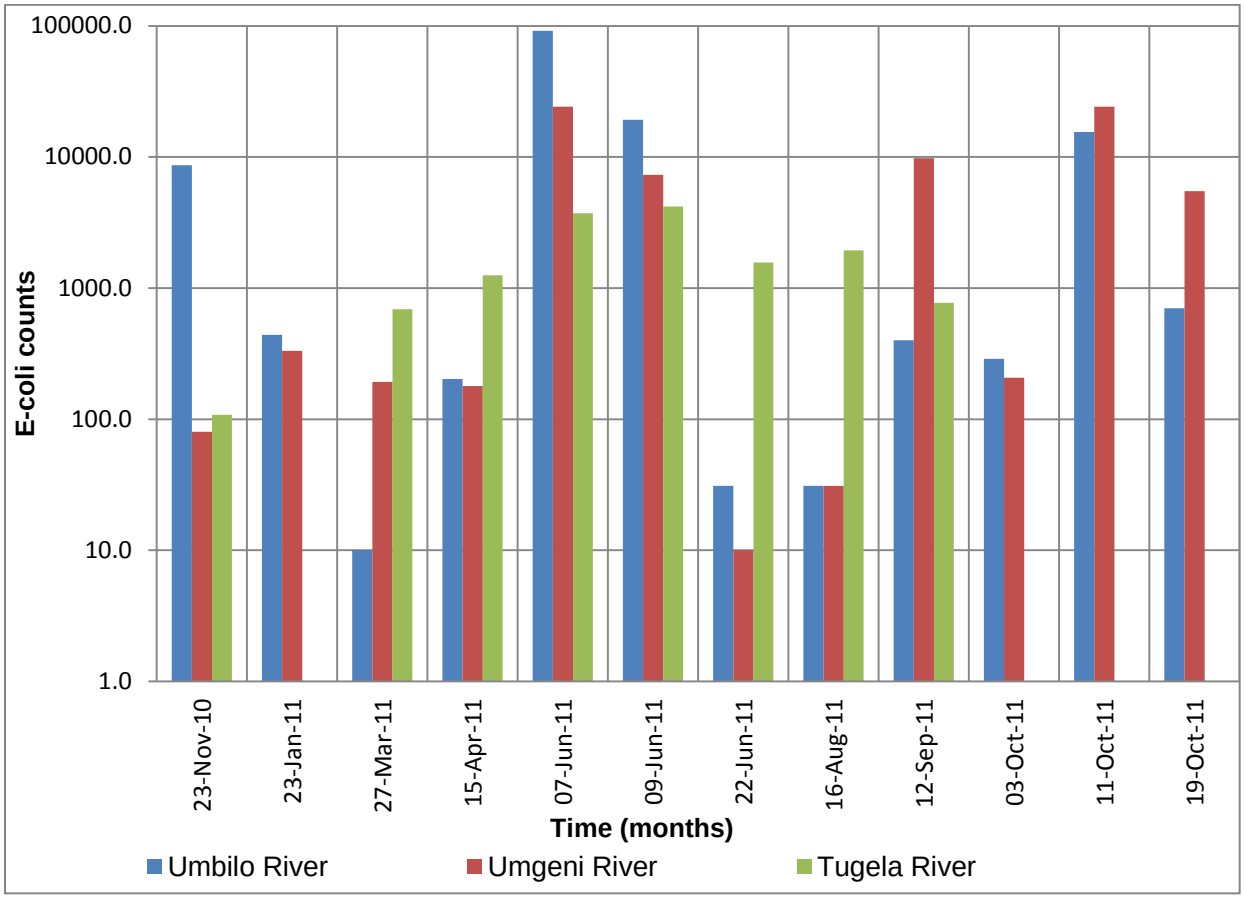


FIGURE 4.6: Raw water E-coli-Time plot for different rivers

From Figure 4.6, it can be noted that Umbilo River had the highest E-coli concentrations on average followed by Umgeni River. Again on 07 June 2011, high E-coli concentrations can be observed. The results obtained in Figure 4.6 were found to be corresponding to those obtained in Figure 4.5 in terms of concentration variations. For example, when looking on the 7th of June 2011, it can be observed that high concentrations of E-coli and Total coliforms were experienced due to the rain event which occurred prior to sampling.

4.3.2.5 Removal of E-coli and Coliforms

TABLE 4. 3: Microbiological Permeate Quality obtained for different rivers.

River	Permeate Bacterial (Count per 100mL sample)	
	E-coli	Total Coliforms
Umbilo	0	0
Umgeni	0	0
Tugela	0	0

Table 4.3 shows the results obtained for the permeate analysis in terms of microbiological analysis. The permeate E-coli and Coliforms test were conducted twice a week for the first month of experimentation and thereafter, once a week for the remaining months. It can be noted that the Bio-UF membrane system provides permeate that is free of E-coli and Coliforms from all samples which were analysed in the duration of the experiments regardless of feed concentrations. This was found to be corresponding to WHO 2008 guidelines as well as SANS 241:2011 standard which states that the E-coli should not be detectable and that the total coliform should be ≤10 in drinking water.

4.3.3 Flux-time profiles

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. These three rivers which were used for this evaluation are Umgeni River, Umbilo River and Tugela River. For this investigation, a system will be regarded stable if it produces decline in flux rates that differs from that of normal dead-end filtration mode.

4.3.3.1 Creteria for the identification of stable fluxes

For the purpose of this study, the trends obtained for the flux rates will be compared to those obtained by Peter-Varbanets et.al. (2010) and regarded stable if a linear relation exist between $\frac{t}{V}$ vs V as described in Section 2.5.2.

4.3.3.2 Flux Stabilisation

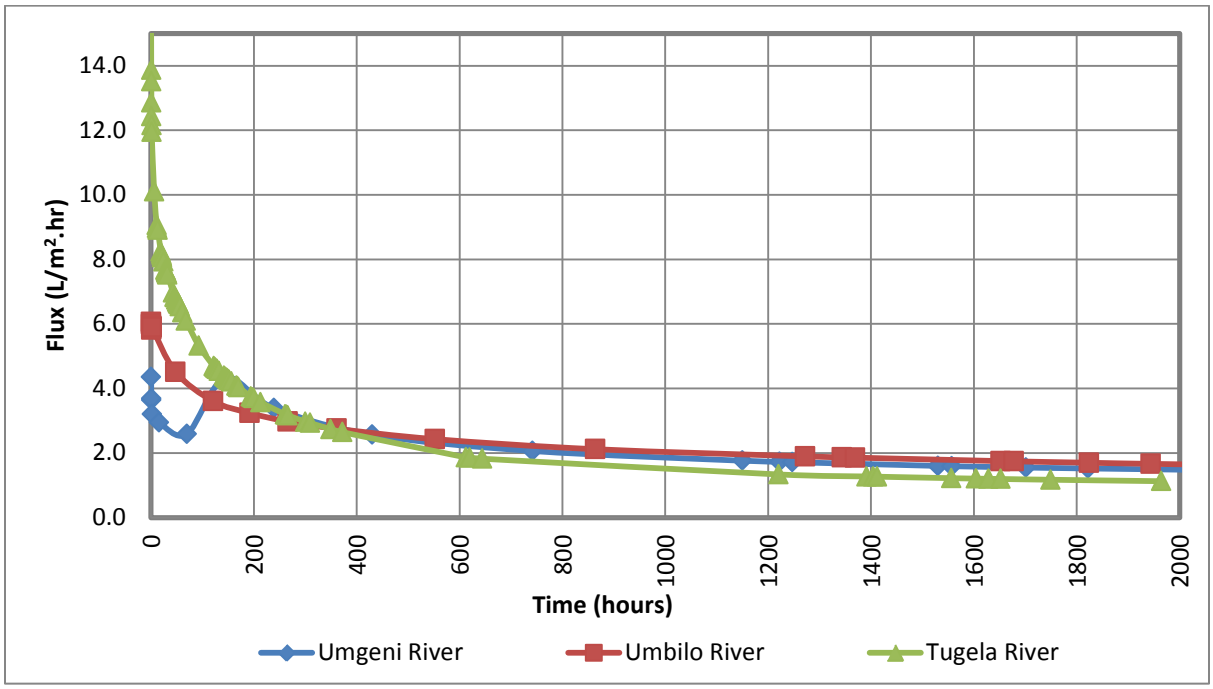


FIGURE 4. 7: Flux – Time plots obtained during the evaluation of Bio-UF

From Figure 4.7, it can be noted that the initial flux for Umgeni River is 4.4 LMH followed by a sharp decrease to 2.6 LMH. Another sharp increase in flux to 4.3 LMH is also observed between 100 – 200 hrs of operation. Thereafter, the sharp decline continues to 1.9 LMH after 1000 hours. Stabilisation in flux appears to be occurring at approximately 1.5 LMH during a period of 1200 hrs and 2000 hrs of operation. The sudden sharp decrease in flux observed for Umgeni River within the first 50 hrs of operation, could have been brought about by the fact that the system was air locked.

The initial flux for Umbilo River is approximately 6 LMH and this is followed by a sharp decrease in flux rate to 2.8 LMH for the first 500 hrs. Thereafter, there is a slow decline to approximately 1.7 LMH at 1600 hrs. A very slow decline in flux rate is noted to be continuing throughout the experimentation period.

For Tugela River, the initial flux is greater than 14 LMH and this river also experiences a sharp decline in flux during the first 500 hrs to approximately 2.6 LMH. A very slow decrease to approximately 1.3 LMH at 1400 hrs after which there appears to be stabilisation of flux for the remaining hours of the experimentation.

The observed trends for the flux profile in Figure 4.7 were noted to be similar to those noted by Peter-Varbanets *et al.* (2010) who clasified the trends as stable fluxes.

In order to understand the concept of flux stabilisation clearly, Figure 4.7 was further analysed by plotting data for the duration of 600 hrs to 2000 hrs as shown in Figure 4.8. From the obtained results, it was noted that flux stabilisation was not occurring and that a slow decline in flux was noticeable from 1200 hrs.

From Figure 4.8 (b), Umgeni River appears to be yielding a different response to that of Tugela River and Umbilo River. Hence it becomes necessary to evaluate if the obtained responses from the three rivers used were of any difference from normal dead-end filtration response.

Figure 4.9 shows the trends obtained when plotting t/V vs V for Umbilo River (Figure 4.9 (a) and Tugela River (Figure 4.9 (b) for the duration of 1200 hrs to 2000 hrs of operation

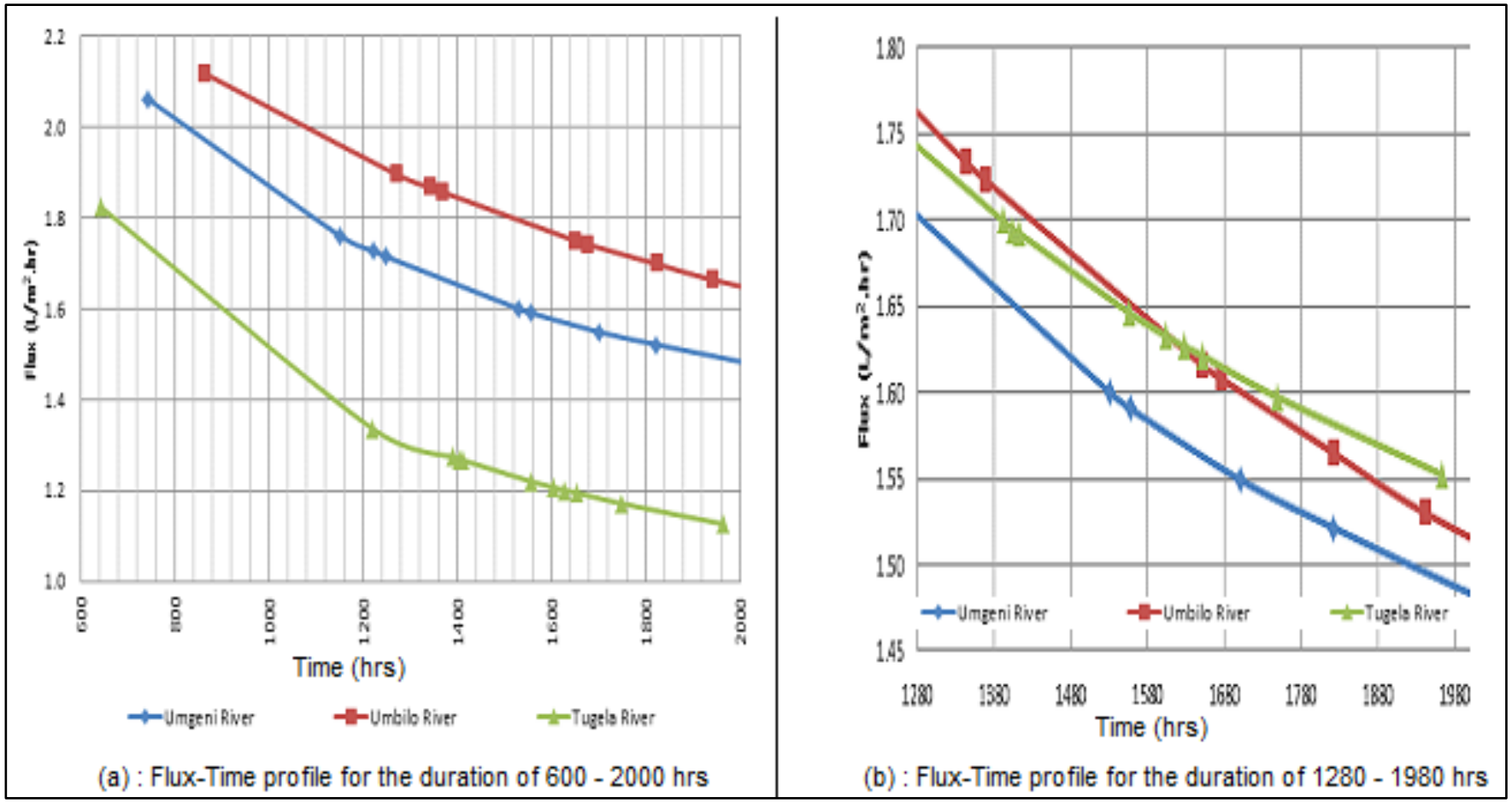
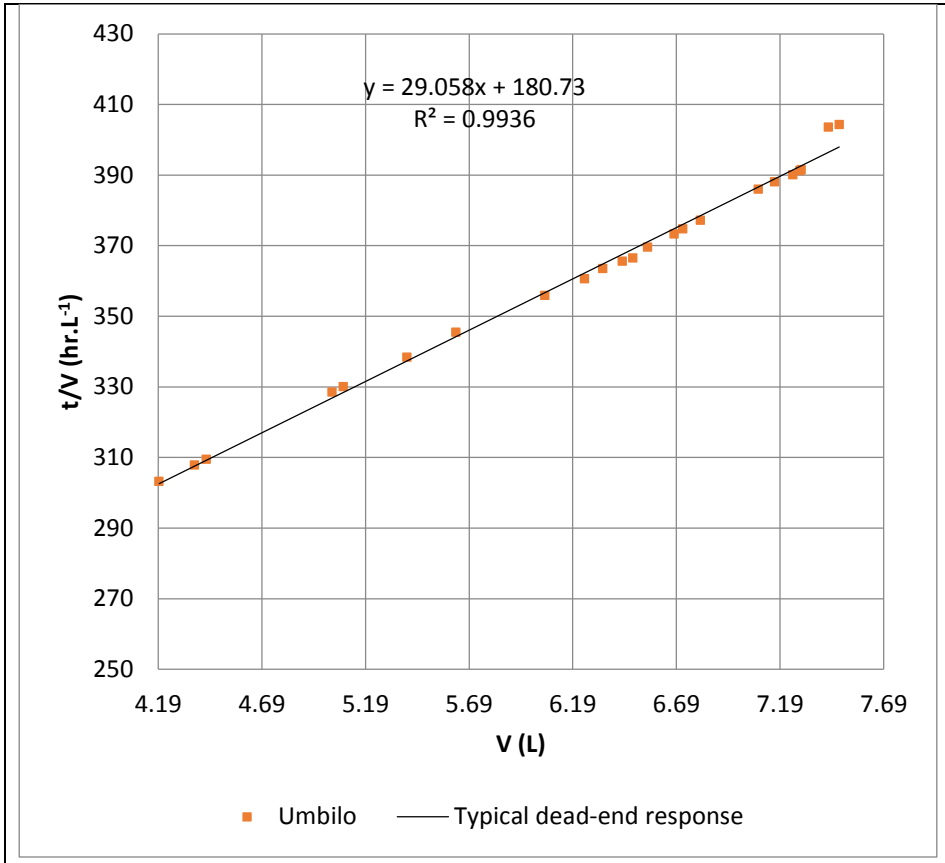
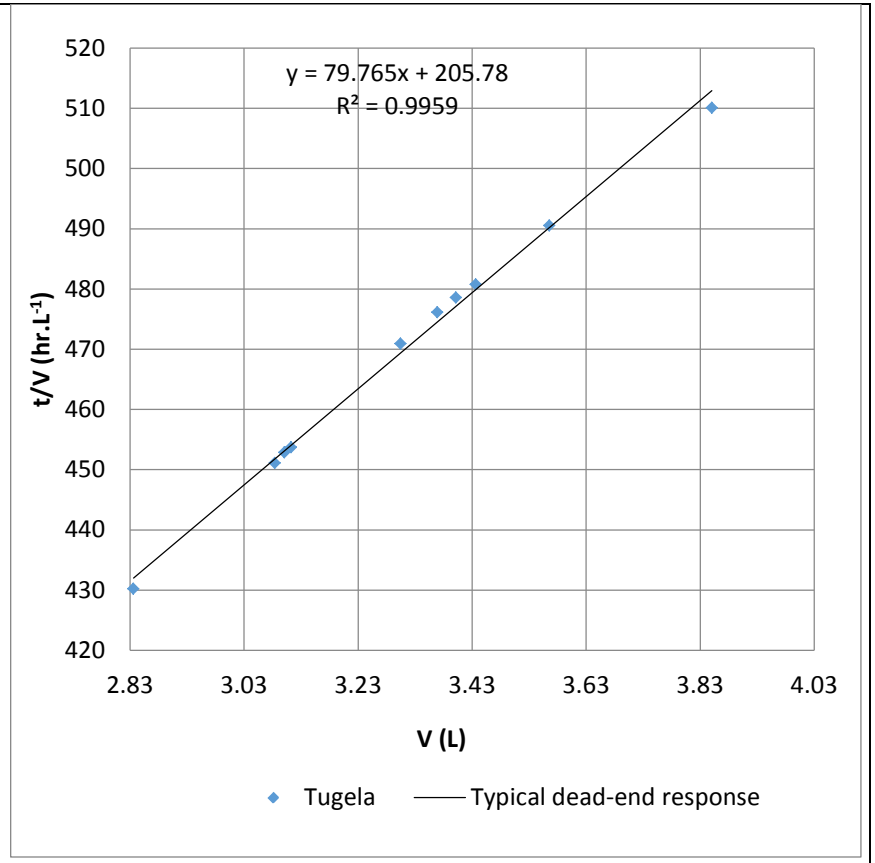


FIGURE 4. 8: Flux-Time plots obtained during the stabilisation zone for the three rivers



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



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

FIGURE 4. 9: Dead-end filtration curve response for Umbilo River (a) and Tugela River (b)

When looking at Figure 4.9, it can be noted that both Umbilo River (Figure 4.9 (a)) and Tugela River (Figure 4.9 (b)) yields a similar response to the expectant typical response for a dead end ultrafiltration membrane system operated under constant pressure. This implies that there was actually no stabilisation of flux noted from Figure 4.7 but rather a normal dead-end decline in flux (Coulson and Richardson, 2003).

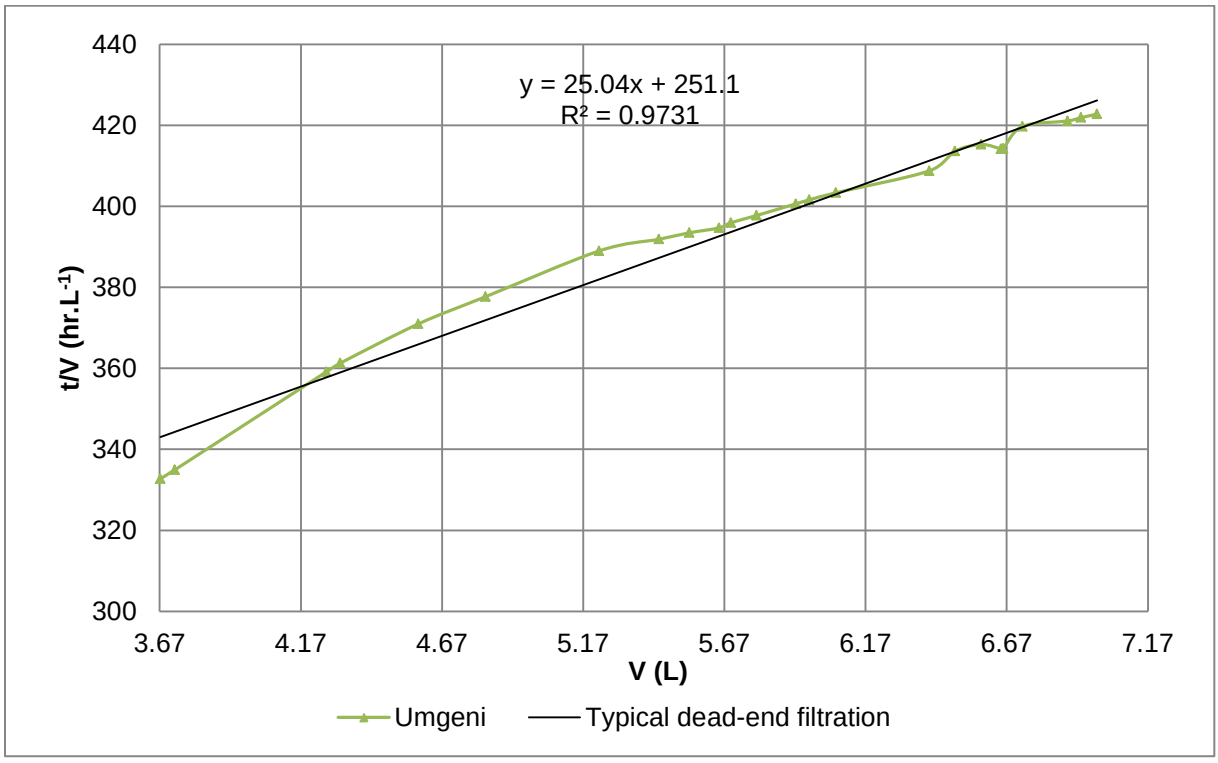


FIGURE 4. 10: Dead End filtration curve response for Umgeni River

From Figure 4.10, it can be observed that the response for Umgeni River seems to be deviating from the normal dead end response as described by Coulson and Richardson, (2003). This response was also noted to be deviating from that obtained for Tugela River and Umbilo River in Figure 4.9.

From Figure 4.4, it can be noted that Umgeni River has the highest organic content compared to the other rivers and in Figure 4.5, it can also be noted that Umbilo River has the highest Total coliforms count. From these figures in comparison with Figure 4.8, Figure 4.9 and Figure 4.10, it can be noted that there appears to be a relationship

between the rate of decline in flux and the water quality. From Figure 4.4 Umgeni River has the highest organic content, in Figure 4.5 and Figure 4.6, the same river has the second highest concentrations of bacterial content while in Figure 4.2, Umgeni River has the raw water turbidity of less than 20 NTU. From these mentioned trends and those noted for the Umbilo River and Tugela River, it can be observed that water with high bacteria count, low turbidity and high organic content seem to be producing slower declining flux rates when compared to the water of low turbidity, high bacteria count and low organic content.

Hence, from the above obtained results, it can be deduced that stabilisation of flux rate is not obtainable when using the Bio-UF membrane system on the three rivers used for this investigation. However, it can also be deduced that the quality of the raw water appears to play a major role in the system's ability to reduce the rate of flux decline during a dead-end filtration mode.

4.3.4 Effects of Algae growth of flux

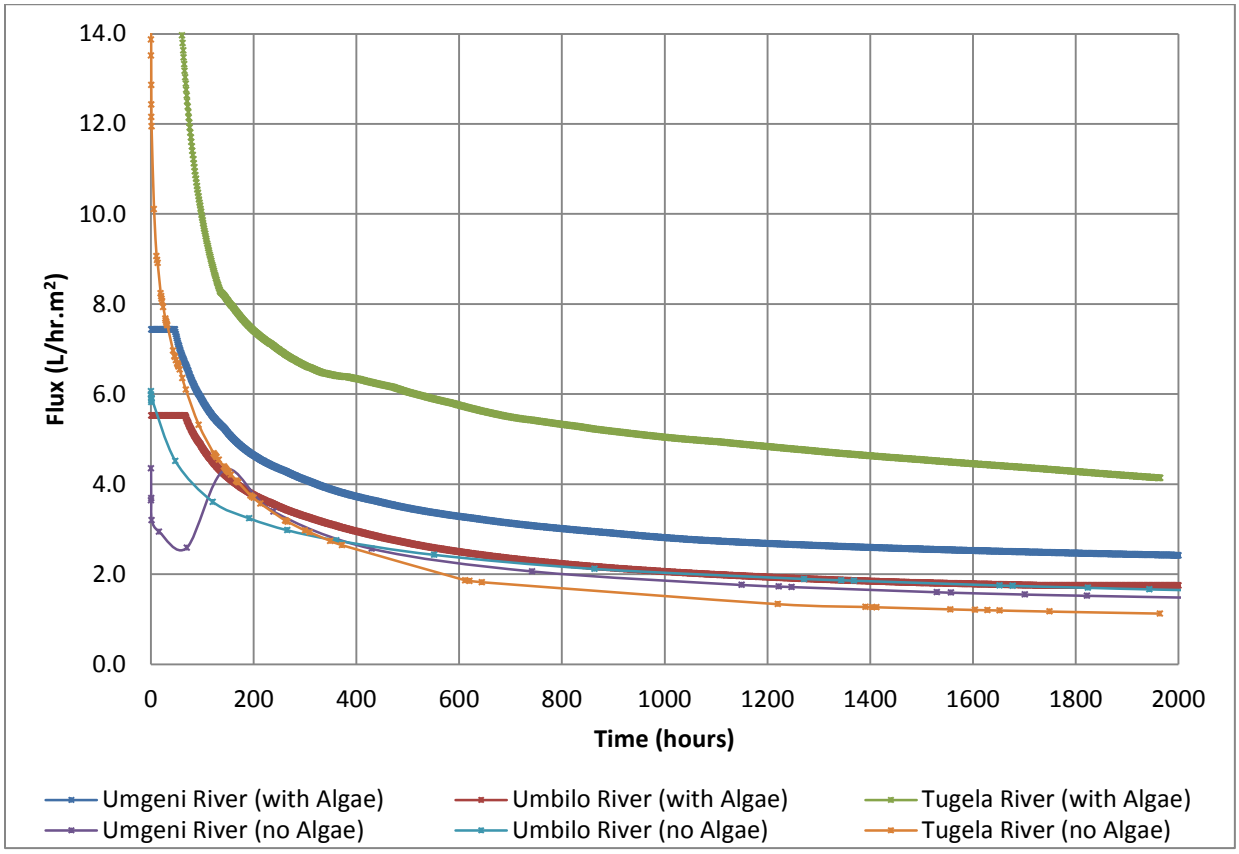


FIGURE 4. 11: Flux-Time plots obtained on South African waters using Bio-UF with and without the presence of algae growth

Figure 4.11 shows that the system for Umgeni River that was operated without algae growth had an airlock which resulted in a sharp decrease in flux for the first 70 hrs. It can also be observed that all the system that were operated in the presence of algae growth produced higher flux rates than those operated without the presence of algae growth. This implies that the presence of algae growth during the use of a Bio-UF membrane system results in increased flux rate. However, this finding needs to be further investigation in order to identify the courses of the obtained response.

4.3.4.1 Visual observations of Algae

This subsection outlines the photographic and microscopic images obtained from evaluating the fouling layer after each experimental set-up.

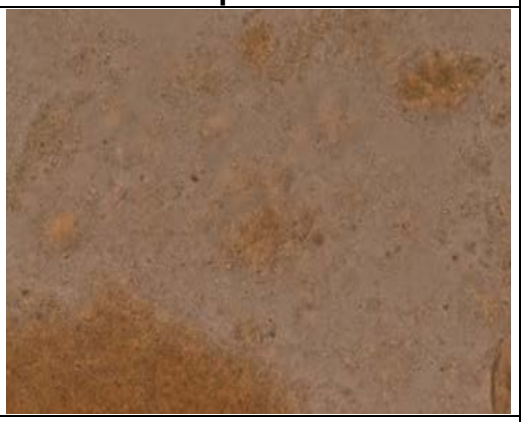
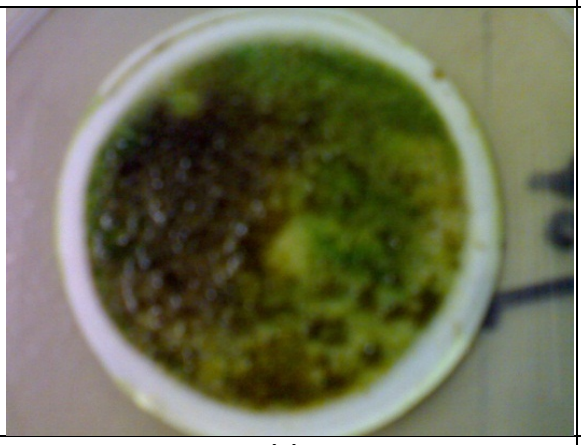
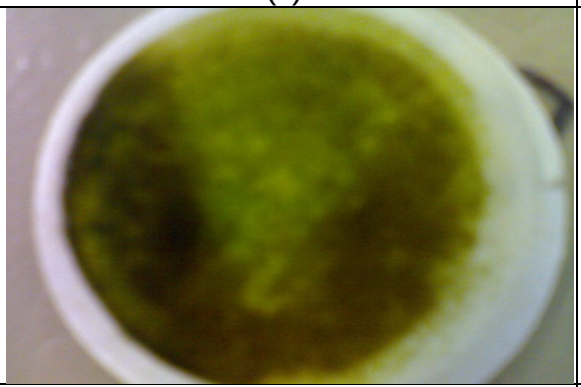
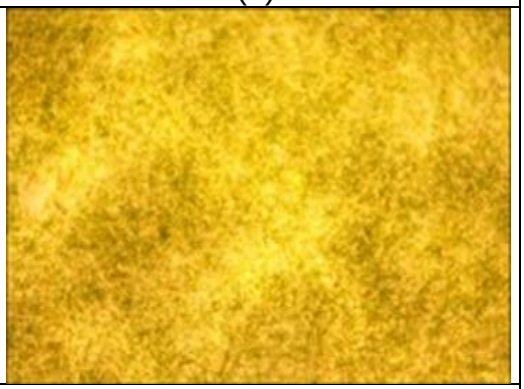
RIVER	Photographic images using a 6 megapixel camera	Microscopic Analysis using Nikon Eclipse 80i camera
Tugela		
	(a)	(b)
Umbilo		
	(c)	(d)
Umgeni		
	(e)	(f)

FIGURE 4. 12: Photographic images of UF membranes with a fouling layer for runs with algae growth

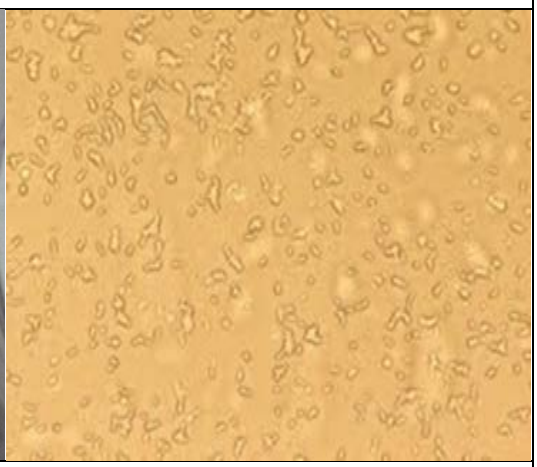
RIVER	Photographic images using a 6 megapixel camera	Microscopic Analysis using Nikon Eclipse 80i camera
Tugela		
	(a)	(b)
Umbilo		
	(c)	(d)
Umgeni		
	(e)	(f)

FIGURE 4. 13: Photographic images of UF membranes with a fouling layer for runs without algae growth

Figure 4.12 and Figure 4.13 presents the observations noted when operating the bio-UF membrane system with and without the presence of algae growth, respectively. From Figure 4.12, it can be noted that all rivers had algae growth on the membranes and it can also be noted that Tugela River also had deposits of mud on the membrane surface (Figure 4.12 (a) and (b)).

From Figure 4.13, it can be noted that no algae growth was observed and that Tugela River, (Figure 4.13 (a)), and Umbilo River (Figure 4.13 (c)) were having more suspended matter on the surface of the membrane compared to Umgeni River. A protozoa was also noted from Umbilo River (Figure 4.13 (d)). According to Totora (1995) and CSIR (2010), protozoa feed on micro-organisms. This could explain the obtained trends for flux in Figure 4.7 and Figure 4.9 even though the river had low turbidity as outline in Table 4.2.

In Figure 4.13 (e) and (f)) Umgeni River can be noted to be having a very thin fouling layer compared to the other rivers. When operating the system with algae growth, it can also be noted that there is a fouling layer visible below the algae growth (Figure 4.12 (e)).

4.3.5 Summary

From the obtained results, it was noted that Umbilo River and Tugela River do not produce stable fluxes. The decline in flux rates from these two rivers was noted to be similar to that of normal dead-end filtration. However, it was also noted that the decline in flux rate for Umgeni River was very slow (Figure 4.10) when compared to other two rivers (Figure 4.9) and that the river yielded a response which varied from the normal dead-end ultrafiltration system response. This could have been due to the fact that the raw water from Umgeni River had low turbidity and high TOC concentrations for the duration of the experimentation (Table 2, Figure 4.2).

The Bio-UF system is noted to be able to treat surface water to the required standards for SANS 241:2011 in terms of turbidity, total coliforms and E-coli removal (Figure 4.3 and Table 4.3). It was also noted from Figure 4.4 that the concentrations of TOC in the

raw water plays a major role in the system's ability to produce permeate that is complaint to SANS 241:2011 standard of ≤ 10 mg/L

Figure 4.11 show that the presence of algae growth in the Bio-UF membrane system results in the increased the flux rates. From Figure 4.12 it can be noted that when the system is operated in the presence of algae growth, there is more accumulation of suspended matter than when operated without algae growth (Figure 4.13). It was also noted that bio-fouling occurs even in the presence of algae (Figure 4.12 (b) and Figure 4.12(c)).

CHAPTER 5

CORRELATION BETWEEN FEED WATER QUALITY AND THE RATE OF FLUX DECLINE

5.1 INTRODUCTION

According to the study conducted by Peter-Varbanets *et al.,* (2010) the micro-organisms present in the feed form a biological layer on the membrane surface and thus enhance the stabilisation of flux. In that study, the stabilisation of flux during the use of a bio-UF membrane system is stated to be directly linked to the presence of micro-organisms in the feed which enhances the formation of a biological layer.

From the results presented in chapter 4, it can be observed that stable fluxes are not obtainable. However, the rate of flux decline obtained for Umgeni River seemed to deviate from normal dead-end (Figure 4.10). In section 4.3.2, the raw water from Umgeni River was also noted to be having the highest TOC and the second highest E-coli concentration when compared to Umbilo River and Tugela River. These results outline that there seems to be a correlation between feed water quality and the rate of flux decline, (Section 4.3.2, 4.3.3 and 4.3.4). From the results obtained in Figure 4.13, there is no doubt that there is a bio-layer forming on the surface of the UF membranes. However, it could not be concluded that the flux response noted for Umgeni River (Figure 4.10) was brought about by the presence of micro-organisms in the feed water. Therefore, there was a need to further investigate the relationship between feed water and flux rate from the results obtained in chapter 4; hence the following hypothesis was drawn:

Hypothesis:

- "The presence of feed water with 1000 or more bacterial counts per 100 mL sample, turbidity that is ≤ 15 NTU and TOC concentrations that are ≤ 50 mg/L enhances slow decline in flux rates during the operation of a gravity driven Bio-UF"

Hence this chapter focuses on investigating the correlation between feed water quality and flux rates. It is structured as follows:

- Section 5.2 presents the methodology used.
- Section 5.3 presents the results and discussions obtained from the investigation.

5.2 METHODOLOGY

5.2.1 Feed water characteristics

In order to evaluate the above mentioned hypothesis, raw water from Umgeni River was used since the river was noted to yield a response which deviated from normal dead-end response (Figure 4.10). Three Bio-UF membrane systems were set up as shown in Figure 3.2 and feed water of different concentrations for turbidity, micro-organisms and total organic carbon was used as outlined in Table 5.1.

TABLE 5.1: Feed Water quality compositions for evaluating the hypothesis.

System No.	Bacteria	Turbidity	Organics
1	Low	Low	High
2	High	Low	High
3	Low	High	High

It is not known which type of bacteria or organic carbon enables slow decline of flux, hence it was difficult to make-up artificial water. However, since the micro-organisms could be easily cultured within the institution and a microfiltration membrane is known to be unable to remove 100% of TOC (Beier, 2010 and Suarez, 2013). For the purpose of this study, the turbidity and bacterial concentrations for the three systems were varied and the compositions are outlined in Table 5.1. These compositions were obtained as follows:

5.2.1.1 System No.1

Raw water was obtained from Umgeni River and fed into a Woven Fibre Microfiltration (WFMF) system for the removal of turbidity and reduction of bacterial counts. The WFMF is unable to remove 100% of the TOC, hence this permeate was poured into system No.1.

5.2.1.2 System No.2

The E-coli was cultured from the E-coli inoculum which was obtained from the Department of Biotechnology at the Durban University of Technology. The culturing of E-coli was as stipulated by Achisa (2013). The WFMF was also used for the pre-treatment of the raw water from Umgeni River prior and permeate from the WFMF was spiked with the cultured E-coli in order to yield the required composition for system 2 in Table 5.1.

5.2.1.3 System No.3

100 grams of clay was collected from Umgeni River. The raw water sample collected from the river was pre-treated using the WFMF system. WFMF permeate was spiked with the 100 g of clay to yield the required composition for system 3 in Table 5.1.

Table 5.2 outlines the targeted concentrations in each of the systems for the duration of the investigation.

TABLE 5.2: Targeted feed water quality for each of the systems.

System No.	Bacteria (E-coli counts/100 mL sample)	Turbidity (NTU)	Organics (mg/L)
1	≤100	≤ 5.0	≥ 70.0
2	≥30000	≤ 5.0	≥ 70.0
3	≤ 100	≥ 20.0	≥70.0

5.2.2 Experimental protocol

1. A minimum of 4 x 25L containers of feed raw water was collected from Umgeni River every four days for the first two weeks and then once every week thereafter. However, due to lack of resources, in some cases the raw water samples was used for up to two weeks.
2. The quality of the collected raw water was evaluated in terms of turbidity, total organic carbon, E-coli and total coliforms.
3. The collected raw water was then fed into a WFMF system for the removal of suspended matter.
4. The quality of permeate from the WFMF system was evaluated in terms of turbidity, E-coli, TOC and total coliforms.
5. Permeate from the WFMF system was the feed into system No.1, No.2 and No.3 as describe in section 5.2.1.1, 5.2.1.2 and 5.2.1.3; respectively.
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 to calculate the flux during that period assuming flux was constant at night.
7. The experimentation was allowed to run for a minimum of 30 days.

5.3 RESULTS AND DISCUSSIONS

5.3.1 Water quality

The raw water collected from Umgeni River was analysed for turbidity, total carbon content, E-coli and total coliforms. Table 5.3 outlines the range of the raw water quality for the duration of the experimentation.

TABLE 5.3: Actual feed water quality for Umgeni River.

Range	RAW WATER			
	E-coli counts/100mL	**Total Coliforms counts/100mL**	**Turbidity (NTU)**	**Total Organic Carbon(mg/L)**
Minimum	310	14300	4.05	23.63
Maximum	1000	27900	14.1	82.15

From the obtained results, it can be noted that the minimum raw water turbidity obtained was 4 NTU while the E-coli and TOC was 310 counts per 100mL and 24 mg/L; respectively. The TOC was noted to be in the range of 80 mg/L except for the once incident where the concentration was noted to be 23.63 mg/L. The sample that had TOC of 23.63 mg/L was used for refilling the make-up tanks.

The raw water from Umgeni River was initially filtered through a WFMF system for a maximum of 30 minutes prior to introducing the river water into the different system noted in Table 5.1. The WFMF system was noted to be unable to significantly reduce the concentration of TOC in permeate. However, the system was noted to produce permeate with a turbidity of less than 1 NTU and bacterial count (E-coli and total coliforms) of less than 100 counts per 100 mL sample within the 30 minutes of filtration. The obtained permeate results were noted to be corresponding to those reported by Pikwa et al., (2009).

Table 5.4 presents the quality of permeate from the WFMF system after spiking with cultured E-coli and clay for increasing the concentrations of bacteria and turbidity; respectively.

TABLE 5.4: Water quality for WFMF permeates spiked with Bacteria and Turbidity.

Range	**Spiked WFMF Permeate**			
	Bacterial (count/ 100 mL sample)		**Turbidity (NTU)**	**Total Organic Carbon (mg/L)**
	E-coli	**Total Coliforms**		
WFMF permeate	10 - 89	93- 150	0.87	70.89
WFMF permeate after spiking	29240	>241960	19.1	

The results obtained in Table 5.4 show that the spiking of the WFMF permeate with cultured E-coli and clay was sufficient to yield the targeted feed concentrations for system No. 2 and system No. 3 (as stipulated in Table 5.2). The system WFMF system was also noted to have a TOC removal efficient of less than 20% for the allowed filtration period of 30 minutes.

5.3.2 Flux rates

Figure 5.1 presents the results obtained from the monitoring the flux rates from the three systems outlined under section 5.2.1.

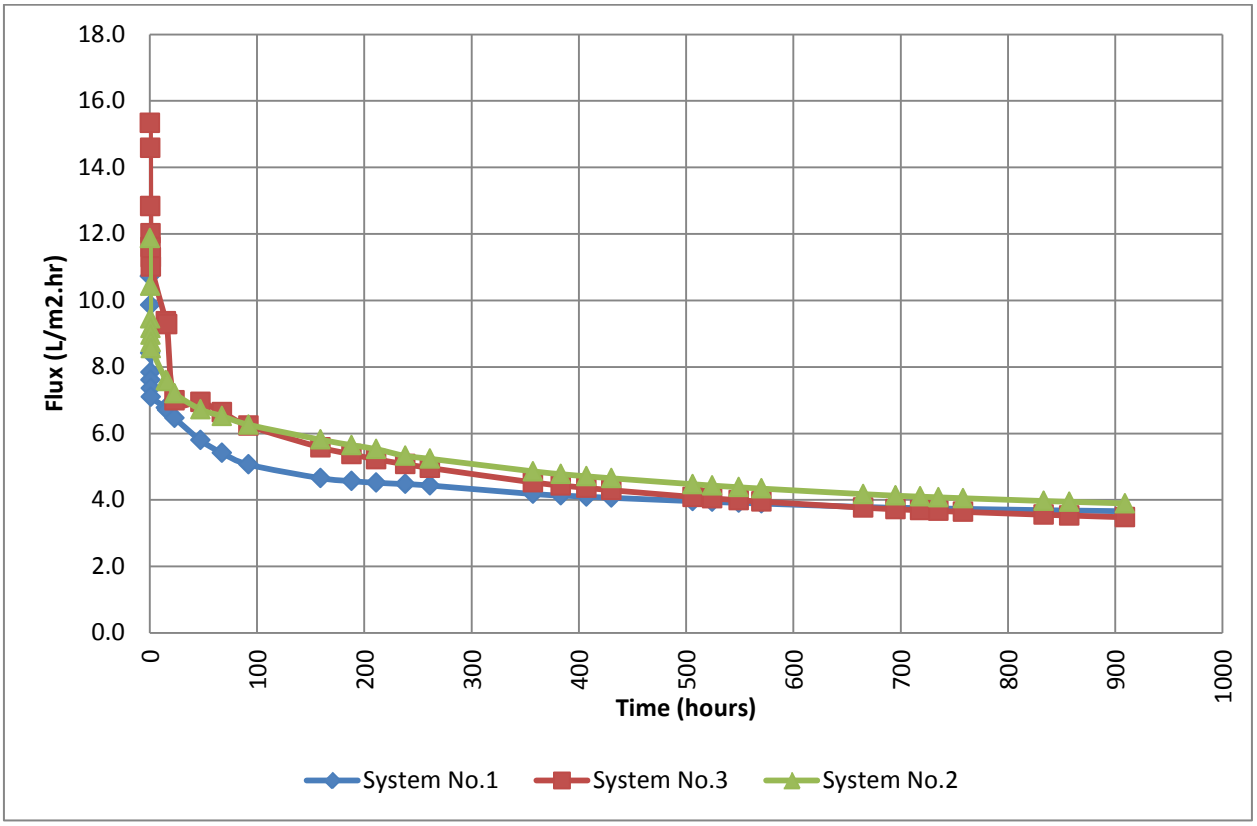


FIGURE 5. 1: Average Flux – Time plots obtained from the testing of the hypothesis.

From Figure 5.1, it can be noted that for system No.3, the initial flux is approximately 15 LMH and decreases sharply for the first 20 hrs to approximately 7 LMH. A steady decline in flux is further observed to approximately 4.2 LMH at 400 hrs. Thereafter, there appears to be stabilisation occurring between 700 – 900 hrs of operation.

For runs on system No.1; the initial flux is approximately 10 LMH and a sharp decrease for the first 100 hrs is observed to 5 LMH. Thereafter, a slow decrease in flux is observed until 700 hrs. There appears to be stabilisation of flux 3.7 LMH also occurring for this system between 730 and 900 hrs.

For runs with system No.2, the initial flux is 12 LMH. A sharp decrease is observed for the first 100 hrs to a flux of 6 LMH and thereafter, a slow decline in flux is observed to fluxes of approximately 4.2 LMH at 600 hrs. Again, there seems to be stabilisation of flux occurring at 4 LMH between 650 and 900 hrs of operation.

From Figure 5.1, it can also be noted that system No.2 produced the highest flux rates while with system No.3 produce the lowest flux rate when compared to the other systems.

The sharp decrease in flux for all three systems for the 100 hrs is brought about by the initial fouling of the membrane and the trends obtained from all three systems were noted to be similar to those observed on Figure 4.7 in chapter 4. These trends were also noted to be similar to those observed by Peter-Varbanets et.al. (2010). However, as already observed in section 4.3.3, this trend does not necessarily imply that stabilisation of flux is occurring as stipulated by Peter-Varbanets et.al. (2010). Hence, it becomes necessary to evaluate the obtained trends with reference to a normal dead-end filtration curve.

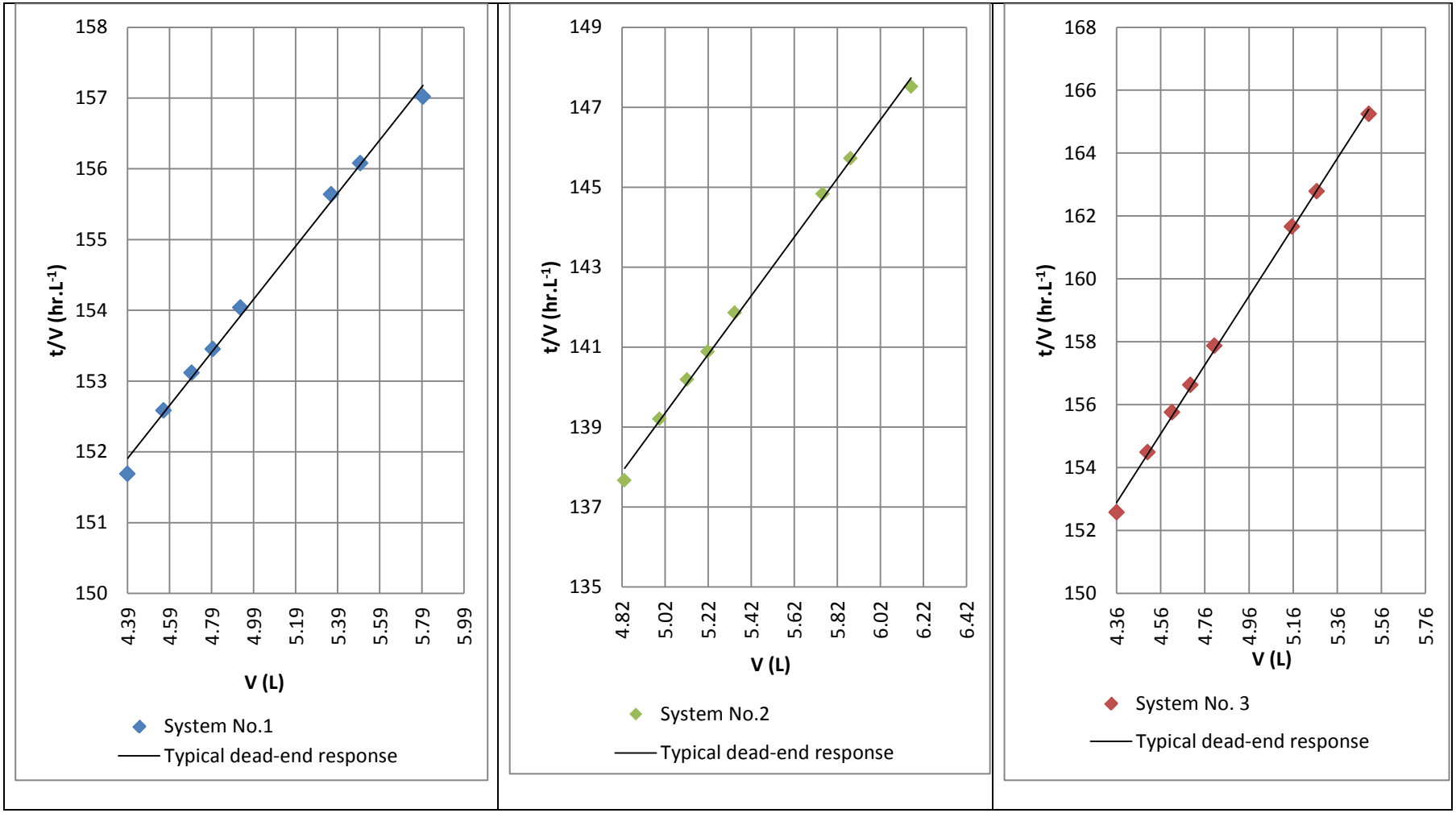


FIGURE 5. 2: Dead end filtration curve responses for Umgeni River water with different feed water qualities.

Figure 5.2, shows that the presence of high concentration of turbidity and total organic carbon in the feed water results in the system responding similar to a normal dead end filtration system and also reduces the membrane run time due to rapid fouling (System No.3). This response water noted to be similar to that obtained in Figure 4.9b for Tugela River. A slight deviation is also observed for runs with low concentration of bacteria and turbidity (System No.1). This system is noted to slightly increase the membrane run time in comparison to system No.3. System No.2 is noted to be having slightly higher permeate volume and run time when compared to the other systems even though the system were allowed to run for the same duration.

From Figure 5.2, it is also evident that all the systems yield a response that is similar to that of normal dead-end filtration. However, both system No.1 and system No.3 are noted to be fouling at a higher rate and consequently the high decline in flux when compared to system No.2.

Hence it can be concluded that the hypothesis is true as it is evident that the quality of the water plays a major role in the rate of flux decline. System No.2 is noted to be having the lowest rate of flux decline and this is the system which had bacterial counts that were greater than 29 000 per 100 mL sample; turbidity of less than 1 NTU and TOC concentrations of 70 mg/L.

CHAPTER 6

CONCLUSIONS AND RECOMMEMDATIONS

5.1 Conclusions

The overall aim of this project was to evaluate the ability of a gravity-driven Bio-UF membrane system to produce stable fluxes and water that is complaint to SANS 241:2011 standard. The complaint of the permeate quality to SANS 241:2011 was evaluated through the monitoring of turbidity, total organic carbon, total coliforms and E-coli concentrations. The system was also used to evaluate the impacts that the growth of algae has on flux rates.

From the obtained results, it is evident that Bio-UF cannot produce stable flux rates on the evaluated surface waters. However, the system is able to reduce the rate of flux decline which in turn extends the membrane run time. The obtained results for flux rates are noted to differ from those reported by Peter-Varbanets (2010).

The system is noted to be able to produce permeate that is compliant to SANS 241:2011 standard and WHO 2008 guidelines in terms of the concentrations of turbidity, TOC, E-coli and total coliforms. It is also noted that the system's removal efficiency for TOC is dependent on the concentrations of TOC in the raw water.

From the experiments carried out with the aim of comparing the performance of the Bio-UF membrane system in the presence of algae growth and without algae growth; it is observed that the presence of algae growth appears to be decreasing the rate of flux decline. From the photographic and microscopic analysis of the membranes, it is evident that Umbilo River had protozoa in the raw water while Tugela River was dense in suspended matter.

Hence it can be concluded that a gravity driven Bio-UF membrane system can be used for the removal of turbidity, E-coli, total coliforms and total organic carbon in surface water to acceptable SANS 241:2011 standards. It can also be concluded that the system is unable to produce stable fluxes; however, it has the ability to reduce the rate of flux decline especially when used in conjunction with the presence of algae growth.

5.2 Recommendations

It is recommended that:

1. The impacts of algae growth on the flux decline should be investigated in depth with the aim of determining the role of algae in flux decline rate.
2. The type and ratio of bacteria and organic carbon that enables slow decline in flux rates should be investigated.
3. The phenomenon of slow flux decline, due to biological fouling, should be evaluated on a WFMF membrane since this system is affordable and produced locally.

REFERENCES

Abbaspour, S. 2011. Water Quality in Developing Countries, South Asia, South Africa, Water Quality Management and Activities that Cause Water Pollution. Paper presented at the *International Conference on Environmental and Agriculture Engineering.* Singapore, IPCBEE 94 - 102.

Achisa, M. C. 2013. *Evaluation of silver nanoparticles impregnated woven fabric microfiltration membranes for potable water treatment* Master of Technology, Durban University of Technology, South Africa.

Adham, S. ed. 2005. *Development of microfiltration and ultrafiltration knowledge base.* AWWA Research Foundation.

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: 38.

Atlas, R. M. 1997. *Principles of Microbiology*. 1st ed. United States of America: Wm. C. Brown Publishers.

Baker, R. W. 2004. *Ultrafiltration. Membrane Technology and Applications*. Chichester, England: John Wiley & Sons, Ltd.

Beier, S. P. 2007. *Pressure Driven Membrane Processes*. 2nd. Retrieved 26 January, 2011, from http://nabro.co.uk/ebooks/chemeng/pressure-driven-membrane-processes.pdf.

Beier, P.S. and Jonsson, G. 2010. Critical flux determination by flux-stepping, *American Institute of Chemical Engineers*, 56 (7) (2010)1739 –1747.

Berube, P. 2009. Membrane bioreactor: theory and applications to wastewater reuse. *Sustainability Science and Engineering*, 2: 255 –292.

Biazin, B., Sterk, G., Temesgen, M., Abdulkedir, A. and Stroosnijder, L. 2012. Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa – A review. *Physics and Chemistry of the Earth*, *Parts A/B/C.* 47–48: 139-151.

Booker, R. 2010. Ceramic membranes: A pilot evaluation of an emerging reuse technology. In: *25th Annual water reuse symposium*, Washington, 12 – 15 September 2010.

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

Buteyn, J. 2010. Microfiltration with a macro future. *Water Technology,* 33(5): 26.

Cheryan, M. 1986. *Ultrafiltration Handbook*. 1st ed. Lancaster, Pennsylvania: Techomic Publishing.

Chen, A., Fan, Q. and Tian, Q. 2013. Study on dynamic of ultrafiltration membrane materials preparing and used in drinking water treatment. *International Journal of Environmental Science and Development*, 4 (4): 383 – 385.

Choi, Y.J. and Dempsey, B.A. 2005. Bench-scale evaluation of critical flux and trans-membrane pressure for low-pressure membrane filtration, *Journal American Water Works Association,* 97(7):134-143.

Chorus, I. and Bartram, J. 1999. *Toxic Cyanobacteria in Water.* Geneva: World Health Organization.

Clasen, T., Brown, J., Suntura, O. and Collin, S. 2004. Safe household water treatment and storage using ceramic drip filters: a randomised controlled trial in Bolivia. *Water Science and Technology*, 50(1): 111 - 115.

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

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.

CSIR. 2010. *A CSIR Perspective on water in South Africa.* CSIR Natural Resources and the Environment: CSIR/NRE/PW/IR/2011/0012/A. Retrieved 07 March, 2012, from http://www.csir.co.za/nre/docs/CSIR%20Perspective%20on%20Water_2010.PDF

Dalvie, M. A., Cairncross, E., Solomon, A. and London, L. 2003. Contamination of rural surface and ground water by endosulfan in farming areas of the Western Cape, South Africa. *Environmental Health: A Global Access Science Source* 2(1): 1.

Dankovich, T. A. and Smith, J. A. 2014. Incorporation of copper nanoparticles into paper for point-of-use water purification. *Water Research*, 63: 245-251.

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

Domènech, L. and Saurí, D. 2011. A comparative appraisal of the use of rainwater harvesting in single and multi-family buildings of the Metropolitan Area of Barcelona (Spain): social experience, drinking water savings and economic costs. *Journal of Cleaner Production*, 19: 598-608.

Donev, G., et al. 2012. Solar water heating potential in South Africa in dynamic energy market conditions. *Renewable and Sustainable Energy Reviews* 16(5): 3002-3013.

Dong, B., Sun, W., Liu, J. and Chu, H. 2013. Review: Pretreatment and membrane hydrophilic modification to reduce membrane fouling. *Membranes*, 3: 226 – 241.

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): 570.

Dunstan, R. H., Harrison, T., Coombes, P. J. and Evans, G. A. Extensive bacterial diversity indicates the potential operation of a dynamic micro-ecology within domestic rainwater storage systems. *Science of the Total Environment,* 407: 5206 – 5215.

Durancear, S. J. 2001. *Membrane practices for water treatment*. Denver: American Water works Association.

EAWAG. 2011. *Gravity-driven membrane (GDM) technology*. Retrieved 15 November, 2011, from http://www.eawag.ch/forschung/eng/gruppen/gdm/index_EN.

Edzwald, J.K., Tobiason, J.E., Dunn, H., Kaminski, G., Galant, P., 2001. Removal and fate of Cryptosporidium in dissolved air drinking water treatment plants. *Water Science and Technology*, 43 (8): 51- 57.

Elfil, H., Hamed, A. and Hannachi, A. 2006. Technical evaluation of a small-scale reverse osmosis desalination unit for domestic water. *Desalination*, 203: 319 – 326.

Evans, L. V. ed. 2005. *Biofilms: recent advances in their stdudy and control.* Netherlads: Harwood academi publishers.

Falsanisi, D., Liberti, L. and Notarnicola, M. 2010. Ultrafiltration (UF) pilot plant for municipal wastewater reuse in agriculture: Impact of the operation mode on process performance. *Water,*1: 872 – 885.

Farahbakhsh, K., Smith, D.W. 2004. Removal of coliphages in secondary effluent by microfiltration – mechanisms of removal and impact of operating parameters. *Water Research*, 38: 585 – 592.

Field, R. W., Wu, D., Howell, J. A. and Gupta, B. B. 1995. Critical flux concept for microfiltration fouling. *Membrane Science*, 100: 259 - 272.

Fonseca, A. C., Summers, R. S. and Hernandez, T. M. 2001. Comparative measurements of microbial activity in drinking water biofilters*. Water Research,* 36 (16): 3817 - 3824.

Freeman, B. D., Paul, D. R., Miller, J. D. and Kasemset, S. 2014. Comparison of membrane fouling at constant flux and constant transmembrane pressure conditions. *Membrane Science,* 454: 505 – 515.

Glucina, K., Derekx, Q., Langlais, C. and Laine, J.M. 2009. Use of advanced CFD tool to characterize hydrodynamic of commercial UF membrane module. *Desalination and Water Treatment*, 9: 253-258.

HACH. 1997. *Water Analysis Handbook*. 3rd ed. Colorando, U.S.A: Loveland.

Hörsch, P., Gorenflo, A., Fuder, C., Deleage, A. and Frimmel, F. H. 2005. Biofouling of ultra- and nanofiltration membranes for drinking water treatment characterized by fluorescence in situ hybridization (FISH). *Desalination*, 172: 41 – 52.

Hossain, Md. M. and Lowe, J. 2008. Application of ultrafiltration membranes for the removal of humic acid from drinking water. *Desalination,* 218: 343 – 354.

Huang, H., Lee, N., Young, T., Gary, A., Lozier, J. C. and Jacangelo, J. G. 2007. Natural organic matter fouling of low-pressure, hollow-fiber membranes: Effects of NOM source and hydrodynamic conditions*. Water Research*, 41 (17): 3823-3832.

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

IRC. 2002. *Small Community Water Supplies: Technology, peope and partnership*. Delft, Netherlands: IRC (International Water and Sanitation Center).

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 wat*er*. *Membrane Science*, 252: 51 - 63.

Jermann, D., Pronk, W., Meylan, S. and Boller, M. 2007. Interplay of different NOM fouling mechanisms during ultrafiltration for drinking water production. *Water Research*, 41 (8): 1713-1722.

Kahinda, J. M., Taigbenu, A. E. and Boroto, J. R. 2007. Domestic rainwater harvesting to improve water supply in rural South Africa. *Physics and Chemistry of the Earth*, 32: 1050 – 1057.

Kaiser, N., Liang, K. R., Maertens, M. and Snider, R. 2002. *Biosand household water filter evaluation 2001: A comprehensive evaluation of the Samaritan's Purse Biosand Filter (BSF) Projects in Kenya, Mozambique, Cambodia, Vietnam, Honduras and Nicaragua.* Samaritan's Purse,Canada*.*

Kang, I. J., Yoon, S. H. and Lee, C. H. 2002. Comparison of the filtration charateristics of organic and inorganic membranes in a membrane-coupled anaerobic bioreactor. *Water Research*, 36 (7): 1803 - 1813.

Kimura, K., Hanea, Y., Watanabea, Y., Amyb, G. and Ohkumac, N. 2004. Irreversible membrane fouling during ultrafiltration of surface water. *Water Research*, 38: 3431 - 3441.

Koivunen, J. 2007. Effects of conventional treatment, tertiary treatment and disinfection processes on hygienic and physico-chemical quality of municipal wastewaters. Doctoral, University of Kuopio, Finland.

Le Clech, P., Chen, V. and Fane, T. A. G. 2006. Fouling in membrane bioreactors used in wastewater treatment. *Journal of Membrane Science*, 284: 17 - 53.

Lee, J.Y., Yang, J.S., Han, M. and Choi, J. 2010. Comparison of the microbiological and chemical characterization of harvested rainwater and reservoir water as alternative water resources. *Science of the Total Environment*, 408 (4): 896‑905.

Loeb, S. and Sourirajan, S. 1963. Sea water demineralisation by means of an osmotic membrane. *Advanced Chemistry,* 38: 117 - 132.

Luyt, C. D., Tandlich, R., Muller , J. W. and Wilhelmi, B. S. 2012. Microbial Monitoring of Surface Water in South Africa: An Overview. *Environmental Research and Public Health*, 9: 2669-2693.

Mara, D. and Horan, N. J. 2003. *Handbook for Water and Wastewater Microbiology*. London: Academic Press.

Mara, D. D. 2003. Water, sanitation and hygiene for the health of developing nations. *Public Health*, 117 (6): 452-456.

Mbulawa, X. P. 2005. *Development and Evaluation of Silicon membrane as aerators for membrane bioreactors*. Master of Technology, Durban University of Technology, South Africa.

Mbungua, J. and Nissen-Peterson, E. 1995. *Rainwater: an underutilised resource*. Kenya: SIDA (Swedish International Development Authority).

Meng, F., Chae, S., Drews, A., Kraume, M., Shin, H. and Yang, F. 2009. Recent advances in membrane bioreactors (MBRs): Membrane fouling and membrane material. *Water Research*, 43 (6): 1489 -1512.

Mexel. 2012. *Bio-flim formation.* Retrieved 30 October, 2012, from http://www.mexelenergy.co.za/mexel432.php.

Moulin, P., Nauleau, F., Perot, J., Wyart, Y. and Guo, H. 2010. Review: Low-pressure membrane integrity tests for drinking water treatment. *Water Research,* 44: 41 – 57.

Mulder, M. 1996. *Basic principles of membrane technology*. 2nd ed. Netherlands: Kluwer Academic Publishers.

Ndinisa, V. N. 2006. *Experimental and CFD simulation investigations into fouling Reduction by Gas-Liquid Two-Phase flow for submerged flat sheet membranes.* Doctor of Philosophy, University of New South Wales in Sydney, Australia.

Nguyeni, T. T. 2010. *Development of a water treatment system for emergency situations*. Masters of Engineering in Environment engineering and management, Asian Institute of *Technology, Thailand*.

Noor, Z. Z., Mutamim, N. S. A., Hassan, M. A. A. and Olsson, G. 2012. Application of membrane bioreactor technology in treating high strength industrial wastewater: A performance review. *Dessalination*, 305: 1 – 11.

Ognier, S., Wisniewski, C. and Grasmick, A. 2002. Characterisation and modelling of fouling in membrane bioreactors. *Desalination*, 146: 141 - 147.

Pearce, G. 2007. Introduction to membranes: Membrane Selection. *Filtration & Separation*, 44 (3): 35-37.

Pearce, G. 2008. UF/MF pre-treatment to RO in seawater and wastewater reuse applications: A comparison of energy costs. *Desalination,* 222: 66 – 73.

Peiris, R. H., Budman, H., Moresoli, C. and Legge, R. L. 2010. Understanding fouling behaviour of ultrafiltration membrane processes and natural water using principal component analysis of fluorescence excitation-emission matrices. *Journal of Membrane Science*, 357: 62-72.

Peletz, R. 2006. *Cross-sectional epidemiological study on water and sanitation practises in the northern region*. Master of Technology, Massachusett Insitute of Technology, Kenya.

Peter-Varbanets, M., Gujer, W. and Pronk, W. 2012. Intermittent operation of ultra-low pressure ultrafiltration for decentralized drinking water treatment. *Water Research*, 46 (10): 3272-3282.

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

Peter-Varbanets, M., Margot, J., Traber, J. and Pronk, W. 2011. Mechanisms of membrane fouling during ultra-low pressure ultrafiltration. *Journal of Membrane Science*, 377: 42-53.

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

Pikwa, K., Dlamini, T. and Pillay, V. L. 2009. Development of a gravity fed microfilter for potable water production in remote rural areas. In: Proceedings of *Water Institute of Southern Africa 2010 Biennial Conference,* Durban ICC, South Africa.

Pouliot, Y. 2008. Membrane processes in dairy technology—From a simple idea to worldwide panacea. *International Diary Journal*, 18: 735 – 740.

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: 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 Research*, 46 (5): 1490-1500.

Ramesh, A., Lee, D. J. and Lai, J. Y. 2007. Membrane biofouling by extracellular polymeric substances or soluble microbial products from membrane bioreactor sludge. *Applied Microbiology and Biotechnology,* 74(3): 699-707.

Roddick, F. A., Fan, L. and Nguyen, T. 2012. Review: Biofouling of water treatment membranes: A review of the underlying causes, monitoring techniques and control Measures. *Membranes,* 2: 804 – 840.

Sagle, A. and Freeman, B. 2004. Fundamentals of membrane technology in water treatment. Retrieved 12 February, 2012, from http://www.twdb.state.tx.us/Publications/reports/numbered_reports/doc/R363/C6.pdf.

Sano, D., Ueki, Y., Watanabe, T., Omura, T. 2006. Membrane separation of indigenous noroviruses from sewage sludge and treated wastewater. *Water Science and Technology*, 54 (3): 77- 82.

SANS 241. 2011. *South African National Standard-Specifications for Drinking water*. Pretoria: SABS Standards Division.

Saurez, M. 2013. *Microfiltration of Anaerobically Digested Industrial Wastewaters Emphasis on Fouling Control*. Masters Thesis, Lund University, Sweden.

Schwinge, J., Neal, P.R., Wiley, D.E., Fletcher, D.F. and Fane, A.G. 2004. Spiral wound modules and spacers: Review and analysis. *Journal of Membrane Science*, 242: 129-153.

Snow, J. 1855. *On the Communication of Cholera*. 2nd ed. London: UK: Churchill.

Sobsey, M. D. 1989. Inactivation of health related micro-organisms in water by disinfection process. *Water Science and Technology,* 21: 179 - 185.

Sobsey, M. D. 2002. Managing Water in the home: Accelerated Health Gains from Improved Water Supply. *World Health Organization:* 1 - 70.

Sobsey, M. D., Stauber, C. E., Casanova, L. M., Brown, J. M. and Elliott, M. A. 2008. Point of Use household drinking water filtration: A practical, effective solution for providing sustained access to safe drinking water in the developing world. *Environmental Science and Technology*, 42 (12): 4261-4267.

Statistics, S. A. 2005. *Water quality accounts for South Africa.* South Africa, Pretoria: Statistics South Africa.

Statistics, S. A. 2010. *Mid year population Estimates.* South Africa, Pretoria: Statistics South Africa.

Stednick, J. D. 1991. *Wildlands water quality sampling and analysis.* San Diego, California: Academic Press.

Susanto, H., Arafat, H., Janssen, E. M. L. and Ulbricht, M. 2008. Ultrafiltration of polysaccharide–protein mixtures: Elucidation of fouling mechanisms and fouling control by membrane surface modification. *Separation and Purification Technology*, 63 (3): 558-565.

Sutherland, K. 2009. Membrane filtration: What's new in membrane filtration?. *Filtration & Separation*, 46 (5): 32-35.

Tian, J. Y., Enrst, M., Cui, F. and Jekel, M. 2013. Correlations of relevant membrane foulants with UF membrane fouling in different waters. *Water Research,* 47(3): 1218-1228.

Totora G.J., Funke, B. R. and Case, C. L. 1995. *Microbiology: An introduction,* The Benjamin/ Cummings Publishing Company Inc: Bridge Parkway.

Tung, K. and Li, Y. 2008. The effect of curvature of a spacer-filled channel on fluid flow in spiral-wound membrane modules. *Journal of Membrane Science*, 319: 286 – 297.

Tung, K. and Li, Y. 2011. Scale-up design of a spacer-filled disk-type membrane module using CFD. *Journal of Water Sustainability*, 1(1): 59–74.

United Nations. 2006. The *Millenium Development Goals Report 2006*. Retrived 25 November, 2009, from www.un.org/zh/millenniumgoals/pdf/MDGReport2006.pdf.

Waite, T.D., Fane, A.G. and Schafer, A.I. 2001. Cost factors and chemical pretreatment effects in the membrane filtration of waters containing natural organic matter. Water Research, 35 (6):1509–1517.

Wang, L., Wang, X. and Fukushi, K.-i. 2008. Effects of operational conditions on ultrafiltration membrane fouling. *Desalination*, 229: 181-191.

Wang, H. and Zhou, H. 2013. Understanding the basics of membrane filtration. *American Institute of Chemical Engineers – CEP April Magazine:* 33 – 40.

Water for Africa. Department of Trade and Industry. 2010. *Fund for research into industrial development, growth and equity: consolidating recommendations of water quality*. Pretoria: South Africa.

WHO and UNICEF. 2000. *WHO 2000 Assessment: Global Water Supply and Sanitation Assessment Report.* United State of America.

WHO. 2004. *Meeting the MDG drinking water and sanitation target: a midterm assessment of progress.* World Health Organization and United Nations Children's Fund.

WHO. 2008. Guidelines for drinking-water quality: second addendum to 3rd edition. Genera.

Worm, J. and van Hattum, T. 2006. *Rainwater Harvesting for domestic use*. Digigrafi, Wageningen, Netherlands.

Cicek, N., Yang, W. and Ilg, J. 2006. State of the art of membrane bioreactors: worldwide research and commercial applications in North America, *Journal of Membrane Science*, 270: 201–211.

Vestergraard, F. (2013). "*LifeStraw*." Retrieved 08 September, 2013, from http://www.vestergaard.com/our-products/lifestraw.

ANNEXURES

ANNEXURE A

Experimental Procedures

A.1 Turbidity calibration procedure

This calibration procedure comprises of four standards which comprises of 0.1 NTU, 20 NTU, 100 NTU and 800 NTU.

- Rinse the outer part of all calibration standards with deionised water and gentle wipe with a damp towel.
- Hold each standard with its lid to prevent the interference of the finger prints with the reading.
- Switch the meter ON and press calibrate.
- The meter will request that you place the 0.1 NTU standards.
- Place the 0.1 NTU calibrations standard in the meter and close with the cover of the meter.
- Press READ.
- The meter will show a countdown starting from 60 NTU to 0 NTU. Thereafter the meter will ask for the next calibration standard of 20 NTU, 100 NTU and 800 NTU.
- Repeat the above steps until all calibration standards have been used.
- After the countdown of the 800 NTU standards, remove it from the meter and press calibrate. The meter has been successfully calibrated and ready for use.

A.2 Testing Procedure for Turbidity (HACH, 1997)

- Rinse the inside part of the colourless glass bottle with deionised water.
- Pour 18 mL of sample into the glass sample bottle (ensure that the water is above the white mark as shown in figure B1).
- Close the lid of the bottle, rinse the outside of bottle with deionised water and gently wipe with a damp towel.
- Switch the meter ON.
- Place the bottle into the meter while holding it by it cap and close the lid of the meter.
- Press READ. And record the reading

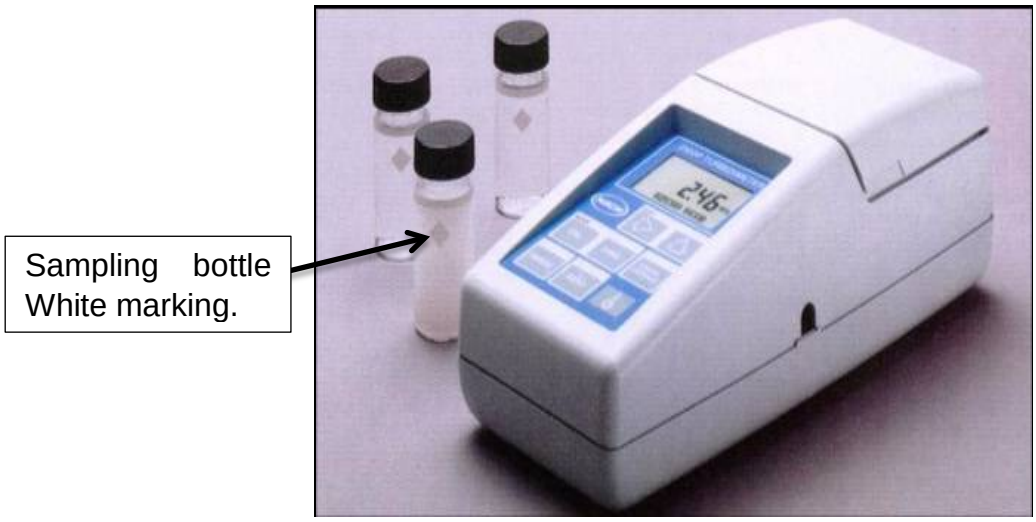


FIGURE A. 1: A visual presentation of the HACH 2100P Turbidity meter.

A.3 Testing procedure for COD (HACH 1997)

- Homogenize 250 ml of sample to be tested for one minute using a magnetic stirrer.
- Switch ON the COD Reactor and Preheat to 150 ^{0}C.
- Select COD Digestion Reagent vials from the range you will be working with.
- Remove the caps of the vials, hold the vial at a 45 degree angle and use a pipette to add 2 mL of sample to the vial.
- A Blank is required for each set of runs, thus hold another vial at a 45^0 angle using a clean pipette to add 2 ml of deionised water to the vial.
- Close the caps the vials; rinse them with deionised water and wipe them with a damp cloth.
- Invert gently several times for proper mixing.
- Place the vials in the preheated COD reactor, adjust the time to two hours and allow for heating.
- After 2 hours of heating, turn off the reactor and wait for 20 minutes for the vials to cool down to 120^{0}C.
- After 20 minutes of cooling, invert the vials several times while still warm, place them into a vial rack and allow them to cool to room temperature.
- Once at room temperature, Switch ON the HACH DR 3900 Spectrophotometer.
- Select the relevant program, depending on the range used, on the user stored programs.
- Wipe the outside of the vial with a damp followed dry cloth to remove fingerprints.
- Place the blank vial into spectrophotometer and press Zero for calibration of the equipment. The displayed reading should be 0 mg/L.
- Place sample vial into the spectrophotometer and press read and record the results.

A.4 Testing procedure for E-coli and Total Coliforms

- Rinse 100 mL measuring cylinder with deionised water.
- Measure 100mL of sample to be tested in a measuring cylinder.
- Pour the sample into the sterile bottle and add the colilert medium.
- After the medium has settled, shake well till it is completely dissolved.
- Pour the content into a Quanti-tray and seal using the Qaunti-tray sealer.
- Place the sealed Quanti-tray into an incubator set at 37^{o}C for 18 – 22 hours.
- After incubation period, count the Total coliforms, identified by yellow wells, see Figure B2.
- Place the tray under UV light for E-coli counts. The wells with E-coli will fluoresce blue.

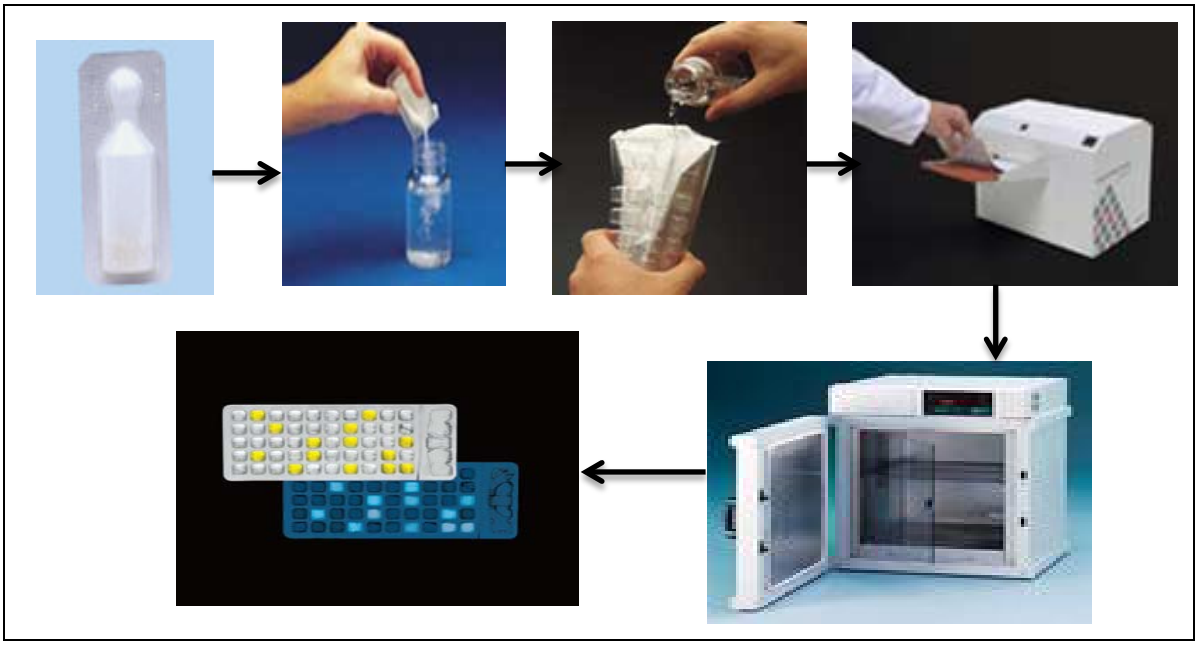


FIGURE A. 2: A visual presentation of the colilert procedure. (IDEXX Laboratories 2013)

ANNEXURE B

B.1 Collected raw data

Due to the high volume of raw data collected, the following tables of raw data shown only a portion of the data collected from the different rivers.

- Umbilo River

TABLE B. 1: Raw data obtained for Umbilo River when the system was operated without algae growth (right) and with algae growth (left).

Area of membrane	**0.0017** m2							
Time			**Collected Volume (mL)**					
min	**hr**	**day**	**1**	**2**	**3**	**4**	**5**	**6**
15	0.25	0.01	2.4	2.98	2.4	2.8	2.9	2.3
30	0.5	0.02	4.6	5.48	4.9	5.9	5.9	4.4
45	0.75	0.03	6.8	7.98	6.8	9	7.9	7.3
60	1	0.04	9	10.98	9.1	12	10.5	9
75	1.25	0.05	11.5	13.98	11.7	15	13.5	11.3
90	1.5	0.06	13	16.98	14.1	17.9	16.4	13.8
105	1.75	0.07	15	19.68	16.6	20.9	19.3	16
2865	47.75	1.99	352	391.68	358.6	397.9	396.3	347
7245	120.75	5.03	702	786.68	753.6	807.9	806.3	677
11505	191.75	7.99	992	1106.68	1082.6	1172.9	1136.3	977
15945	265.75	11.07	1262	1406.68	1384.6	1497.9	1436.3	1247
21645	360.75	15.03	1587	1776.68	1744.6	1877.9	1786.3	1565
33105	551.75	22.99	2149.5	2378.68	2396.6	2489.9	2398.3	2147
51825	863.75	35.99	2957.5	3216.68	3294.6	3337.9	3266.3	2973
76305	1271.75	52.99	3947.5	4246.68	4274.6	4387.9	4296.3	3943
80625	1343.75	55.99	4119.5	4416.68	4444.6	4567.9	4465.3	4103
82125	1368.75	57.03	4175.5	4474.68	4502.6	4628.9	4522.3	4158
99105	1651.75	68.82	4760.5	5084.68	5142.6	5198.9	5132.3	4768
100665	1677.75	69.91	4812.5	5138.68	5196.6	5258.9	5187.8	4822
109425	1823.75	75.99	5102.5	5440.68	5506.6	5573.9	5497.8	5127
116625	1943.75	80.99	5352.5	5671.68	5771.6	5842.9	5759.8	5267
129285	2154.75	89.78	5747.5	6091.68	6211.6	6287.9	6194.8	5695
135165	2252.75	93.86	5919.5	6284.68	6413.6	6490.4	6390.8	5881
138165	2302.75	95.95	5990	6373.68	6506.6	6582.4	6482.8	5969.5
141045	2350.75	97.95	6074	6467.68	6604.6	6681.4	6578.8	6062.5
142485	2374.75	98.95	6131.5	6484.68	6663.6	6743.4	6634.8	6111
145245	2420.75	100.86	6131.5	6563.18	6749.1	6833.4	6722.8	6195
149625	2493.75	103.91	6251.5	6698.18	6890.1	6963.4	6852.8	6310
151125	2518.75	104.95	6286.3	6744.68	6938.1	7008.4	6897.8	6340
154005	2566.75	106.95	6369.3	6831.68	7027.1	7093.4	6980.8	6418
164085	2734.75	113.95	6599.3	7131.68	7332.1	7383.4	7265.8	6676

Area of Membrane =	1.74E-03	m^2					
		Volume of filtrate (mL)					
Time (min)	**Time (hr)**	**6.00**	**5.00**	**4.00**	**3.00**	**2.00**	**1.00**
60	1.0	4	9	10	4	11	9
120	2.0	7	18	20	9	21	18
180	3.0	11	27	30	13	32	27
240	4.0	15	35	40	18	42	36
300	5.0	18	44	49	22	53	46
360	6.0	22	53	59	27	64	55
420	7.0	26	62	69	31	74	64
480	8.0	29	71	79	36	85	73
540	9.0	33	80	89	40	95	82
600	10.0	37	88	99	45	106	91
660	11.0	40	97	109	49	117	100
720	12.0	44	106	119	54	127	109
780	13.0	48	115	129	58	138	119
840	14.0	51	124	139	63	148	128
900	15.0	55	133	148	67	159	137
960	16.0	59	141	158	72	170	146
1020	17.0	62	150	168	76	180	155
1080	18.0	66	159	178	81	191	164
1140	19.0	69	168	188	85	201	173
1200	20.0	73	177	198	90	212	182
1260	21.0	77	186	208	94	223	191
1320	22.0	80	194	218	99	233	201
1380	23.0	84	203	228	103	244	210
1440	24.0	88	212	237	107	254	219
1500	25.0	91	221	247	112	265	228
1560	26.0	95	230	257	116	276	237
1620	27.0	99	239	267	121	286	246
1680	28.0	102	247	277	125	297	255
1740	29.0	106	256	287	130	307	264
1800	30.0	110	265	297	134	318	274
1860	31.0	113	274	307	139	329	283

- Umgeni River

TABLE B. 2: Raw data obtained for Umgeni River when operated without algae growth (right) and with algae growth (left)

Area of Membrane =	1.74E-03	m^2					
		Volume of filtrate (mL)					
Time (min)	Time (hr)	1.00	2.00	3.00	4.00	5.00	6.00
60	1	13	14	7	11	13	6
120	2	26	27	14	23	27	11
180	3	40	41	20	34	40	17
240	4	53	55	27	46	54	23
300	5	66	68	34	57	67	29
360	6	79	82	41	69	80	34
420	7	92	96	48	80	94	40
480	8	106	109	54	92	107	46
540	9	119	123	61	103	121	52
600	10	132	137	68	115	134	57
660	11	145	150	75	126	147	63
720	12	158	164	82	138	161	69
780	13	171	178	89	149	174	75
840	14	185	191	95	161	188	80
900	15	198	205	102	172	201	86
960	16	211	219	109	184	214	92
1020	17	224	232	116	195	228	98
1080	18	237	246	123	207	241	103
1140	19	251	260	129	218	255	109
1200	20	264	273	136	230	268	115
1260	21	277	287	143	241	281	121
1320	22	290	301	150	253	295	126
1380	23	303	314	157	264	308	132
1440	24	317	328	163	276	322	138
1500	25	330	342	170	287	335	144
1560	26	343	355	177	299	348	149
1620	27	356	369	184	310	362	155
1680	28	369	382	191	322	375	161
1740	29	383	396	197	333	389	167
1800	30	396	410	204	345	402	172
1860	31	409	423	211	356	415	178
1920	32	422	437	218	368	429	184

Area of membrane =	**0.0017**	m2						
Time			Collected Volume (mL)					
min	hr	day	1	2	3	4	5	6
20.00	0.33	0.01	3.50	0.50	2.90	3.00	3.10	2.10
40.00	0.67	0.03	5.50	0.70	4.80	5.33	5.55	3.40
50.00	0.83	0.03	7.90	0.70	5.80	6.73	6.96	3.90
110.00	1.83	0.08	14.40	0.70	11.90	12.93	14.26	6.90
950.00	15.83	0.66	100.60	11.70	92.40	109.93	112.26	58.90
4205.00	70.08	2.92	380.60	48.70	364.40	421.93	427.26	247.90
8645.00	144.08	6.00	680.60	97.70	683.40	778.93	3766.26	472.90
14345.00	239.08	9.96	1029.60	257.70	1056.40	1200.93	4148.26	745.90
25805.00	430.08	17.92	1609.60	377.70	1686.40	1920.93	4798.26	1091.90
44525.00	742.08	30.92	2448.60	565.70	2554.40	2868.93	5696.26	1799.90
69005.00	1150.08	47.92	3418.60	820.70	3559.40	3939.93	6711.26	2639.90
73325.00	1222.08	50.92	3578.60	870.70	3729.40	4119.93	6884.26	2789.90
74825.00	1247.08	51.96	3635.60	887.70	3788.40	4181.43	6944.26	2838.90
91805.00	1530.08	63.75	4250.60	1057.70	4428.40	4799.43	7584.26	3368.90
93425.00	1557.08	64.88	4305.60	1075.70	4486.40	4859.43	7639.76	3417.90
102065.00	1701.08	70.88	4615.60	1170.70	4808.40	5193.43	7954.76	3692.90
109325.00	1822.08	75.92	4884.60	1250.70	5088.40	5483.43	8223.76	3931.90
121985.00	2033.08	84.71	5334.60	1388.70	5566.40	5973.43	8674.76	4331.90
127865.00	2131.08	88.80	5576.60	1466.20	5812.40	6225.43	8912.76	4542.90
130925.00	2182.08	90.92	5698.60	1502.20	5937.40	6356.43	9032.76	4652.90
133805.00	2230.08	92.92	5818.60	1538.20	6060.40	6483.43	9149.76	4755.90
135245.00	2254.08	93.92	5858.60	1581.20	6108.40	6532.43	9198.76	4781.10
138005.00	2300.08	95.84	5956.60	1603.20	6213.40	6647.43	9308.76	4871.10
142385.00	2373.08	98.88	6115.60	1648.20	6378.40	6817.43	9468.76	5011.10
143885.00	2398.08	99.92	6171.60	1664.70	6432.90	6874.43	9521.76	5059.10
146765.00	2446.08	101.92	6281.60	1694.70	6537.90	6984.43	9624.76	5160.10
156845.00	2614.08	108.92	6661.60	1808.70	6922.90	7384.43	9994.76	5490.10
160985.00	2683.08	111.80	6766.60	1843.70	7027.90	7494.43	10095.76	5581.10
163925.00	2732.08	113.84	6881.60	1843.70	7138.90	7612.43	10205.76	5680.10
165245.00	2754.08	114.75	6926.10	1890.70	7343.90	7656.43	10246.26	5719.60
165485.00	2758.08	114.92	6933.90	1899.20	7351.90	7664.43	10254.26	5728.80
169385.00	2823.08	117.63	7052.90	1939.20	7471.90	7664.43	10254.26	5856.80

- Tugela River

TABLE B. 3: Raw data obtained from running Tugela River operated without algae growth (right) and with algae growth (left)

Area of Membrane =	1.74E-03	m^2			
		Volume of filtrate (mL)			
Time (min)	**Time (hr)**	**1.00**	**2.00**	**3.00**	**4.00**
60	1	29	30	33	22
120	2	58	59	67	45
180	3	88	89	100	67
240	4	117	118	133	89
300	5	146	148	167	111
360	6	175	177	200	134
420	7	204	207	233	156
480	8	233	237	267	178
540	9	263	266	300	201
600	10	292	296	333	223
660	11	321	325	367	245
720	12	350	355	400	268
780	13	379	385	433	290
840	14	408	414	467	312
900	15	438	444	500	334
960	16	467	473	533	357
1020	17	496	503	567	379
1080	18	525	532	600	401
1140	19	554	562	633	424
1200	20	583	592	667	446
1260	21	613	621	700	468
1320	22	642	651	733	490
1380	23	671	680	767	513
1440	24	700	710	800	535
1500	25	730	741	835	563
1560	26	759	772	871	590
1620	27	789	803	906	618
1680	28	818	834	942	645
1740	29	848	865	977	673
1800	30	877	896	1013	700
1860	31	907	927	1048	728

Area =	**0.001735**	m^2			
Time			**Volume (mL)**		
Time (min)	Time (hr)	Time (days)	1	2	3
10	0.17	0.01	4.5	5.5	7
21	0.35	0.01	7.6	8.2	12
32	0.53	0.02	10.7	10.8	17
40	0.67	0.03	13.7	12.8	20.4
50	0.83	0.03	16.1	14.8	24.9
60	1.00	0.04	18.7	16.9	29.1
70	1.17	0.05	21.6	19.1	33.1
80	1.33	0.06	24.2	21.3	37.4
370	6.17	0.26	102.2	78.3	143.9
670	11.17	0.47	171.2	129.8	225.9
730	12.17	0.51	185.7	139.8	242.9
790	13.17	0.55	200.2	150.8	259.9
1150	19.17	0.80	274.2	204.7	342.9
1210	20.17	0.84	287.2	214	356.9
1270	21.17	0.88	300.2	223.3	370.9
1330	22.17	0.92	313.2	232.6	384.4
1450	24.17	1.01	338.2	250.1	409.9
1690	28.17	1.17	382.2	284.1	458.9
1750	29.17	1.22	394.2	293.1	471.9
1810	30.17	1.26	406.2	302.2	484.9
1870	31.17	1.30	418.2	311.2	497.1
1930	32.17	1.34	430.2	320.3	509.3
2590	43.17	1.80	541.2	407.3	617.3
2770	46.17	1.92	569.7	431.3	644.3
2830	47.17	1.97	579.9	440.3	654.3
2950	49.17	2.05	599.4	456.5	672.3
3070	51.17	2.13	618.4	472.7	690.3
3130	52.17	2.17	628.9	481.7	699.8
3190	53.17	2.22	638.4	489.7	708.8
3250	54.17	2.26	648.4	497.7	717.8
3370	56.17	2.34	666.4	512.7	733.9

B.2 Obtained results from water quality analysis

- Umbilo River

TABLE B. 4: Results obtained from analysing Umbilo River water.

	TURBIDITY					COD	TOC		ECOLI		COLIFORMS	
DATE	Raw	DATE	Day	Permeate	DATE	Raw	Raw	DATE	Raw	Permeate	Raw	Permeate
29-Sep-10	6.2	01-Oct-10	1.00	1.45	28-Mar-11	39.0	14.6	23-Nov-10	8664.0	0.0	17329.0	0.0
01-Oct-10	6.06	04-Oct-10	4.00	1.24	09-Jun-11	14.0	5.3	23-Jan-11	439.0	0.0	>2419.6	0.0
19-Nov-10	17.2	02-Dec-10	67.00	0.85	16-Aug-11	14.0	5.3	27-Mar-11	10.0	0.0	2851.0	0.0
05-Apr-11	2.28	09-Feb-11	134.00	0.75	09-Sep-11	26.0	9.8	15-Apr-11	203.0	0.0	747.0	0.0
10-Aug-11	5.75	09-Jun-11	254.00	0.712	11-Sep-11	11.0	4.1	07-Jun-11	92000.0	0.0	>241960	0.0
08-Sep-11	7.14	22-Jun-11	267.00	0.691	03-Oct-11	27.0	10.1	09-Jun-11	19300.0	0.0	91000.0	0.0
30-Sep-11	4.59	09-Sep-11	345.00	0.656	23-Oct-11	48.0	18.0	22-Jun-11	31.0	0.0	203.0	0.0
06-Oct-11	11.9	29-Sep-11	365.00	0.573				16-Aug-11	31.0	0.0	199.0	0.0
17-Oct-11	8.41	04-Oct-11	370.00	0.503				12-Sep-11	400.0	0.0	>24196	0.0
		11-Oct-11	377.00	0.491				03-Oct-11	288.0	0.0	>2005	0.0
		20-Oct-11	386.00	0.478				11-Oct-11	15531.0	0.0	17329.0	0.0
								19-Oct-11	701.0	0.0	3784.0	0.0

- Umgeni River

TABLE B. 5: Results obtained from analysing Umgeni River water.

TURBIDITY					COD	TOC		ECOLI		COLIFORMS	
Raw	Date	Day	Permeate	Date	Raw	Raw	DATE	Raw	Permeate	Raw	Permeate
14.73	08-Dec-10	1.00	1.46	28-Mar-11	83	31.1328	23-Nov-10	80	0	2723	0
7.29	28-Jan-11	3.00	1.23	08-Apr-11		0	23-Jan-11	333	0	>2419.6	0
9.44	10-Mar-11	7.00	1.06	09-Jun-11	43	16.129	27-Mar-11	193	0	248	0
3.45	20-Mar-11	20.00	0.968	16-Aug-11	136	51.0128	15-Apr-11	179	0	1050	0
9.39	31-Mar-11	49.00	0.71	09-Sep-11	18	6.75169	07-Jun-11	>24196	0	>24196	0
13.1	06-Apr-11	116.00	0.608	11-Sep-11	22	8.25206	09-Jun-11	7300	0	54100	0
	05-May-11	207.00	0.551	03-Oct-11	158	59.2648	22-Jun-11	10	0	148	0
	13-Jun-11	259.00	0.51	23-Oct-11	237	88.8972	16-Aug-11	31	0	146	0
	09-Sep-11		0.708				12-Sep-11	9804	0	>24196	0
							03-Oct-11	207	0	>2005	0
							11-Oct-11	>24196	0	>24196	0
							19-Oct-11	5493	0	8297	0

- Tugela River

TABLE B. 6: Results obtained from analysing Tugela River water.

	TURBIDITY					COD	TOC		ECOLI		COLIFORMS	
DATE	Raw	Date	Day	Permeate	DATE	Raw	Raw	DATE	Raw	Permeate	Raw	Permeate
29-Sep-10	19.8	01-Oct-10	1.00	1.285	28-Mar-11	78	29.2573	23-Nov-10	108	0	6488	0
02-Nov-10	21.4	05-Oct-11	39.00	0.637	16-Aug-11	11	4.12603	23-Jan-11	>2419.6	0	>24196	0
19-Nov-10	418	07-Oct-10	40.00	0.545	11-Sep-11	18	6.75169	27-Mar-11	692	0	2230	0
29-Nov-10	1000	02-Dec-10	100.00	0.46	20-Sep-11	26	9.75244	15-Apr-11	1252	0	1947	0
14-Dec-10	593	15-Dec-11	125.00	0.432	03-Oct-11	28	10.5026	07-Jun-11	3720	0	12033	0
15-Aug-11	60	09-Feb-11	189.00	0.4	11-Oct-11	40	15.0038	16-Aug-11	4198	0	6167	0
24-Sep-11	68.8	10-Oct-11	210.00	0.397	23-Oct-11	45	16.8792	12-Oct-11	1565	0	10462	0
08-Oct-11	>1000		257.00	0.41				19-Oct-11	1947	0	11199	0
17-Oct-11	272							21-Nov-11	771	0	6910	0
15-Nov-11	114									0		0
21-Nov-11	226									0		0
										0		0

B.3 Raw data for the testing of the hypothesis

TABLE B. 7 : Raw data obtained from running systems under controlled water quality.

Time			Volume (mL)								
			Low NTU & Bact, High O			Low Bact, High O & NTU			Low NTU & High O & Bact		
Time (min)	Time (hr)	Time (days)	1	2	3	4	5	6	7	8	9
10	0.17	0.01	2.5	4.5	2.3	4	4.3	5	1.8	5.5	3
20	0.33	0.01	5.0	8	4.1	7.1	8.2	10	2.8	9.8	5.5
30	0.50	0.02	6.8	10.5	4.6	9.1	11.2	13.1	3.8	13.3	7.5
40	0.67	0.03	8.6	13	5.6	11.1	14	16.6	5.1	17.2	9.5
50	0.83	0.03	10.5	15.9	6.6	13.1	17.1	20.1	6.4	20.9	11.6
60	1.00	0.04	12.3	18.4	7.6	15.2	20.1	23.5	7.6	24.4	13.5
70	1.17	0.05	14	20.9	8.2	17.2	23	26.7	8.6	27.9	15.5
910	15.17	0.63	182	248.9	103.7	205.2	256	278.7	129.1	294.9	175.5
970	16.17	0.67	192.5	261	110.7	216.7	270	294.2	138.1	311.9	186.5
1390	23.17	0.97	274.6	354	150.7	81.2	365	396.5	198.1	413.9	256.5
2830	47.17	1.97	531.6	631	260.7	332.2	652	721.5	413.1	740.9	496.5
4030	67.17	2.80	712.6	831	348.7	522.2	862	936.5	614.1	969.9	696.5
5530	92.17	3.84	912.6	1049	466.7	731.2	1092	1165.5	866.1	1209.9	927.5
9550	159.17	6.63	1405.6	1584	866.7	1219.2	1672	1730.5	1486.1	1809.9	1519.5
11290	188.17	7.84	1595.6	1794	1081.7	1399.2	1912	1950.5	1735.1	2046.9	1749.5
12670	211.17	8.80	1735.6	1949	1278.7	1535.2	2092	2111.5	1925.1	2225.9	1924.5
14290	238.17	9.92	1900.6	2129	1518.7	1695.2	2302	2294.5	2147.1	2375.9	2074.5
15670	261.17	10.88	2040.6	2279	1708.7	1827.2	2472	2444.5	2332.1	2544.9	2243.5
21430	357.17	14.88	2550.6	2829	2386.7	2317.2	3112	2986.5	3002.1	3173.9	2858.5
22990	383.17	15.97	2695.6	2979	2568.7	2442.2	3277	3126.5	3172.1	3333.9	3018.5
24430	407.17	16.97	2827.6	3119	2738.7	2560.2	3428	3256.5	3332.1	3483.9	3168.5
25810	430.17	17.92	2952.6	3248	2897.7	2668.2	3567	3376.5	3482.1	3624.9	3309.5
30370	506.17	21.09	3367.6	3666	3407.7	3013.2	4005	3756.5	3954.1	4075.9	3754.5
31450	524.17	21.84	3460.6	3761	3526.7	3092.2	4103	3843.5	4064.1	4174.9	3853.5
32950	549.17	22.88	3598.6	3896	3691.7	3204.2	4243	3964.5	4214.1	4316.9	3993.5
34210	570.17	23.76	3711.6	4008	3826.7	3299.2	4357	4064.5	4339.1	4434.9	4109.5
39910	665.17	27.72	4196.6	4503	4417.7	3714.2	4842	4484.5	4869.1	4954.9	4629.5
41710	695.17	28.97	4352.6	4664	4611.7	3848.7	4995	4617	5036.6	5120.4	4781.5
43090	718.17	29.92	4475.6	4791	4763.7	3955.7	5115	4722	5166.6	5251.4	4906.5
44110	735.17	30.63	4566.6	4884	4880.7	4035.7	5205	4800	5264.6	5348.4	4996.5
45490	758.17	31.59	4686.6	5006	5030.7	4140.7	5325	4900	5393.6	5477.4	5116.5
49990	833.17	34.72	5074.6	5408	5530.7	4479.7	5705	5232	5803.6	5897.4	5507.5
51430	857.17	35.72	5199.6	5538	5690.7	4588.7	5825	5338	5933.6	6029.4	5632.5
54550	909.17	37.88	5469.6	5816	6034.7	4815.7	6080	5563	6209.6	6324.4	5902.5

ANNEXURE C

Sample calculations

C.1 COD conversion to TOC

Recorded data from analysis of COD = 83 mg/L

From section 3.3.6.3 we know that:

$$\frac{COD}{TOC} = 2.666 \qquad [\mathbf{3.2}]$$

Therefore: $TOC = \frac{COD}{2.666} = \frac{83\ mg/L}{2.666} = 31.1\ mg/L$

C.2 Flux Calculations

Flux is a measure of collected volume over a specific areas and time frame

$$Flux = \frac{Volume}{(TimexArea)} = \text{L / (h.m}^2\text{)} \qquad [\mathbf{2.2}]$$

Recorded Data from experimentation:

Time	10	minutes
Volume	4.5	mL
Diameter of membrane	47	Mm

C2.1 Area of membrane

$$Area = \frac{\pi\ x\ D^2}{4} \qquad [\mathbf{C.1}]$$

$$= \frac{3.142\ x\ (47\ x10^{-3})^2}{4}$$

$$= 0.00174\ m^2$$

C2.2 Conversion of collected volume

$$Volume = 4.5\ mL\ x\ \frac{1\ L}{1000 mL} = 0.0045\ L$$

C2.3 Conversion of time

$$Time = 10\ minutes\ x\ \frac{1\ hour}{60\ minutes} = 0.1667\ hour$$

Therefore substituting in Eq. (3) we get:

$$Flux = \frac{0.0045}{0.00174\ x\ 0.1667} = 15.5\ \frac{L}{m^2\ x\ hr}$$

C.3 Statistical Analysis of data

Recorded data from Umgeni Rover without covering:

Area of Membrane =	1.74E-03	m^2													
		Volume of filtrate (mL)				Volume of filtrate (L)				Flux (L/m2.hr)				AVG Flux	Standard Deviation
Time (min)	Time (hr)	1.00	2.00	4.00	5.00	1.00	2.00	4.00	5.00	1.000	2.000	4.000	5.000		
60	1	13	14	11	13	0.013	0.014	0.011	0.013	7.58	7.85	6.60	7.70	7.43	0.56
120	2	26	27	23	27	0.026	0.027	0.023	0.027	7.58	7.85	6.60	7.70	7.43	0.56
180	3	40	41	34	40	0.040	0.041	0.034	0.040	7.58	7.85	6.60	7.70	7.43	0.56
240	4	53	55	46	54	0.053	0.055	0.046	0.054	7.58	7.85	6.60	7.70	7.43	0.56
300	5	66	68	57	67	0.066	0.068	0.057	0.067	7.58	7.85	6.60	7.70	7.43	0.56
360	6	79	82	69	80	0.079	0.082	0.069	0.080	7.58	7.85	6.60	7.70	7.43	0.56

Mean sample calculation for Umgeni River without covering for the first 1 hour:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad \textbf{[C.2]}$$

$$= \frac{7.58 + 7.85 + 6.60 + 7.70}{4}$$

$$= 7.43$$

Standard Deviation calculation for BL without covering for 60 minutes

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(x - \bar{x}\right)^2}{(n-1)}} \qquad \textbf{[C.3]}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(7.58 - 7.43)^2 + (7.85 - 7.43)^2 + (6.60 - 7.43)^2 + (7.70 - 7.43)^2}{(4-1)}}$$

$$= \sqrt{\frac{(0.0225 + 0.1764 + 0.6889 + 0.0729)}{3}}$$

$$= 0.565$$

ANNEXURE D

TABLE D. 1: Microbiological safety requirements obtained from the series of drinking water quality framework for South Africa (SANS 241:2011).

Determinand	Risk	Unit	Standard Limits
E. coli [a] or faecal coliforms [b]	Acute health – 1	Count per 100 mL	Not detected
Cytopathogenic viruses [c]	Acute health – 2	Count per 10 L	Not detected
Protozoan Parasites [d]			
Cryptosporidium spp	Acute health – 2	Count per 10 L	Not detected
Giardia spp	Acute health – 2	Count per 10 L	Not detected
Total coliforms [e]	Operational	Count per 100 mL	≤ 10
Heterotrophic plate count [f]	Operational	Count per mL	≤ 1 000
Somatic coliphages [c, g]	Operational	Count per 10 mL	Not detected

[a] Definitive, preferred indicator of faecal pollution.

[b] Indicator of unacceptable microbial water quality, could be tested instead of *E. coli*, but is not the preferred indicator of faecal pollution. Also provides information on treatment efficiency and after growth in distribution networks.

[c] Confirms a risk of human infection and faecal pollution, and also provides information on treatment efficiency. The detection of selected viruses confirms faecal pollution of human origin.

[d] Confirms a risk of infection and faecal pollution, and also provides information on treatment efficiency. The detection of selected protozoan parasites confirms a human health risk.

[e] Indicates potential faecal pollution and provides information on treatment efficiency and after growth.

[f] Process indicator that provides information on treatment efficiency, after growth in distribution networks and adequacy of disinfectant residuals.

[g] Process indicator that provides information on treatment efficiency.

TABLE D. 2: Physical, organoleptic and chemical requirements for South African safe drinking water (SANS 241:2011).

Determinand	Risk	Unit	Standard Limits [a]
Physical and aesthetic determinands			
Free chlorine	Chronic health	mg/L	≤ 5
Monochloramine	Chronic health	mg/L	≤ 3
Colour	Aesthetic	mg/L Pt-Co	≤ 15
Conductivity at 25 °C	Aesthetic	mS/m	≤ 170
Odour or taste	Aesthetic	—	Inoffensive
Total Dissolved Solids	Aesthetic	mg/L	≤ 1 200
Turbidity [b]	Operational	NTU	≤ 1
	Aesthetic	NTU	≤ 5
pH at 25 C [c]	Operational	pH units	≥ 5 – ≤ 9.7
Chemical determinands — macro-determinands			
Nitrate as N [d]	Acute health - 1	mg/L	≤ 11
Nitrite as N [d]	Acute health - 1	mg/L	≤ 0,9
Sulfate as SO_4^{2-}	Acute health - 1	mg/L	≤ 500
	Aesthetic	mg/L	≤ 250
Fluoride as F^-	Chronic health	mg/L	≤ 1,5
Ammonia as N	Aesthetic	mg/L	≤ 1,5
Chloride as Cl^-	Aesthetic	mg/L	≤ 300
Sodium as Na	Aesthetic	mg/L	≤ 200
Zinc as Zn	Aesthetic	mg/L	≤ 5
Chemical — micro-determinands			
Antimony as Sb	Chronic health	µg/L	≤ 20
Arsenic as As	Chronic health	µg/L	≤ 10
Cadmium as Cd	Chronic health	µg/L	≤ 3
Total Chromium as Cr	Chronic health	µg/L	≤ 50
Cobalt as Co	Chronic health	µg/L	≤ 500
Copper as Cu	Chronic health	µg/L	≤ 2 000
Cyanide (recoverable)	Acute health - 1	µg/L	≤ 70
Iron as Fe	Chronic health	µg/L	≤ 2 000
	Aesthetic	µg/L	≤ 300
Lead as Pb	Chronic health	µg/L	≤ 10
Manganese as Mn	Chronic health	µg/L	≤ 500
	Aesthetic	µg/L	≤ 100
Mercury as Hg	Chronic health	µg/L	≤ 6
Nickel as Ni	Chronic health	µg/L	≤ 70
Selenium as Se	Chronic health	µg/L	≤ 10

Determinand	Risk	Unit	Standard Limits [a]
Uranium as U	Chronic health	µg/L	≤ 15
Vanadium as V	Chronic health	µg/L	≤ 200
Aluminium as Al	Operational	µg/L	≤ 300
Chemical — organic determinands			
Total organic carbon as	Chronic health	mg/L	≤ 10
Trihalomethanes			
Chloroform	Chronic health	mg/L	≤ 0.3
Bromoform	Chronic health	mg/L	≤ 0.1
Dibromochloromethane	Chronic health	mg/L	≤ 0.1
Bromodichloromethane	Chronic health	mg/L	≤ 0.06
Microcystin as LR [e]	Chronic health	µg/L	≤ 1
Phenols	Aesthetic	µg/L	≤ 10

[a] The health-related numerical limits are based on the consumption of 2 L of water per day by a person of a mass of 60 kg over a period of 70 years.

[b] Values in excess of those given in column 4 may negatively impact disinfection.

[c] Low pH values can result in structural problems in the distribution system.

[d] This is equivalent to nitrate at 50 mg NO_3/L and nitrite as 3 mg NO_2/L.

[e] Microcystin only needs to be measured where an algal bloom (>20 000 cyanobacteria cells per millilitre) is present in a raw water source. In the absence of algal monitoring, an algal bloom is deemed to occur where the surface water is visibly green in the vicinity of the abstraction, or samples taken have a strong musty odour.