TECHNICAL AND SOCIAL ACCEPTANCE EVALUATION OF AN ULTRAFILTRATION MEMBRANE SYSTEM FOR POTABLE WATER SUPPLY TO RURAL AND REMOTE COMMUNITIES.

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Dedicated to my Mother

ABSTRACT

When considering water treatment in small rural and peri-urban communities, sustainability is one of the most important factors to be considered. Sustainability needs to be considered from financial, technological and socio-political perspectives. The major problems with sustainability of conventional small water treatment systems are the difficulty of controlling chemical treatment processes, especially when the raw water quality changes, and the production of substandard quality water. Another very important problem is lack of community involvement, especially over the longer term. The acceptance of new technologies by the community is of crucial importance in ensuring successful water supply projects.

The anticipation of more stringent drinking water quality regulations and decrease in adequate water sources have brought membrane separation processes such as microfiltration and ultrafiltration on the advantage for potable water supply to rural and peri-urban areas. Membrane processes have the advantage of production of superior quality water and addition of fewer chemicals in the treatment process.

The purpose of this study was to further investigate the potential of ultrafiltration capillary membranes as a one-step membrane water treatment system for potable water supply to developing communities. To successfully transfer a technology to a particular community, the technology must be suitable and acceptable and a social study was therefore also done to understand the social acceptance factors that govern the acceptance of these new technologies. In conducting this research, a literature review on the advanced treatment technologies: ultrafiltration, microfiltration, reverse osmosis and electrodialysis was carried out.

The study focused on establishing the influence of process conditions on the rate of fouling and process efficiency, using four different waters in the Western Cape Province. Low-pressure capillary ultrafiltration membranes with a medium molecular cut off (MWCO) of approximately 50 000 Dalton were used for the study.

For the various waters two sets of evaluations were done using the same membranes viz a first set of tests would represents the results from clean membranes and the second set would represents results from fouled membranes. Each of the water samples were analysed after tests at different water percentage recoveries, ranging from 0% to 60%.

A comparison between their experimental behaviour under these process conditions was done, indicating that the first set of results has better permeate fluxes and a higher efficiency of production and operation than the second set of results. All the experiments were performed in the cross-flow mode of operation at a constant pressure of 1bar. Removal efficiencies of 99% for turbidity and TSS, and 97% for colour have been obtained for all ultrafiltration tests operating at a low constant pressure of 1 bar.

Capillary UF membranes have shown considerably potential for the supply of potable water to small communities. However correct choice and application of treatment technologies is crucial in ensuring long-term sustainability of the project. Therefore a specific community should be identified before hand where the technology would be refined further and evaluated on site in order to increase the general applicability and acceptability thereof, ensuring sustainability of the technology in place.

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SYMBOLS AND ABBREVIATIONS

SYMBOLS

(A/P)	- Amortisation Factor	
A_m	- membrane surface area	[m^2]
A_{mod}	- membrane area per module	[m^2]
a_p	- mass of one particle	[kg]
c	- particle concentration	[kg/m^3]
c_b	- concentration of particle in the bulk solution	[mg/l]
c_g	- concentration of particles in the gel	[mg/l]
c_{memb}	- specific membrane cost	[Rand]
c_{mod}	- specific cost of the module	[Rand]
C_{mod}	- cost per module	[Rand]
C_p	- solute concentration in permeate	[kg/m^3]
c_p	- concentration of particle in permeate	[mg/l]
C_s	- saturation concentration of air in water	[mg/l]
C_{tot}	- Annualised capital cost	[Rand]
c_w	- concentration of particles at the membrane wall	
d_s	- diameter of the solute molecules	[m]
g	- accelaration due to gravity	[m/s^2]
i	- intrest rate	
J	- permeate flux	[$l/m^2.h$]
K	- specific permeability of a medium	[m^2]
ΔL	- thickness of the medium	[m]
M_w	- molecular weight	[g/mole]
n	- number of particles per m^3	
N	- number of pores per m^2 of a membrane filter	
n_{mod}	- number of modules	
ΔP	- pressure difference across the medium	[Pa]
P_{bw}	- back wash pressure	[bar]
P_{feed}	- feed pressure	[bar]
Q_{bw}	- BW flow rate	[l/hr]

Q_{des}	- design capacity of the plant	[m^3/h]
Q_f	- feed flow rate	[l/hr]
r_c	- specific cake resistance	[m^{-2}]
R_m	- membrane resistance	[m^{-1}]
R_s	- solute hydraulic resistance	[m^{-1}]
TMP	- Transmembrane pressure	[Pa]

GREEK SYMBOLS

α	- specific cake resistance	[m/kg]
δ	- thickness of the cake	[µm]
$\Delta\pi$	- osmotic pressure difference across a membrane	[Pa]
η	- fluid absolute viscosity	[Ns/m^2]
ρ_s	- density of sediment particles	[kg/m^3]
ρ_s	- density of water	[kg/m^3]
ϖ	- Van der Waals constant	[Joule]
ε	- porosity of the cake layer	[%]
Π	- osmotic pressure	[Pa]
γ	- recovery	[%]

ABBREVIATIONS

DWAF- Department of Water Affairs and Forestry

IPS - Institute of Polymer Science

MF - Microfiltration

NF - Nanofiltration

RO - Reverse Osmosis

SABS - South African Bureau of Standards

TSS - Total Suspended Solids

UF - Ultrafiltration

WHO - World Health Organisation

WRC - Water Research Commission

NOM - Natural Organic Material

PSF - Polysulphone

1 INTRODUCTION

1.1 General

Water is a scarce and precious commodity in Southern Africa. South Africa in particular is a semi-arid country where 65% of the country receives less than 500mm of rainfall per annum. Twenty one percent of the country receives less than 200mm and as such all effluent has to be purified and returned to the rivers. (Botes J. *et al*, 1998). In many areas the available surface and subsurface resources cannot sufficiently supply the rapidly increasing water demand. In many areas water is being redirected from one catchment area to supplement that in another area.

There is also lack of adequate sanitation and this contributes to diffuse pollution with a resultant gradual deterioration in the quality of the water supplies. In many areas, the water quality is not monitored and the communities cannot afford even basic treatment facilities such as disinfection. Consequently, untreated groundwater or surface water is used in these areas for domestic purposes (Jacobs *et al*, 2000). A number of studies have shown that the drinking water quality in rural/peri urban areas and small communities, in South Africa, is very poor. Water-borne diseases have a direct impact on primary health in South Africa with diarrhoea alone being responsible for some 43 000 deaths per annum (Pergrum *et al,* 1998) with 20% of all deaths in the one to five years age group (Bourne and Coetzee, 1996). These matters are receiving significant government attention, and the Water Services Act (WSA) of 1997 and the National Water Act of 1998 herald some landmark changes in South African water law.

The Cape Peninsula is faced with the problem of rapid urbanization, and serious water shortages are forecasted. Because of the limited number of sites available for dam construction, and with relatively small rivers, an alternative would be to turn to unconventional resources in the longer term.

The Eastern cape is often faced with droughts and water had to be redirected from the Orange River to the Fish River to augment the regional water supply. The Orange River flows through desert regions with low rainfall and very high evaporation losses.

In South Africa every person is guaranteed the "right to access to health care services, sufficient food and water" for basic domestic needs and "social security" as reflected in the Bill of Rights. It is also considered to be a national development strategic priority to supply potable water to rural and peri-urban areas as reflected in the White Paper on water supply and sanitation, compiled by the Department of Water Affairs and Forestry (DWAF). Furthermore, the Water Research Commission (WRC) has also acknowledged the need for research into appropriate technology for rural and peri-urban areas as highlighted in the 1992 WRC master plan on research in potable water.

It is with the above in mind that water sources and treatment methods need to be investigated to supplement the existing water supplies (surface and borehole waters). Alternative sources that need to be investigated include the following.

- Waste water recycling to augment potable water supply
- Sea water desalination to augment potable water supply

- Industrial effluent reclamation to augment industrial water needs

For all of these sources above, it should be emphasized that each source needs a different effective method of investigation due to the very nature of the sources. Irrespective of the treatment method, the quality standards, as per the South African Bureau of standards (SABS 241 [1999]) and World Health Organization (WHO), both of which are very stringent, should be taken into consideration.

1.2 Problem Identification

The problem identified then is mainly about the water supply projects to small and remote communities, and more specifically treatment to produce potable water. The communities must have a need for the water supply and water treatment systems and must be given something that they would accept so that the water supply schemes can be successful and they can operate and maintain the systems in the longer run. They should then be involved right from the start of the project. The social acceptance factors for the rural communities should be fully known and taken care of, so that the new technologies are fully accepted and owned by the communities. Most of the effective water treatment plants in South Africa have failed to sustain because the poor communities do not even decide on the technology options and locating of water points. The local communities should be empowered and have a sense of ownership on the water supply scheme. They should be given what they want so that the technology can be easily accepted, operated and maintained to high standards.

Traditionally in South Africa small water treatment systems have made use of conventional processes. These unit processes, although effective on large-scale applications, have however proven to be troublesome for smaller-user systems, the result being production of sub-standard water and non-sustainability with the plant eventually falling into disuse (Mackintosh *et al*, 2000)

The anticipation of more stringent water quality regulations, a decrease in adequate water resources and an emphasis on water re-use have made membrane separation processes such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) more visible for potable water supply to rural and peri-urban areas. Membrane processes have the advantages of production of superior quality water, addition of fewer chemicals in the treatment process, reduced environmental impact of residual, low energy requirements for operation and maintenance and design and construction of smaller-scale systems which are easier to site and scale up. (Owen *et al*, 1995). The major limitation to membrane filtration is the fouling of the membrane, which result in flux decline.

1.3 Hypothesis

- Sustainable water treatment for small communities requires correct choice and application of water treatment technology.
- Effective community participation in water supply projects will ensure a fully trouble-free acceptance of the new technologies. Active participation in planning and implementation ensures community empowerment and has a direct influence on the sustainability of the technologies, thus producing healthy, safe and acceptable drinking water.

1.4 Goals

- Evaluate Ultrafiltration membrane technology for different raw water qualities, with the view of establishing guidelines for effective technology transfer to small and remote communities.
- Determine what the critical social acceptance factors are for technology transfer to small and remote communities.

1.5 Objectives of the Study

- Evaluation of Ultrafiltration membrane technology for potable water supply to rural and remote communities.
- To understand the social acceptance factors for the use of membrane technology systems for water supply to rural and developing areas.
- Report on cost comparisons between membrane filtration package plants and conventional treatment plants.

1.6 Scope of the study

This study was carried out to evaluate technical and social acceptance of membrane technologies for water supply to rural and remote communities in the Western and Eastern Cape Provinces. The bench scale evaluation of the UF system was done on four raw waters in the Cape Town/Boland area. The identified waters are Eutrophic water (algae water) from Voëlvlei Dam, coloured water from Duivenhoks River, tertiary wastewater effluent from Bellville Waste Water Treatment Plant, ground water from Peninsula Technikon Lake. The UF technology was evaluated at Peninsula Technikon water laboratories for treatment of each of these waters, for the removal of unwanted organic and inorganic substances from the water. Water quality parameters that were analysed of the treated water to determine the removal efficiency by the membrane were, turbidity, colour, iron and algae. Feacal Coliform (FC) and *Escherichia coli* were also analysed to determine the removal efficiency of the membrane. Literature study was based on the technologies and what other people have done in South Africa. Social acceptance factors are very critical in ensuring:

- Trouble-free acceptance by the communities
- Project success
- Long-term sustainability of the water supply projects.

2 LITERATURE REVIEW

A membrane can be defined as a selective barrier that permits separation of certain species in a fluid by a combination of sieving and sorption diffusion mechanisms (Singh, 2000). In terms of energy, membrane separations have an important advantage in that, unlike evaporation and distillation, no change of phase is involved in the process, thus avoiding latent heat requirements. No heat is necessarily required with membranes, thus it is very possible to produce products with functional properties superior in some respect to those produced by conventional processes.

A membrane can selectively separate components over a wide range of particle sizes and molecular weight, from macromolecular materials such as starch and protein to monovalent ions (Singh, 2000). A membrane should be selected such that the sizes of the pores are smaller than the size of the smallest particle in the feed stream that is to be retained by the membrane. Membranes are available in several different configurations – i.e. tubular, hollow fiber, plate and frame, and spiral-wound. Some of these designs may work better than the others for a particular application, depending on such factors as viscosity, concentration of suspended solids, particle size, and temperature.

The membrane processes are classified according to the driving force used in the process. The various membrane processes along with the driving force are listed in Table 2.1.

Table 2.1 *Membrane Processes with their driving forces* (Singh, 2000).

Driving Force	Processes
Pressure	Microfiltration, Ultrafiltration, Nanofiltration, Reverse Osmosis
Electrical Potential	Electrodialysis
Partial pressure	Pervaporatoin
Concentration Gradient	Dialysis

The process of cross-flow pressure-driven membrane filtration is very simple, requiring only the pumping of the feed stream tangentially across the appropriate membrane i.e. parallel to the membrane surface. The membrane splits the feed stream into two streams: one stream is the permeate, consisting of components small enough to pass through the membrane pores; the other stream is the concentrate (retentate) consisting of all the components large enough to be retained by the membrane. The retentate stream is usually recirculated through the membrane module because one passage through the membrane may not deplete the feed significantly.

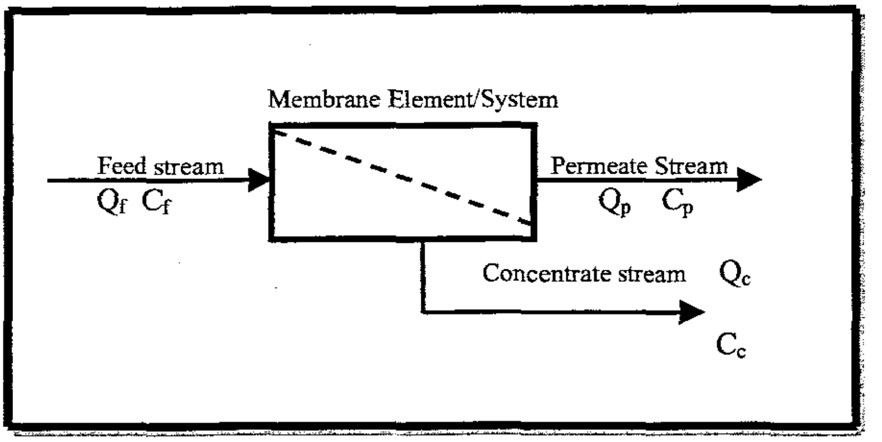
Cross-flow velocity is the average rate at which the process fluid flows parallel to the membrane surface. The velocity has a major effect on the permeate flux. The permeate flux depends on the applied transmembrane pressure for a given surface area up to a threshold transmembrane pressure. It is very important to check on the applied pressure, since high pressure may aggravate fouling of the membrane (Cheryan, 1986)

2.1 Membrane Processes in Drinking Water Treatment

Membrane filtration is the general name for processes that use a semi-permeable membrane for the separation of water and various contaminants (AWWA, 1992). Separation through the membrane takes place as a result of a ***driving force*** i.e., the difference of pressure or concentration, temperature and electrical potential applied to the membrane. Pressure-driven membrane processes which are mainly used in the water industry nowadays, are often categorized according to the size of contaminants that a membrane will effectively remove, *i.e., microfiltration, ultrafiltration, nanofiltration* and *reverse osmosis* (AWWA, 1992).

These processes differ in the size range of permeating species, the mechanism of rejection, the relative magnitudes of permeate flux and the pressure differential across the membrane (Wiesner, 1995). The basic difference of separation mechanisms between them is that during filtration in UF/MF solute separation mainly occurs by a *sieving action* although the separation is influenced by interactions between the membrane surface and the solution whereas solute separation by RO/NF depends not only on size differences but can be affected by other factors, *e.g.,* diffusion, material, ionic charge, or vapor pressure (Taylor, 1987). In many cases, however, removal by adsorptive mechanisms in UF/MF is also very significant and under such conditions UF/MF may remove species, *i.e.,* dissolved organics matter well below the membranes rating (Gutman, 1988). Figure 2.1.1 shows the schematic representation of a membrane process with appropriate streams (Cartwright, 1992)

Figure 2.1-1 Schematic representation of a membrane process with *appropriate streams (Cartwright,1992)*



Q_f = feed flow rate
C_f = solute concentration in feed
Q_p = Permeate flow rate
C_p = Solute concentration in permeate
Q_c = Concentrate flow rate
C_C = Solute concentration in concentrate

2.1.1 Reverse Osmosis

Reverse Osmosis, often referred to as *hyperfiltration,* is a membrane operation in which the solvent of the solution is transferred through a dense membrane to retain salts and high molecular weight solutes. RO membranes, which are usually operating under very high pressure differentials, *i.e.,* 10 to 100 bar, in order to overcome the osmotic pressure of a solution, are capable of rejecting contaminants or particles with diameters as small as 0,0001µm (AWWA *et al,* 1996). Osmotic pressure is a property of the solutions, not depending in any way on the properties of the membrane. For dilute solutions, osmotic pressure is given by the modified ***van't Hoff*** equation

$$\Pi = N_i * C * \left(\frac{R_g}{M}\right) * T$$

where,

Π = osmotic pressure (Pa)

C = concentration (mg/l)

M = molecular mass

R_g = universal gas constant (J/mol * k)

T = absolute temperature (K)

N_i = number of ions formed if the solute dissociates.

This type of membrane process has traditionally been employed for desalination of seawater but is recently used for surface water treatment.

2.1.2 Nanofiltration

Nanofiltration, often called *membrane softening* or *loose RO,* lies between RO and ultrafiltration in terms of selectivity of the membrane (Talor *et al*, 1987). It was primarily developed as a membrane softening process to serve as an alternative to chemical softening, but more recently it has also been used for organics control. NF can reject contaminants greater than 0,001 μm, *i.e.,* nanometer size, and are operating under pressure between *ca.* 10-30 bar. In drinking water treatment, NF is applied for partial desalination, softening, removal of pesticide and disinfection by-products (DBP_s) precursors depending on the membrane material and molecular weight of the pesticide. Additional disinfection is recommended to ensure the safety of water.

2.1.3 Ultrafiltration

Ultrafiltration is a membrane process with membranes in the wide range of the pore size of 0,001 – 0,1μm, operating under pressure range of 3-10 bar (Cheryan, 1986). The primary separation mechanism in ultrafiltration is selective sieving through the membrane pores. Dissolved salts, non-ionic materials and small particles (< 0,1μm) pass through the semi-permeable membrane in the liquid phase while larger solids are rejected and concentrated (Tansel B. *et al*, 1995). UF has the capability to retain colloidally dispersed particles, such as clays and paints, silts as well as macro molecules such as proteins and all bacteria whereas it allows dissolved substances and low molecular compounds to pass through. UF is particularly attractive for surface water treatment due to its removal efficiency of suspended solids, colloids and microorganisms because the finer separation capabilities of RO/NF will probably not be needed in some cases (AWWA *et al*, 1996). In addition, they require much lower pumping pressure for operation and also yield higher flux and no brine disposal is associated with them. Ultrafiltration is used as a pretreatment for NF/RO, or direct treatment for surface water as combined with UF/powered activated carbon, UF/oxidation and UF/bioreactor (Aptel, 1994).

2.1.4 Microfiltration

Microfiltration is a pressure driven membrane process of retaining particles down within a micron size (0,1-10 μm), operating with low pressure (50-500 kPa) (Roesink, 1989). Microfiltration allows removal of bacteria, colloidal and suspended matter larger than its pore size whereas smallest microorganisms such as virus can pass through the MF membrane. The primary application for this membrane process is particle and microbial removal. Microfiltration membrane can be divided into two broad groups on their pore structure. These are membranes with capillary type pores, hereafter called screen membranes and membranes with tortuous-type pores, hereafter called depth membranes. Table 2.1.1 shows the classification of membrane process used in drinking water treatment.

Table 2.1-1 Classification of pressure driven membrane filtration (Roesink, 1990)

Items	Pore Size	Δ P (bar)	MWCO	Application
MF	0.1 – 10 μm	0.5 – 5	> 100,000	separation of particles
UF	1 – 20 μm	3 – 10	1,000 – 200,000	separation of macromolecules
NF	<1 nm	10 – 30	200 – 1,000	separation of multivalent ions and low molecule mass solutes
RO	< 0.1 nm	30 – 100	200	separation of monovalent and low molecule mass

* MWCO = Molecular weight cut off at which 90% of compound is retained

2.2 Classification of Membranes

A membrane is clearly the most important part of the separation module because every membrane separation process is characterized by the use of a membrane to accomplish a particular separation. The semi-permeable membrane acts as a selective barrier which permits the passage of one component more readily than others. The membranes used in various processes can be classified according to different criteria as mechanisms of separation, physical morphology, chemical nature and geometry (AWWA *et al*, 1996).

2.2.1 Classification according to Separation Mechanism

There are essentially three mechanisms of separation, which depend on one specific property of the components to be selectively removed or retained by the membrane, *i.e.*, sieving effect, solution-diffusion mechanism and electrochemical effect. The classification of membranes based on separation mechanisms leads to three main classes *i.e.*, **porous, non-porous** and **ion-exchange membranes.**

Porous membrane: Porous membranes are mainly used in UF/MF and their pore dimension mainly determines the separation characteristics. High selectivity can be obtained when the solute size is large relative to the pore size in the membrane (Mulder, 1990).

Non-porous membrane: Non-porous membranes, which are considered as dense media, are mainly used in reverse osmosis, gas separation and pervaporation process. Its separation is based on the differences in solubility and diffusivity of materials in the membrane, *i.e.*, the intrinsic properties of the polymer material determine the extent of selectivity and permeability (Mulder, 1990).

Ion-exchange membrane: Ion-exchange membranes are a specific type of non-porous membranes, consisting of highly swollen gels carrying fixed positive or negative charges. A membrane with fixed positive charges is called an anion exchange membrane whereas a cation exchange membrane has fixed negative charge (AWWA, 1996).

2.2.2 Classification according to Morphology

Membranes can be classified into two categories according to morphology, *i.e.,* symmetric or asymmetric.

Symmetric membrane: Symmetric membranes mean a constant pore size (or pore size distribution) over the whole cross section of the membrane (Weink, 1993). These membranes usually have a thickness a 10 to 200μm with pore or non-pore (Mulder, 1990). The flux of permeate is inversely proportional to thickness of membrane, meaning that decrease in membrane thickness results in increased permeation rate. Therefore, asymmetric membranes were developed for this purpose.

Asymmetric membrane: Asymmetric membranes have a thin dense *skin-layer* (0,1-1μm) supported by a porous sublayer with a thickness of about 50-150μm. The small thickness of the skin layer results in a low resistance for transport through the membrane, easy to clean, and fairly high flux. The membranes usually used in UF are these types of membranes. *Composite* membranes are a special group of asymmetric membranes with a very thin dense top layer. In these membranes, the top layer and sub layers originate from different materials. Each layer can be optimized independently.

2.2.3 Classification according to Chemical Nature

The synthetic membranes which are mostly used in drinking water treatment can be subdivided into **organic** and **inorganic** membranes (Mulder, 1993)

Organic Membrane: Organic membranes are most common and offer the greatest degree of flexibility with respect to rejection characteristics and module design. In general, the advantages of organic membranes compared to inorganic membranes are mostly: easy processing, low cost, availability of wide structure variations, possibility to realize any configuration (Roesink, 1989). Disadvantages are their inferior stability at high temperature, the reduced chemical resistance and also time dependent relaxation phenomena.

The main types of polymer membranes are cellulose acetate membrane, polyamide membrane and polysulfone membrane. Polysulfone membranes are widely used in UF applications which are considered quite a breakthrough to a UF application due to wide temperature limits (up to 75°C), wide structure, pH tolerances (pH 1-13), fairly good chlorine resistance, easy to fabricate in a variety of configuration and wide range pore size available for UF applications when compared to other organic membranes. The main limitations of polysulfone membranes are the low pressure limits *i.e.,* typically 1,5 bar with hollow fiber, 7 bar with flat sheet (Cheryan, 1986).

Inorganic membrane: Inorganic membranes, often described as mineral or ceramic membranes, can be made from silica-glass (SiO_2) or alumina materials. They generally have greater mechanical strength and greater tolerance to chlorination and extremes in pH and temperature compared with organic membranes (AWWA, 1992). Ceramic membranes are presently available in tubular form and microfiltration pore size, and their initial cost is greater than the cost of polymer membranes (Roesink, 1989). Table 2.2.1 shows the properties of various types of membranes used in UF/MF.

Table 2.2-1 Properties of various membranes (AWWA, 1992)

Membrane Material	pH range	Tolerance to Chlorine(mg/l)	Max. temperature (°C)
Membrane Acetate	2 - 10	~1	50
Polyamide	2 - 12	< 0.1	80
Polysulfone	1 - 13	~100	80
Aluminum Oxide (Ceramic)	0 - 14	> 100	> 100

2.2.4 Classification according to Geometry

Membranes can be classified in two different configuration (*modules*), *i.e.,* flat and tubular (Weink, 1993). *Flat* membranes involve plate-and-frame and spiral wound module whereas tubular, capillary and hollow fiber modules are based on tubular membrane configurations. The difference between the latter types of modules is the dimensions of the tubes employed (Weink, 1993):

- tubular membrane : internal diameter > 5mm
- capillary membrane : internal diameter 1-5mm
- hollow-fiber : internal diameter <1mm

Hollow fiber: Hollow fibre modules have the advantage of a large surface area-to-volume ratio (packing density) and simplicity of construction, but they are more susceptible to fouling than any of the other modules due to narrow spacing. They can be cleaned by backflushing which tends to compensate for their propensity to fouling. In UF, backwashing is carried out by placing the permeate under a pressure greater than the feed pressure (AWWA *et al*, 1996).

Tubular: Tubular membrane modules are used in cases where the concentration of suspended solids are sufficiently high so as to block flow channels *e.g.* wastewater. Tubular membranes are preferred in view of the ease of cleaning (with sponge-balls) but are more expensive and cost more to operate than spiral wound membranes (Roensink, 1990).

Spiral wound: Spiral wound modules, is essentially a flat sheet rolled, i.e., an envelope of two membranes enclosing a permeate spacer which is sealed along three edges and the fourth edge is connected and rolled up onto a perforated tube which carries the product water. They have shown the best compromise in compactness, sturdiness and limited susceptibility to fouling (AWWA, 1996). In drinking water treatment the hollow fibre and spiral wound modules are the most often applied. Table 2.2.2 below shows the characteristics of membrane modules commonly used in water treatment.

Table 2.2-2: *Qualitative comparison of various membrane configurations (Mulder, 1990)*

Items	**Tubular**	**Plate-and-frame**	**Spiral wound**	**Hollow fiber**
Packing density	low	→	→	very high
Investment	high	→	→	low
Fouling tendency	low	→	→	very high
Cleaning	good	→	→	poor
Operating cost	high	→	→	low
Membrane replacement	yes/no	yes	no	no

2.3 Process Modes in Membrane Operation

In order to use membranes in the treatment process, the membranes are packed in units called modules. Membrane modules can then be operated in two process modes namely ***dead-end*** (normal) and ***cross-flow,*** which are represented in figure 2.3.1.

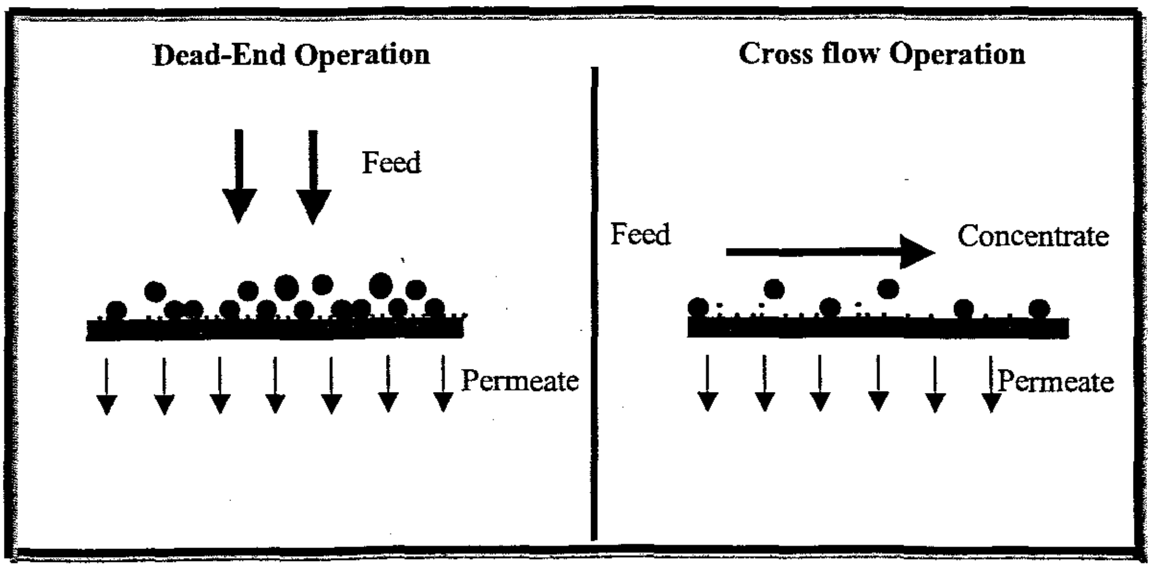
2.3.1 Dead-End Mode

In dead-end mode, the flow direction of feed is perpendicular to the membrane surface, leading to the continuous formation of a cake layer that causes a rapid flux decline. The main advantage of the dead-end filtration mode is simplicity. The feed suspension is not recycled or passed across the membrane and costly exit ports to accomplish this are unnecessary. In this mode, the cake grows with time and consequently the flux decreases with time. Intense polarization and membrane fouling can occur under these conditions (Belfort, 1994). The permeate flux drag all solutes, suspended and dissolved materials towards the membrane resulting in solute intrusion and adsorption into and / or deposition onto the membrane. As a result, the dead-end filtration process must be stopped periodically in order to remove the particles or to replace the filter media or else, the cake must be continuously discharged (Davis, 1992).

2.3.2 Cross-Flow Mode

In cross-flow mode, the flow direction of feed is parallel to the membrane surface. Unlike dead-end filtration, a cake layer does not build indefinitely. Instead, the high shear exerted by the suspension flowing tangential to the membrane surface sweeps the particles toward the filter exit so that the cake layer remains relatively thin (Davis, 1992). This allows relatively high fluxes to be maintained over prolonged time periods. For industrial applications, cross flow operation is preferred because of the *lower fouling tendency* relative to dead-end mode (Belfort, 1984), but they require *higher energy* to maintain a high velocity over membrane for continuous operation.

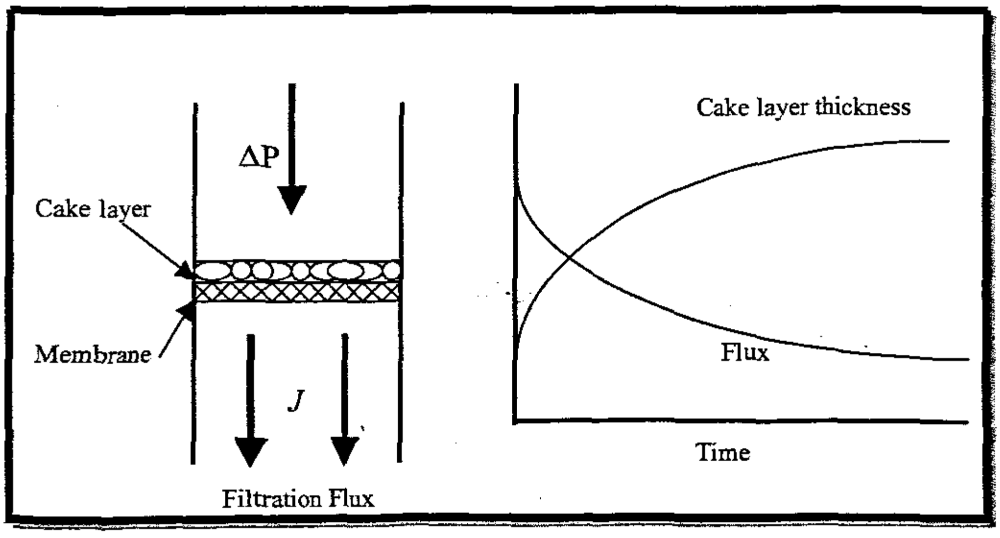
Figure 2.3-1 *Schematic drawing of the two operational modes (Roensink, 1989)*



2.4 Flux Decline

The flux (rate of permeate production per unit membrane area) during UF/MF will decrease over time as the filtration process takes place. Flux decline is one of the most important reasons why membrane processes are not used on much scale (van den Berg *et al.*, 1990). It is caused by several phenomena inside, on and near the membrane which lead to a decrease in driving force and/or an increased resistance. Flux decline is relatively smaller in the cross flow mode and can be controlled and adjusted by proper module choice and cross-flow velocities. In dead-end UF, fouling is the major cause of flux decline. The cake deposits growth with time of filtration and can only be controlled by appropriate cleaning. The consequences of fouling in dead-end systems are shown schematically in figure 2.4.1 (Mulder, 1990).

***Figure 2.4-1** Flux decline in dead-end filtration (Mulder, 1990)*



2.4.1 Characteristics of Flux Decline

Flux during membrane process of a solution or suspension decreases over time. It can be caused by several reasons *i.e.*, change in **membrane properties, concentration polarization** and **membrane fouling** (Renard, 1998). Among them, flux decline is mainly due to concentration polarization and fouling (Mulder, 1990).

(a) Change in Membrane Properties

Change in membrane properties can occur as a result of physical, chemical and biological deterioration. *Physical* deterioration of the membrane can be described as a *"compaction"* phenomenon. Compaction is the mechanical deformation of the membrane matrix due to the imposed pressure during the process. During the pressure-driven processes, the membrane structure densifies and as a result the flux declines. By reducing the pressure, the flux will not return to its original value depending on whether the deformation due to compaction was reversible or irreversible (Mulder, 1990). Compaction is usually not of concern in UF/MF applications where pressures are low because it usually occurs when pressures are hundreds of pounds per square inch (Cheyan, 1986).

Chemical deterioration could occur if the pH, temperature, and other environmental factors are incompatible with the particular membrane. In addition, different chemical agents used such as acid/base, chlorine and detergents may also cause change in membrane properties, resulting in flux decline. *Biological* deterioration is the accumulation of microorganisms in the membrane which result in *biodegradation* of the membrane (Cheryan, 1986).

(b) Concentration Polarization

Concentration polarization results from a build-up of a boundary layer of more highly concentrated solute on the membrane than in the bulk solution due to the convective transport of both solvent and solute. As a result, flux lowers due to either an increased hydrodynamic resistance in the boundary layer or higher local osmotic pressure decreasing the driving force. This phenomenon is reversible since its effect can be reduced by changing operating conditions *i.e.,* by decreasing pressure along the membrane or lowering the feed concentration (Cheryan, 1986).

In a cross-flow mode of the membrane process, polarization can be controlled and minimized by the use of crossflow. Cross-flow provides an effective mechanism for the transportation of accumulated solutes away from the surface of the membrane. In particular, concentration polarization phenomenon is severe in UF/MF because the fluxes and retention are high and the mass transfer coefficients are low as a result of the low diffusion coefficients of macromolecular solutes, small particles and colloids (Mulder, 1990).

This concentration is highest at the membrane surface and decreases exponentially towards the solution. In the case of the higher molecular weight substances, the solubility limit is often reached at the membrane surface. The precipitated layer acts as a secondary membrane referred to as gel-layer. Concentration in the gel-layer may also have a higher retention than the membrane itself, which increases the actual retention of the membrane as the filtration process proceeds. Concentration polarization can be reduced by diluting the process solution, stirring or tangential flow of the solution across the membrane surface (Laine, 1991)

(c) Fouling

Fouling can be defined as a reversible or irreversible deposition or adsorption of retained particles, colloids, and macromolecule on or in the membrane. In general, if flux decline is not reversible by simply changing the operating conditions, it is termed fouling (Scott, 1996). Fouling results in increased power consumption, time consuming and expensive washing and cleaning operations and reduced membrane life time (Howell, 1991).

2.4.2 Factors Affecting Flux Decline

There are four major operating parameters that affect the flux: *i.e.* ***trans-membrane pressure, feed concentration, temperature*** and ***hydraulic conditions*** (flow rate and turbulence) figure 2.4.2 (Cheryan, 1986).

(a) Trans-membrane Pressure

From the Darcy's law as described in Equation 2.5.2, flux is proportional to the applied pressure. Increasing the applied pressure should increase the flux under certain restricted conditions (*e.g.,* at low pressure, low feed concentration, and high feed velocity) which are under conditions where concentration polarization effects are minimal. However, above a *critical point,* increasing the pressure regardless of other operating conditions merely results in a compact concentration layer (gel-layer formation) and becomes less permeable to water (Cheryan, 1986).

$$J = \frac{\Delta P}{\eta R_t} \tag{2.4.1}$$

where:

J = filtrate flux

R_t = total resistance

ΔP = transmembrane pressure

η = fluid absolute viscosity

(b) Feed Concentration

The increased solute concentration on the membrane surface results in a significantly higher osmotic pressure, causing a decrease in the driving force (ΔP - $\Delta\Pi$). In addition, it causes an increase in hydrodynamic resistance of the gel and boundary layer, resulting in the flux decline. This can be explained well by *film theory* as;

$$J = \kappa \ln\left(\frac{C_g}{C_b}\right) \tag{2.4.2}$$

where:

C_g is gel layer concentration, C_b is bulk concentration, and the flux will decrease exponentially with increasing feed concentration.

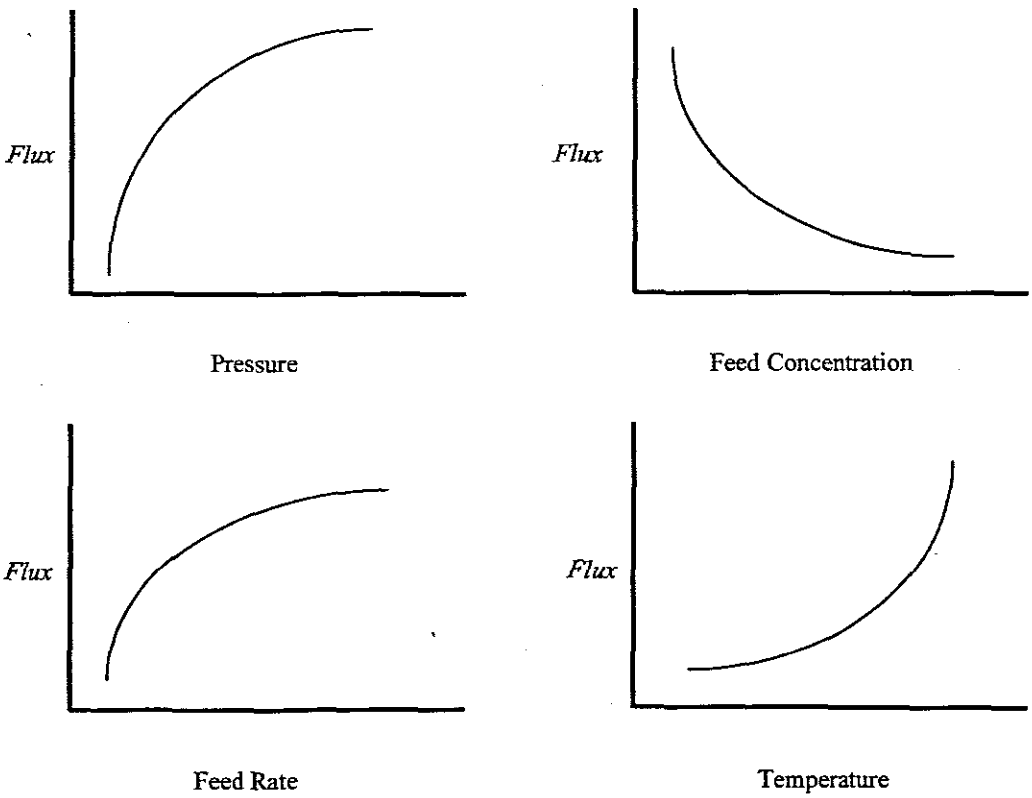
(c) Temperature

Higher temperatures will lead to higher flux because the viscosity decreases. Generally it is best to operate at the highest possible temperature that is consistent with the limits of the feed solution and the membrane (Cheryan, 1986). A rule of thumb is that membrane capacity increases about *3 percent* per degree °C increase in water temperature (Cheryan, 1986).

(d) Flow Rate and turbulence

Turbulence, whether produced by stirring or pumping of the fluid, has a major effect on flux in the mass transfer controlled region. High feed velocity (in crossflow mode) at the membrane surface tends to shear off deposited material and minimize the hydraulic resistance of the concentrated layer. The magnitude of the effect of flow rate on flux will depend on whether the flow is turbulence or laminar and the rheological properties of the fluid, i.e., whether it is Newtonian or non Newtonian (Cheryan, 1986).

Figure 2.4-2 Factors affecting flux decline (Gooding, 1985)



2.5 Flux Models

2.5.1 Clean Water Flux

In an ideal situation, e.g., with uniformly distributed and evenly sized pores in the membrane, no fouling, negligible concentration polarization, etc., the fluid flow through microporous membranes is given by the Hagen-Poiseuille law for laminar flow through pores (Cheryan, 1986):

$$J = \frac{\varepsilon\ r^2\ \Delta p}{8\eta\ \Delta x} \tag{2.5.1}$$

where:

J = flux through the membrane (l/m^2h)

r = channel radius (mean pore radius) (m)

Δx = thickness of membrane skin (m)

ε = porosity of the membrane (%)

η = velocity of the fluid permeating the membrane (Pa.sec)

Δp = transmembrane pressure drop (Pa or $kg/m{*}s^2$)

Several assumptions have been made in deriving this mode, i.e., flow through pores is laminar (Reynolds number less than 1800), density is constant (incompressible fluid), steady-state conditions and Newtonian fluid (Cheryan, 1986). According to this model, flux is directly proportional to the applied pressure and inversely proportional to velocity. Velocity is mainly controlled by two factors, i.e., feed characteristics (composition and concentration) and temperature. Thus, increasing the temperature or pressure should increase the flux.

The relation is true within certain limits, such as low pressures, low feed concentration, high feed velocities. When the process deviates from any of these conditions, flux become independent of pressure (Cheryan, *1986*). The asymptotic relation between flux and pressure is due to the effects of concentration polarization.

2.5.2 Darcy's law

When the sieving mechanism in UF/MF is dominant, a cake layer of rejected particles usually forms on the membrane surface. The cake layer and membrane may be considered as two resistances in series, and the pressure-driven permeate flux is then described by Darcy's law as: (Belfort *et al*, 1984).

$$J = \frac{\Delta p}{\eta \left(R_m + R_c\right)} \tag{2.5.2}$$

where:

R_m = membrane resistance (m^{-1}),

R_c = cake resistance (m^{-1})

The membrane resistance clearly depends on the membrane thickness, its nominal pore size, various morphological features such as the tortuosity, porosity, and pore size distribution. For a membrane whose pores consist of cylindrical capillaries radius perpendicular to the face of the membrane, the membrane resistance is obtained from Hagen-Poiseuille law (Eq. 2.5.1) as;

$$R_m = \frac{8}{\varepsilon} \frac{\Delta x}{r^2} \tag{2.5.3}$$

2.5.3 Filtration Theory

The following mechanisms may be involved in filtration through a membrane (Shippers and Verdouw, 1980):

- Depth filtration,
- Blocking filtration,
- Cake filtration (or gelfiltration) without compression,
- Cake filtration (or gelfiltration) with compression.

a) *Depth filtration*

In depth filtration, the particles penetrate deeply and deposit in the medium through which the water is filtered. It is unlikely that this mechanism can be of significance for any length of time, in view of the structure and thinness of membrane filters. On the other hand, this filtration mechanism, even if it occurs during a very short period, will cause a significant increase in the membrane filter resistance.

b) *Blocking filtration*

During blocking filtration, the pores are blocked by the particles present in the water. The simplest representation of this mechanism is based on the assumption that each particle completely blocks one pore. In this case the phenomenon can be described by the following equation (Schippers *et al*, 1980):

$$\frac{dV}{A\,dt} = \frac{\Delta p}{\eta\, R_m}\left(1 - \frac{c\,V}{a_p\, A\,N}\right) = \frac{\Delta p}{\eta\, R_m}\left(1 - \frac{n\,V}{A\,N}\right)$$

(2.5.4)

where:

V = filtrate volume (m^3)

t = filtration time (s)

A = membrane surface area (m^2)

Δp = pressure drop across filter (Pa)

η = absolute viscosity (kg/m s)

R_m = membrane resistance (m^{-1})

c = particle concentration (kg/m^3)

a_p = mass of one particle (kg)

N = number of pores per m^2 of a membrane filter ($1/m^2$)

n = number of particles per m^3 (l/m^3)

It follows from this equation that in the case of blocking filtration, a linear relationship may be expected between dV/dt and V when Δp and η are constant. When all the pores are blocked $dV/dt = 0$ and $n = A\ N / V_t$ where: V_t is the total volume that can be filtered through the membrane and ($A\ N$) is the number of pores in the filter. The reciprocal value of V_t is an index of the nature and concentration of the colloids present in the water (Schippers, 1980).

c) *Cake filtration*

The following equation can be applied to the filtration rate in respect of flow through a filter on which a cake has formed:

$$\frac{dV}{A\,dt} = \frac{\Delta p}{\eta} * \frac{1}{\left(R_m + R_c\right)}$$

(2.5.5)

where:

R_c = resistance of the cake or gel (m^{-1})

If there is no compression of the cake, then resistance of the cake equals to:

$$R_c = \frac{VR}{A} * I$$

(2.5.6)

where:

V = filtrate volume (m^3),

R = retention by the membrane filter,

I = index for the propensity of the particles in the water to form a layer with a hydraulic resistance (l/m^2).

In the case where all the particles are retained by the membrane, R = 1, I is a measure of the membrane fouling potential of the water. For a colloidal solution, I is a function of the dimensions and nature of particles, which is directly correlated to the concentration and is independent of pressure. The cake resistance can be related to particle properties using the equation 2.5.7 and 5.5.8 below (Schippers *et al.*, 1980).

$$R_s = \frac{V}{A} * \alpha * C_b$$

(2.5.7)

$$\alpha = \frac{180 \ (1-\varepsilon)}{\rho_s \ d_s^2 \ \varepsilon^3}$$

(2.5.8)

where:

α = specific resistance of the deposit (m/kg), calculated from the Kozeny-Carman relation,

C_b = concentration of the solute in the bulk (kg/m³).

ε = voidage of the cake,

ρ_s = density of solute (material forming the cake) (kg/m³).

Combining equation 2.5.2 and 2.5.6 above and neglecting osmotic pressure and integrating at constant ΔP and assuming $R = 1$ the equation below can be obtained;

$$\frac{t}{V} = \frac{\eta R_m}{\Delta P\, A} + \frac{\eta\, VI}{2\Delta A^2} \tag{2.5.9}$$

An index of the tendency of water containing colloidal material to foul a membrane can be obtained from equation 2.5.9 above. -

The term $\dfrac{\eta\, I}{2\ \Delta P\, A^2}$ is called the modified fouling index (MFI) and it can serve as an index of the tendency of water to foul a membrane when fixed reference values are used for ΔP, η and A.

d) Cake filtration with compression

When the pressure is increased further beyond the limiting flux value, the flux may decrease due to compaction of the membrane and/or the cake layer. Because of the low pressures normally applied in UF, it is questionable whether the porosity of UF membrane is influenced to any appreciable extent. It is however, a reasonable assumption that as the porosity of the membrane increases, the susceptibility to deformation also increases.

For a membrane with surface porosity S_p, and cylindrical membrane pores with radius r_p and membrane skin thickness ΔL, the Hagen-Poiseuille equation for laminar flow through pores can be applied (Jõnsson A.S. *et al*, 1990).

$$J = \frac{S_p \, r_p^2 \, \Delta P}{8 \, \eta \, \Delta L} \tag{2.5.10}$$

The hydraulic resistance of a cake layer R_s, may be approximated from the Kozeny-Caman relation as in equation 2.5.11 below:

$$R_s = 180 \, \Delta L_s \, \frac{(1-\varepsilon)^2}{d_s^2 \, \varepsilon^3} \tag{2.5.11}$$

Where:

ΔL_s = thickness of the cake layer,

ε = porosity of the cake,

d_s = diameter of the solute molecules.

Equation 2.5.11 shows that the hydraulic resistance of the cake is very sensitive to the molecule size and porosity. Since compression for many porous materials is an irreversible process, when the pressure is decreased the material does not expand to its original size. This means that if a high pressure has been applied to the cake, decreasing the pressure again may not restore the flux.

2.6 Membrane Fouling

2.6.1 Characteristics of Fouling

Membrane fouling is considered to be a major problem in the widespread application of membrane process into drinking water treatment. Almost all feed components will foul the membrane to a certain extent. Fouling may be defined as a phenomenon which results in the gradual flux decline with time of operation when all operating parameters, such as pressure, flow rate, temperature and feed concentration, are kept constant (Cheryan, 1986).

Fouling refers to the deposition or adsorption of contaminants or foulants in the untreated water on the surface of the membrane or inside the pores. This fouling is usually classified as either *reversible* or *irreversible* (Wiesner, 1995). *Reversible* fouling is that which can be eliminated by backwashing or chemical cleaning of the membrane. It involves a relatively short-term build-up of a gel layer or the formation of a cake layer at the surface of the membrane. *Irreversible* fouling is when backflushing or chemical cleaning does not restore the original flux value. It is caused by more or less permanent deposition of material on the surface or in the pores of the membrane. It is characterized by a longer-term decline in flux (Jone, 1993).

Membrane properties such as surface charge, and rugosity also play an important role in fouling of membranes. (Fane, 1987; Wiesner, 1992), Colloid stability (surface charge) has an influence on particle transport of the hydraulic resistance of a deposited layer of material, i.e., cake composed of negatively charged particles may be more permeable than cakes composed of equal-size and uncharged particles (Mcdonogh, 1984). The hydrophilic membrane such as cellulose derivative membrane was found to be more resistant to fouling than hydrophobic (Laine, 1991).

Fouling also depends on physical and chemical parameters such as temperature, pH, feed concentration and specific interaction (Mulder, 1990). Fane and Fell 1987 reported that the degree of adsorption and fouling is related to both the pH and the salt concentration. A maximum fouling at pH 4.5, known to be near the *isoelectric point* was obtained in bovine serum albumin (BSA) ultrafiltration and when the protein was charged (pH 2 to 10) it was less susceptible to deposition (Fane and Fell, 1987).

2.6.2 Mechanisms of Fouling

Fouling is considered to occur through four mechanisms, *i.e., complete blocking, standard blocking, intermediate blocking, and cake filtration* (Bowen, 1995). Figure 2.6.1 represents a schematic drawing of the fouling mechanisms (Bowen, 1995). Fane and Fell 1987, reported the time dependence of UF membrane flux due to pure solvent passage, an early flux decline during polarization under UF conditions and a long-term flux decline over hours, days, weeks of operation.

In the first phase this flux decline was attributed to pore plugging by bacteria and trace colloids. In the second phase the flux decline was due to build-up of the concentration boundary layer. Long-term flux decline on the hand is caused by time-dependent hydraulic resistances in the third phase.

(a) Complete Blocking

The pore entrance is sealed. Each particle arriving at the membrane participates in blocking some pores(s) with no superposition. Fane and Fell, (1987) reported that UF membranes, particularly their relatively low surface porosity and pore size distributions make them sensitive to fouling by pore blockage.

(b) Standard Blocking

Standard Blocking also called *internal adsorption* is described as the case where each particle arriving on the membrane is deposited onto the internal pore walls leading to a decrease in the pore volume. Internal pore blocking is a particularly serious fouling mechanism because it is exempt from the mediating effects of cross-flow and even a small amount of adsorption can lead to a considerable change in the rejection characteristics of the membrane (Scott, 1996).

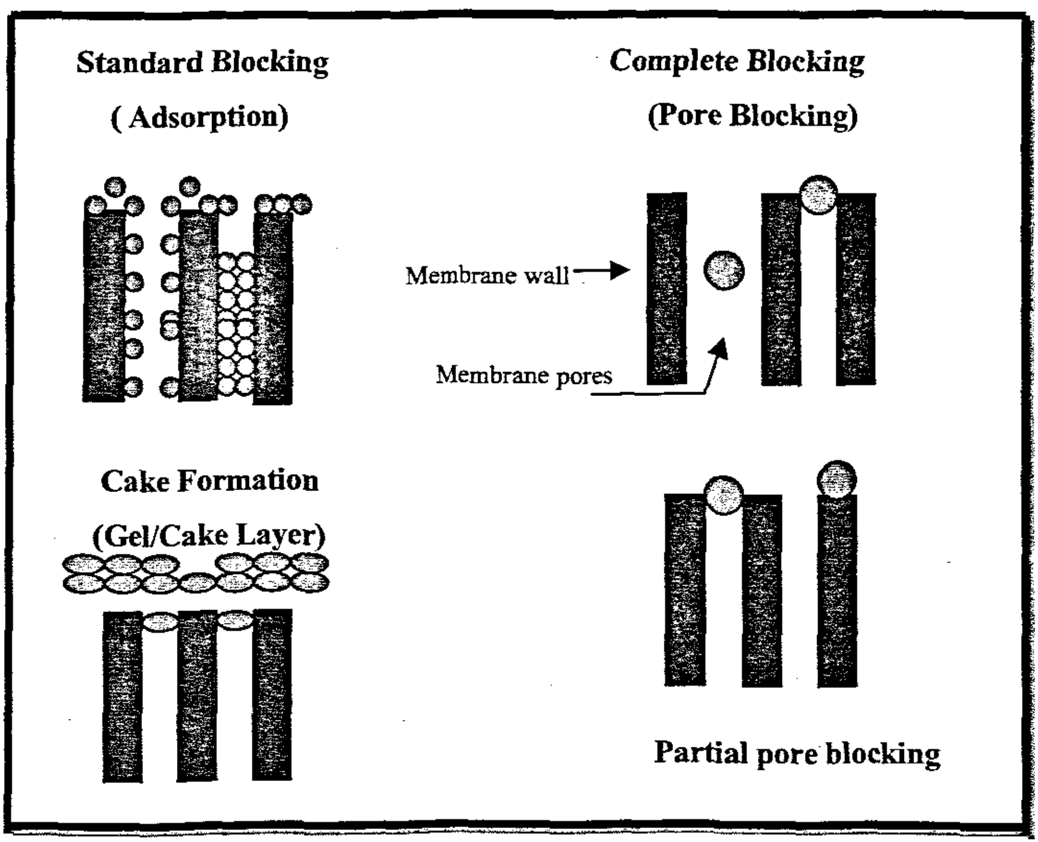
(c) Intermediate Blocking

In this case, each particle can settle on other particles previously arrived and already blocking some pore or it can also directly block some membrane area. It is also known as *long-term blocking* phenomenon.

(d) Cake Filtration

Cake filtration phenomenon represents that each particle locates on other particles already arrived and already blocking some pores and there is no room for directly obstructing some membrane area.

Figure 2.6-1 Schematic drawing of the fouling mechanisms (Bowen, 1995)



2.6.3 Types of Fouling

Foulants can be classified into three categories i.e., particulate matter, dissolved organic compounds, and sparingly soluble inorganic compound. Biological growth is designated as potential foulants (Potts, 1981).

(a) Particulate Fouling

Particulate fouling is frequently encountered in surface water treatment. Particulate fouling results from the deposition of suspended matter, microorganism and colloids on the membrane (Bersillon, 1988). Particle size in crossflow mode plays an important role in determining the transport of particles up to and away from the membrane. As particles concentrate near the surface of the membrane, they may diffuse back into the bulk flow to balance the concentration differential, i.e., back-diffusion as described previously. Particles larger than 10μm are not expected to contribute to the fouling of UF membranes. In MF using hollow-fiber membrane, the smallest particle that should not contribute to fouling is approximately 45μm (AWWA, 1992).

Lahoussine-Turcaud, (1990) reported in crossflow UF that a minimum in back-transport, and therefore a maximum potential for fouling, occurred at particle diameter near 0.2μm. Particles larger than approximately 3μm should not foul membranes. These particles are effectively removed from the membrane by shear-induced diffusion and lateral migration.

(b) Organic Fouling

Organic fouling is caused by at least two different interactions: adsorption onto the membrane, and build-up of a cake or gel-layer at the membrane surface. The first of these interactions can contribute considerably to the irreversible fouling (AWWA, 1992). Dissolved organic materials may form a gel-layer on the surface of a membrane or adsorb within the membrane matrix. Thus, much of the irreversible fouling of membranes is thought to be a result of the adsorption of dissolved organic materials in the porous matrix of the membrane (AWWA, 1992). The hydrophilic membranes were found to adsorb organic material to a much lesser extent relative to the hydrophobic membrane.

(c) Inorganic Fouling (Scaling)

Scaling is caused by the precipitation of sparing soluble salts, i.e., $CaCO_3$, $CaSO_4$, $BaSO_4$, SiO_2, in RO membranes. The scaling problem in UF/MF application is not a matter of concern because inorganic salt can pass through the membrane. It can be avoided by feedwater pretreatments: i.e., removal of one or more of the ionic components of the precipitating salts, chemical addition to inhibit precipitation, or by lowering RO design recovery.

(d) Biological Fouling

Biological fouling is a result of deposition and microbial growth on the membrane, resulting in a layer of material that increases resistance to permeate flux. Microbial fouling can be controlled to a limited extent by maintaining chlorine residual in the membrane feed. However, this practice may limit the use of some polymer membranes that have little tolerance to chlorine e.g. cellulose acetate membranes.

2.6.4 Methods to Reduce Fouling

The methods to reduce fouling can be classified into the following categories: hydrodynamics on feed-side, pretreatment, cleaning, selection of module configuration and optimum operating conditions (Mulder, 1990 and Howell, 1991).

(a) Hydrodynamics on Feed-side

The hydrodynamic approach to improve the flux is either to reduce the concentration polarization by increasing the mass transfer away from the membrane or reduces the fouling based on increasing the wall shear rate. This can be achieved by increasing the cross-flow rate directly or indirectly. The use of turbulence promoters, pulsed flow, baffles and periodic reverse-flow can be involved in this category. The mechanical spacers used in spiral wound also serve this purpose (Howell, 1991).

(b) Pretreatment

The goal of pretreatment is to decrease the amount of irreversible fouling and increase the permeate flux. Pretreatments can be divided into two: pretreatment of the *feed solution*, pretreatment of the *membrane* (Mulder, 1990).

Pretreatment of the feed solution employed in UF includes pH-adjustment, addition of chemical and adsorbents, conventional treatment process, etc. For instance, in treatment of protein by UF, pH-adjustment is very important because fouling can be minimized at the pH value corresponding to the isoelectric point of the protein, i.e., at the point at which the protein is electrically neutral (Scott, 1996, Fane and Fell, 1987).

Pretreatment in UF is very important because UF is less efficient in removing smaller dissolved molecules whereas it can be effective at removing particles. With proper pretreatment, contaminants that are not normally removed by the UF may be removed. It was found that pretreatment with 250 mg PAC/L yielded a 70 percentage increase in the removal of TOC by the overall system and an 85 percent increase in the removal of contaminants that contribute to the Trihalomethane formation potential (THMFP) (Laine, 1989) and coagulation of a surface water with hollow fiber membrane before UF improved steady state flux (Lahoussine-Turcaud *et al*, 1990).

Pretreatment of the membrane such as precoating of membrane surface, charge of membrane surface, enzyme immobilization, and modification of membrane structure can also reduce the fouling to some extend. The use of hydrophilic rather than hydrophobic membranes can help reducing fouling (AWWA, 1992).

(c) Cleaning

Cleaning is a commonly used technique in practice among other methods. Cleaning can be distinguishes: (i) hydraulic cleaning, (ii) chemical cleaning, (iii) mechanical cleaning (iv) biological cleaning (Mulder, 1990). The choice of the cleaning method mainly depends on the module configuration. The chemical resistance of the membrane and the type of foulant encountered (Mulder, 1990). Optimization of the cleaning schedule is important for successful operation because frequent cleaning will result in excessive system downtime, whereas infrequent cleaning can allow accumulation of non-removable foulants on the membrane (Potts, 1981).

(d) Module and Operating Conditions

Fouling can be minimized by the selection of membrane modules most suitable for a given feed water and through optimization of operating conditions, i.e., pressure, pH, recovery and feed flow velocity. The critical and generally low value of transmembrane pressure below which constant flux filtration can be realized depends on the hydrodynamics. Below this critical transmembrane pressure there will be little or even no irreversible surface fouling (Scott, 1996).

2.7 Membrane Cleaning

Membrane cleaning is an essential component of nearly all membrane process because all membranes will foul during operation, causing the membrane performance to drop below some acceptable level. At this point the foulants must be removed using the acceptable cleaning procedure. Membrane cleaning remains very much an art, with the choice of the optimal cleaning cycle for a given application being determined in large part by trial and error (Zeman and Zedney, 1996). As described above, cleaning can be divided into three categories: i.e., *hydraulic, chemical, mechanical and biological cleaning* (Mulder, 1990).

2.7.1 Hydraulic Cleaning

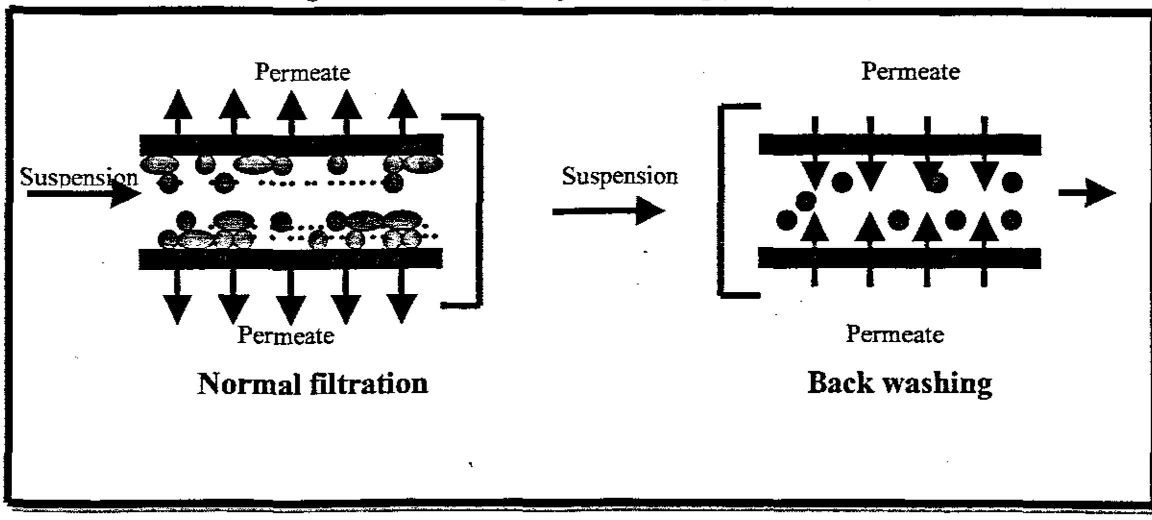
Hydraulic cleaning, i.e., **forward flush** is a well-known remedy to physical fouling when a filtration cake is formed during the filtration in hollow-fiber types of membranes (Bersillon, 1988). Hollow-fiber UF membrane can be cleaned by backflushing the membrane with permeate water whereas spiral-wound membranes, which cannot be backwashed are flushed hydraulically (Laine, 1991). In practice, backwashing is practiced by pumping the permeate water from the permeate tank into shell side of the membrane (from outside to inside). The principle of backflushing is demonstrated in figure 2.7.1.

Backwashing can be performed during actual filtration process, or it can be done in a separate cleaning cycle. This technique in case of drinking water treatment displays a relative efficiency but leaves a fouling residue, which is responsible for a long-term flux decline (Bersillon, 1988). It is generally effective at removing particle cakes from the membrane surface, and it can also remove foulants from the membrane interior, particularly when performed with a chemical cleaning solution, i.e., in case of significant adsorption or tight cake formation in the membrane (so-called *enhanced Backwashing*). This is illustrated in Figure 2.7.2

Transmembrane pressure pulsing is a recent variation of traditional backwashing in which the backpressure is applied in an extremely rapid pulse (pulse duration generally less than 1 sec) every 10-30sec throughout the process (Zeman and Zedney, 1996). The optimal pulse frequency reflects the balance between the flux restoration associated with cleaning and the loss of permeate that occurs during pulsing. This technique has been showed to provide flux enhancement by as much as a factor of 10 in yeast cell microfiltration and by about 1.25 during protein microfiltration. This difference is due to that proteins tend to adhere much more strongly to the membrane (Zeman and Zedney, 1996).

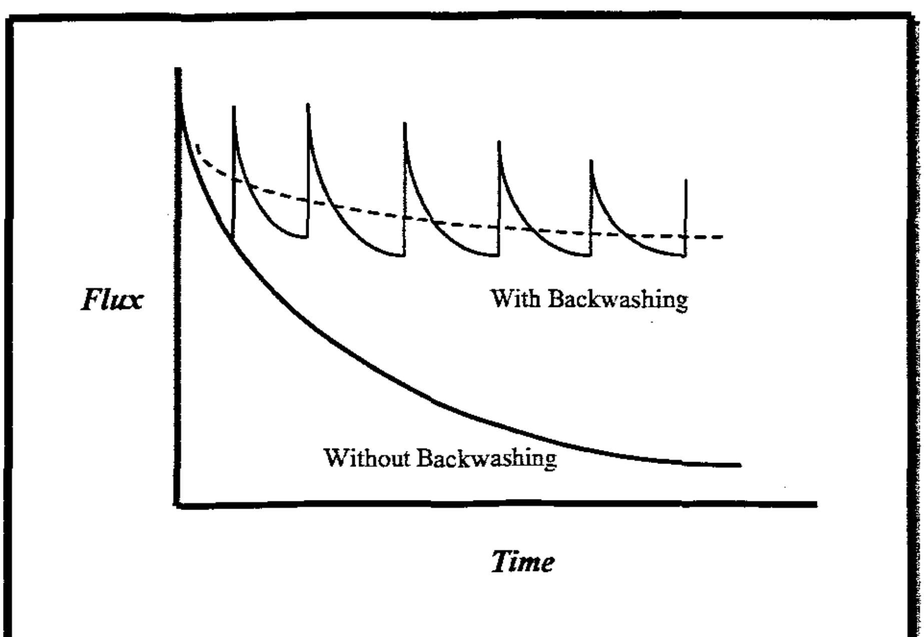
In UF process optimal backwashing conditions, i.e., cycles and length of filtration runs are important because shorter filtration cycles will yield an apparent increase in system productivity, but shorter filtration cycles require a more frequent backwashing cycle that tend to decrease the overall water production (Jones, 1993).

Figure 2.7-1 Principles of Backwashing (Mulder, 1990)



Backwashing has the drawback of permeate consumption in the process, which significantly reduces the net average flux and the system productivity.

Figure 2.7-2 Flux decline behavior with and without Backwashing (Crozes G. et al., 1993)



2.7.2 Chemical Cleaning

Chemical cleaning is performed when backwashing can not restore flux. Cleaning agents fall into different categories (Mulder, 1990):

- Acid/base (NCl, H_2SO_4/ NaOH) – *for dissolving mineral and salt/* protein foulants
- Oxidizing agents (H_2O_2, NaOCl) – for biological foulants
- Enzymes (Protease, Alpha amylase) – for severe fouling
- Surfactants/ detergents (Ultrasil, Froclean, etc) – for organic foulants

The type of cleaning agents to use will depend on the type of foulant and membrane material. Membrane life time can be affected by the type of cleaner and procedure used because cleaning agents can react with the membrane itself while they react with organics at the membrane surfaces, changing the permeate flux, retention characteristics and increasing the frequency of replacement (AWWA, 1992).

2.7.3 Mechanical Cleaning

Tubular membrane types can often be cleaned by forcing rubber sponge balls through the lumens of the large bore tubes. Sponge ball cleaning is most effective at removing soft biological and organic foulants from the membrane surface, but this type of mechanical cleaning is unable to remove such material from within the pores. The sponge balls are typically *ca.* 2 mm in diameter larger than the tube inner diameter to insure intimate contact with the membrane surface (Zeman and Zedney, 1996).

2.7.4 Biological Cleaning

These methods include the use of biological agents, which contain enzymes. Enzymes are ideal cleaning agents for biological fouled membranes as they are highly specific for the decomposition of biological foulants. They will not have a detrimental effect on the membrane surface as they operate under mild conditions of temperature and pH. Cellulose membranes cannot withstand high temperatures and pH, thus the use of enzymes for the cleaning of these membranes are ideal (Swart *et al,* 1996)

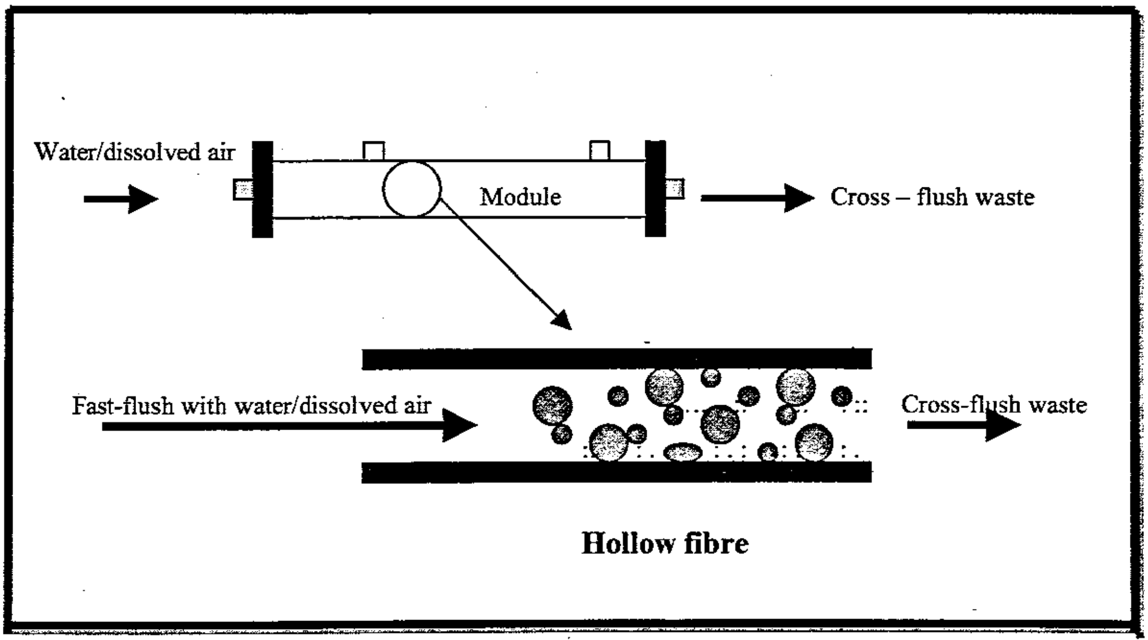
2.8 Improvement of Membrane Cleaning

In practice, the cleaning of membrane involves a combination of backwashing and chemical cleaning at set intervals. In order to optimize the cleaning procedure, a number of improvements have been suggested. Trans-membrane pressure pulsing involves applying pressure pulses at the feed side at every 10 – 30 seconds throughout the filtration process. The pulsing increases solvent flux in the membrane process with laminar crossflow. The TMP pulsing can also alter the concentration polarization boundary layer by translation of body forces through the membrane and minute but significant membrane motion (Zeman & Zedney, 1996)

2.8.1 Cross-flushing

Cross washing involves flushing raw water/feed at a high velocity through the lumen of the membrane fibre thereby shearing away the formed cake layer. A schematic representation is shown in Figure 2.8.1(Cabassud et al, 1997)

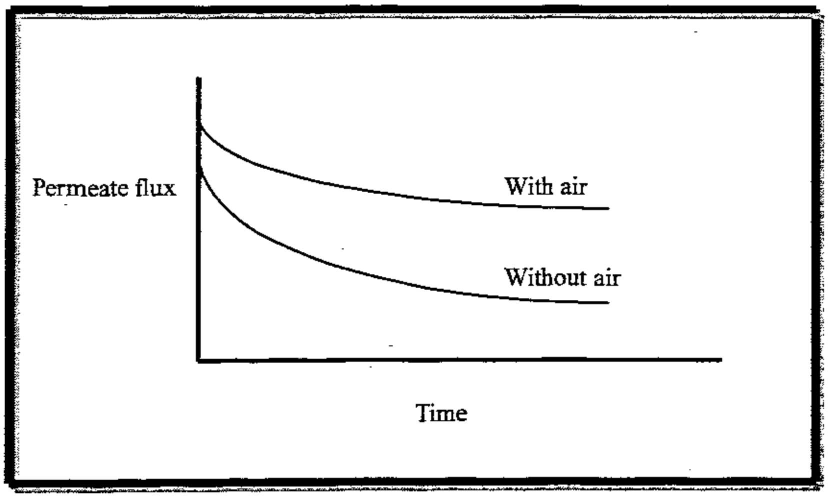
Figure 2.8-1 *Cross – flush process (Cabassud et al, 1997)*



2.8.2 Use of Air to improve Membrane Cleaning

The use of air slugs to provide high wall shear stresses that can reduce particle deposits has been carried out by Cabassud, 1997.It is believed that by injecting air in the feed solution, the flux may be increased by up to 110% for air velocities of 1 m/s and 60 % for air velocities of as low as 0.1 m/s in crossflow filtration (Cabassud *et al*, 1997). Figure 2.8.2 shows the effect of using air slugs on the permeate flux over time of filtration.

Figure 2.8-2 *Effect of air slugs on permeate flux (Cabassud et al., 1997)*



Air slugs have shown promising results in cross-flow because the process is continuos and therefore less blocking of the hollow fibres by the air slugs is expected as long as the cross-flow velocity is high enough. In dead-end systems use of air can be furnished by incorporating it in a cross-flush. Here high level of fibre blocking is expected with slugs and it may be better to use smaller bubbles creating a bubble flow in which the gas phase is uniformly dispersed as small bubbles showing quasi-steady characteristics. In comparison to the conventional single-phase liquid flow, the linear pressure drop is higher, resulting in an increase in the wall shear stress (Mercier *et al.*, 1997). Small bubbles can be created by injecting air with a small nozzle at the upstream end of the module or by use of compressed air in which the bubble come out of solution inside the module. The former case has the disadvantage that the bubbles may block the fibre at the entrance to the module. In both cases the turbulence is generated in the wake of the bubbles.

2.9 Membrane Technology Development in South Africa

2.9.1 Introduction

South Africa, like many other countries faces a challenge of supplying its entire population with adequate and potable water. South Africa is a relatively dry country, which receives an annual rainfall of less than 500mm. Most of the large areas of the country may be classified as desert or semi-desert. Therefore, membrane development in South Africa currently tends to focus more on water related applications. With the help of the Water Research Commission of South Africa (WRC), research and development (R&D) is being undertaken on membrane processes, including reverse osmosis, ultrafiltration, microfiltration and electrodialysis. Most of these technologies have been commercialized or are on the verge of being commercialized.

2.9.2 Background

The research on the use of membrane technology in South Africa started as early as 1953 on electrodialysis systems and their membranes at the Council for Scientific and Industrial Research (CSIR). The research laid the foundation for a better understanding of the processes involved in the use of electrodialysis. Parchment paper membranes were developed for low-cost desalination of brackish gold-mine underground waters (SA Water bulletin, 1996).

In 1973 the Institute for Polymer Science (IPS), University of Stellenbosch started the first research on polymeric membranes, which lead to the establishment of the first local membrane manufacturing company in 1979 (Membratek). Furthermore the company developed low cost tubular reverse osmosis and ultrafiltration system in 1980s in conjunction with IPS.

A lot of development came into place and the tubular UF systems were later successfully combined with anaerobic digestion and were subsequently commercialized. From the beginning the activities have grown to the current situation where R&D on membranes is actively pursued not only at the number of tertiary educational institutions, but also at the private companies and water and power utilities (SA Water bulletin, 1996).

2.9.3 Water Treatment Pilot Plant Studies

Currently, water supply systems worldwide are being challenged by drinking water quality regulations; increased demand; ageing water systems; and high costs of construction, operation and maintenance. A consideration of new or at least non-conventional treatment methods to face challenges is becoming frequent and pilot plant studies are needed to study these alternatives.

Pilot plants must be carefully planned, designed and monitored to achieve results that are applicable for the development and performance prediction of the future full-scale plant.

2.9.4 Application of Membranes in South Africa

South Africa has limited supplies of one strategic commodity that affects the lifes of all its inhabitants, namely, water. Scientists are compelled to make the country self-sufficient with regard to technologies that can be used to augment the volume of water available for use. In the field and application of membrane systems, membrane scientists can play a key role in making the country self-sufficient in the areas of wastewater management, water treatment and by-product recovery. This has already been demonstrated by the successful application and commercialization of the locally developed tubular cellulose acetate (CA) membranes systems and by the advances made with ultrafiltration systems (Sanderson R.D. *et al,* 1994)

Although it has taken some time, the application of membrane technologies are now increasingly being accepted as a viable option in the treatment of water and effluents in South Africa, and a number of local and international companies are marketing membrane-based technologies. Membranes are being used in variety of applications, ranging from potable water supply to the treatment of industrial effluents. A recent application being promoted by the Pollution Research Group of the University of Natal is to install membrane separation systems in strategic places in the production processes to relieve water pinch situation in industry. The use of the South African membrane technology to produce potable water is being tested at pilot plants around the country (Pillay, 1998)

(a) Application of Ultrafiltration Membranes

The types of capillary membranes produced in South Africa currently are polysulfone and polyerthersulfone at the Institute for Polymer Science (see chapter 3, figure 3.1.2 and 3.1.3). They can be produced as skinless, internally skinned, externally skinned or double skinned depending on how the bore fluid and the external spinning bath are introduced. These capillary membranes are applied in membrane bioreactor related research. It separates particles to size ranging from 0.001 to 0.1 microns. With the slight modification in the polymer the membranes also served as a low-pressure filter for the treatment of non-saline surface and subsurface water for potable use (Jacob E.P. *et al,* 1997).

Recently, polysulphone UF membranes were produced with a very thin internal skin layer and the dimension of the voids in the substructure is such that bacteria will not pass through the membrane should the skin layer be punctured during the filtration process. These membranes efficiently filters out very small particles, yet still has a suitably high pure-water flux. The membrane is intended, amongst other for the production of potable water for small communities.

One important goal in membrane fabrication is to control membrane structure and thus its performance. To achieve this goal a lot of factors have to be considered and this includes; proper choice of polymer, proper choice of solvent and non-solvent, composition and temperature of coagulant and casting solution (Jacob E.P. *et al,* 1997). Fabrication protocol (e.g. dope morphological rate) plays an equally important role in controlling morphological properties and performance of the final membrane structure.

There has been joint research in the application of membrane technology to the small communities in South Africa. The University of Stellenbosch, ML Sultan Technikon and the Water Research Commission of South Africa initiated a joint project. The project was initiated to develop a local UF system for potable water production in the rural and peri-urban areas of South Africa (Jacobs E.P. *et al,* 2000). It aimed in developing a technology that would be sustainable in developing economy conditions. Through out all the developments and field evaluations, a truly South African membrane water treatment system was developed.

Various separate pilot-scale investigations were initiated during the course of the project. The sites where the studies were conducted are Southern Cape, Western Cape, Kwazulu Natal and Windhoek in Namibia. In Suurbraak a UF pilot plant was used to treat the water to the community over a period of six months in order to test the application in a rural environment. Another plant at Wiggins Water Works was monitored regularly to assess the particulate removal and disinfection capabilities of the UF membranes for potable water production (Jacob E.P. *et al,* 2000)

This system is ideally suited for drinking water production in South Africa. The system has demonstrated excellent quality of water in all field trials and is ideal for developing economies, thus ensuring the long-term sustainability and reliable long-term operation of the units (Jacob E.P. *et al*, 2000)

In 1994 the Ultrafiltration Rural Watercare Project was initiated by the IPS at the Mon Villa seminar center (Botes J.P. *et al*, 1998). All the farms in the seminar center were supplied with irrigation water from the Theewaterskloof Irrigation Scheme, which are not fit for direct human consumption. The water has high concentration levels of turbidity (> 70 NTU) and colour (100 – 350 units PtCo) caused by natural organic matter, as well as the presence of iron, aluminum and microbiological contamination. The project was initiated with the installation of a 3 m^2 bench scale filtration unit. After initial experimental work the WRC funded a pilot plant for the project. The project was done to evaluate the low-cost modular membrane system produced from IPS for the upgrading of the substandard surface water from Helderberg Irrigation Scheme to potable standards. Subsequent performance and evaluation studies of these membranes indicated they exhibited a medium molecular-mass cut off of about 40 kDa. This evidence suggested that the membranes might be useful in potable water production from raw surface waters found in South Africa. These membranes produced excellent quality drinking water. The membranes were capable of reducing higher concentration levels of turbidity and iron by 97 – 99%. They were also capable of removing all the faecal and other bacteria present in the feed waters.

The need for the reliable supply of potable water to growing remotely located coastal settlements where the only sources of water supply are ground water and seawater have received renewed attention. Ed Jacobs *et al,* (1993) did a study on the development of a locally manufactured UF membrane system for seawater pretreatment prior to reverse osmosis. The main aim of the study was to identify the requirements of a UF system for use in pretreatment by RO, and to develop and evaluate the UF pretreatment through long-term continuous operation.

The cost effectiveness of using these UF membranes for the pretreatment to RO, were found to depend on a combination of membrane configuration, type and frequency of the cleaning regime as well as average productivity. The development of the experimental module has resulted in the commercial manufacture and use of a practical membrane separation system for the treatment of seawater prior to desalination (Ed Jacobs *et al,* 1993)

(b) Application of Microfiltration Membranes

Woven fibre MF technology underwent significant development at the Pollution Research Group, University of Natal on the 1980s, and currently being further refined by ML Sultan Technikon, now called Durban Institute of Technology, in Durban (Pillay, 1998). The system consists of two layers of a woven polymer material, stitched together to form rows of parallel filter tubes, called a curtain. The feed water is from the inside and the clear liquid permeates the tube wall and runs down the outside of the tubes as permeate. The system can either be used in cross-flow or dead-end modes of operations. In its vertical configuration, the system has been adapted successfully as a filter press for cost-effective sludge dewatering (Pillay, 1998). The potential benefits and markets for cross-flow microfiltration encompass both the first and third worlds.

For the application of these woven fibre MF membranes, a study was conducted on the development of a cross-flow microfilter for rural water supply. The study was conducted to assess the applicability of the EXX FLOW process for the production of potable water to rural and peri-urban areas. In this project a full scale EXX FLOW unit was constructed and relocated to the process evaluation facility at Umgeni water's wigging water treatment works. The unit was operated and the performance and its reliability towards rural set-up were monitored.

Overall, therefore, the unit consistently produces very good quality water that is well within the potable water standards. However, at the time of the study the unit was not regarded as the reliable one due to the various mechanical problems which included the poor design of the manifolds and enblocks and the blockages of the spray nozzles Further improvements to the mechanical reliability are necessary before the unit may be regarded as a viable one for the production of potable water in the rural and peri-urban areas.

(c) Application of Reverse Osmosis Membranes

Reverse osmosis is a process where water is demineralized using a semipermeable membrane at a high pressure. Reverse osmosis is osmosis in reverse. To reverse this process, the osmotic pressure equilibrium across the membrane must be overcomed, because the flow is naturally from dilute to concentrate.

Most fundamental research on RO has been taking place at the IPS. Following the initial development work on cellulose acetate tubular RO systems, some of their more recent developments include the following (Hurndall M.J. *et al,* 1997):

- Ultrathin-film tubular membranes were made from poly-2-vinylimidazoline and polyvinyl alcohol, cross-linked with 3,5 dichlorosulphonyl benzoylchloride and were successfully housed and tested in commercially available modules.
- A coating procedure was developed for the regeneration of substandard or degraded cellulose acetate membranes.

Tubular RO technology was further refined and cost-optimized in Cape Town, using a simple low cost support system and employing sponge-ball effluents. It is currently been used in industrial applications locally and internationally. The first commercial plant, situated in Port Elizabeth was commissioned in December 1997 (Furukawa DH, 1999). The plant consists of a MF unit, as pretreatment, followed by RO. The plant supplies approximately 480 m^3/day of potable water from the sea to small communities in Port Elizabeth. Subsequently, a number of plants have been commissioned world-wide (Furukawa DH, 1999). A recent development includes a 400 mm diameter RO module, which also has the full complement of non-fouling devices built into the unit (Furukawa DH, 1999).

The South African government has been especially active in supply of water to the township and rural areas, but the expansion of the electrical grid to supply electricity to all these areas is still lagging behind. Several alternative energy sources are being evaluated in the interim, with diesel, car batteries, etc. However, these forms of energy can be applied for low energy requirements. Therefore Louw, (2001) conducted a study on the development of a solar powered reverse osmosis plant for the treatment of borehole waters. He mentioned that solar power has become an effective method of supplying low cost energy to those in remote areas. The development of reliable solar powered Direct Current (DC) borehole pumps has indeed helped with bringing water to people in remote areas (Louw G.J, 2001).

The study was aimed to design and construct an RO unit, powered by solar energy, capable of producing potable water from brackish borehole feed for rural households and small communities (Louw G.J, 2001). The development and the implementation of this unit will not only be of great benefits to the communities in rural areas, but also seen as a cost effective method of supplying potable water from brackish sources in disadvantaged and or remote communities.

The pilot demonstration unit was developed to evaluate the feasibility of the combined technology; as well as operation, application and commercialization in the local market (Louw G.J, 2001). This concept is relevant to areas where small communities are spread over large areas, where the cost of erecting large desalination plants and reticulation of desalination water is neither practically nor economically viable.

The unit produced good quality water. It proved to be well adapted to a variety of borehole water source although high fouling waters were avoided. The success of the unit has obviously made it a very viable consideration for marketing as a saleable product of drinking water. The end-user will however need to consider several factors before purchasing the unit, and these includes:

- Determine the quantity of potable water required per day.
- Determine the storage and distribution network available or required to implement this unit.
- Determine the quality and quantity of the water source and the integrity of the borehole.
- Operate on borehole water only and not suitable for surface waters due to the design.

2.9.5 Membrane Fouling Studies

Membrane based water treatment plants produce excellent quality drinking water, but the use of these plants is limited to the fouling of the membranes. Research on membrane fouling centers around three aspects (Maartens A. *et al,* 1999)

- Electromagnetic defouling
- Enzymatic and chemical defouling
- Surface modification.

Studies are continuing on the positive effect, the electromagnetic device described above, has on the non-fouling properties of membranes. Visualization experimentation has already been done at the Institute for Polymer Science to see the concentration polarization techniques. Initial success has been achieved and it is now possible to see how a fouling layer forms on the membrane surface, or how the layer can be removed by cleaning methods in real time.

The department of Biochemistry at the Stellenbosch University has achieved success in the enzymatic and chemical defouling of polysulphone membranes (Jacobs E.P. *et al*, 1999). Following from these studies, some useful compounds have been synthesized to modify the membrane surface for various requirements and application.

2.9.6 Problems Associated with the Application of Membranes in Small Communities

Many problems faced with membrane treatment systems in small communities in South Africa are related to a lack of financial input and proper management. Additionally, most plants lack adequate raw water pre-treatment and are not usually well operated and maintained. This means that even when the money could be made available for rehabilitation, without incorporating other aspects such as training of operators, funding, monitoring or even alternative pre-treatment processes, the rehabilitation systems still experience the same problems with time. The technology costs money to install, operate and maintained. It also needs management skills and has to deliver a service that is acceptable to the end-users.

The major problems in most of membrane water treatment plants in South Africa are outlined below:

(a) Lack of skilled manpower

Most of the rural and township water supplies are unable to attract qualified personnel because of their remoteness and inability to pay workers. The problem of unqualified personnel is also common in most urban water supplies. Large water supply in big cities manage to collect part of their water revenues from a large customer base and are able to retain some of the qualified staff. Hence, most qualified personnel in water treatment are lured to large cities and private industries. The lack of skilled manpower has led to:

- Inappropriate operation and maintenance of membrane treatment systems. This has let to plant failures
- Monitoring of the treatment systems is poor since responsible staff and operators are not adequately trained
- In certain plants, raw water bypass treatment, just to increase production without considering the quality consequences
- Inability of available personnel to request water committees or higher authorities to undertake certain measure that would keep the plant in operation.

(b) Lack of equipment and spare parts

Laboratory facilities for evaluating and optimizing treatment processes are not available in most of the peri-urban areas treatment plants. Water quality parameters such as turbidity and pH can easily be measured by simple portable equipment. If there is any plant break down spare parts are hardly available or acquired. This is the point where the need for funding and skilled manpower to good maintenance or repair of these facilities comes in.

(c) Lack of commitment from the local communities

Most of the local communities do not have the full commitment towards their use and operation of their water supply schemes. They do not protect the systems and they end-up being vandalized by the community.

3 MATERIALS AND METHODS

3.1 Evaluation of materials and equipment

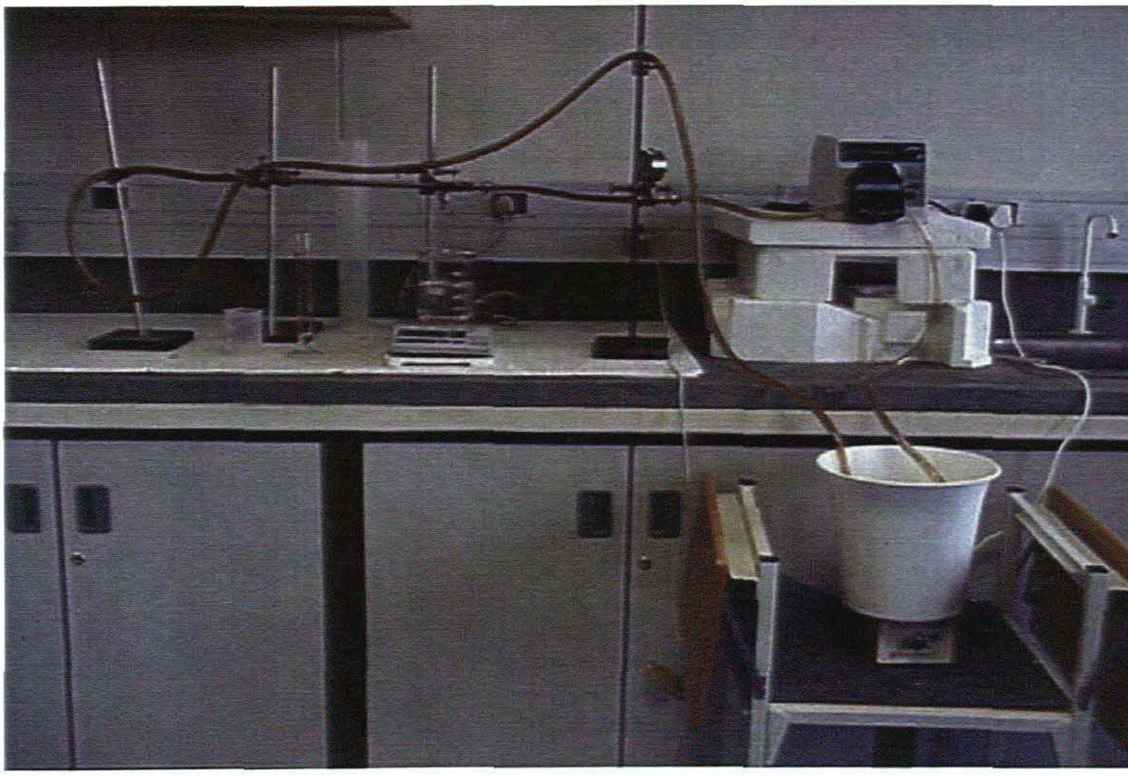
3.1.1 Bench Scale unit

The laboratory bench scale ultrafiltration unit used in this study is shown in Fig 3.1.1 and consists of the following components.

- UF membranes
- Membrane test cell
- Feed water storage tank
- Permeate storage tank
- Volumetric flask
- Feed pump
- Associated piping
- Pressure gauge
- Back pressure valve

The design layout of the experimental bench scale unit allowed for cross flow filtration only and the unit was operated under constant pressure of 1 bar. The experiments were run using one set each of clean membranes for different experimental waters at different percentage recoveries for both sets.

Figure 3.1-1 *Laboratory bench scale ultrafiltration unit*



3.1.2 Membrane Formation and Test Cell Assembling

The low-pressure capillary ultrafiltration membranes used during the study were manufactured at the Institute of Polymer Science, University of Stellenbosch by Dr. Ed Jacobs. The capillary membranes have an internal and external diameter of ~1.2 mm and ~ 1.9 mm, respectively (traveling microscope used). Performance testing indicates that a medium molecular mass cut off (MMCO) of approximately 50 000 Dalton can be achieved and the membranes can withstand an instantaneous burst pressure of 1.6 MPa (figure 3.1.2 and 3.1.3)

From the protocol documented by Jacobs and Leukes, (1996), the UF membranes used for the study were manufactured in an extrusion process, where-by a membrane spinning polymer solution is forced through an annular tube-in-tube spinneret (inside diameter of 2,73 cm and inner diameter of 0,63 cm) by means of a high pressure precision-gear-metering pump to form an asymmetric capillary membrane. A coagulation bath, high in solvent content is introduced and the membranes are coagulated from the inside and the outside with a non-solvent. Excess solvent is removed by rinsing and the membranes are pre-treated in preparation for drying. From this step onwards, the membranes are kept dry until used (Jacobs E.P. *et al*, 2000).

A known number of membranes were housed in a test cell and a quickset epoxy was used to avoid any leakage during the experiment. The O-ring groves with rubbers inside were molded on the outside of the test cell to ensure a leak free fit when the membrane capillaries were inserted into the test cell. Each test cell contained 8 membranes with an effective filtration path-length of 372 mm and membrane area of 0,0112 m^2 (figure 3.1.4 - 3.1.6)

***Figure 3.1-2** The cross-section of an ultrafiltration capillary membrane (Jacobs E.P. et al, 2000)*

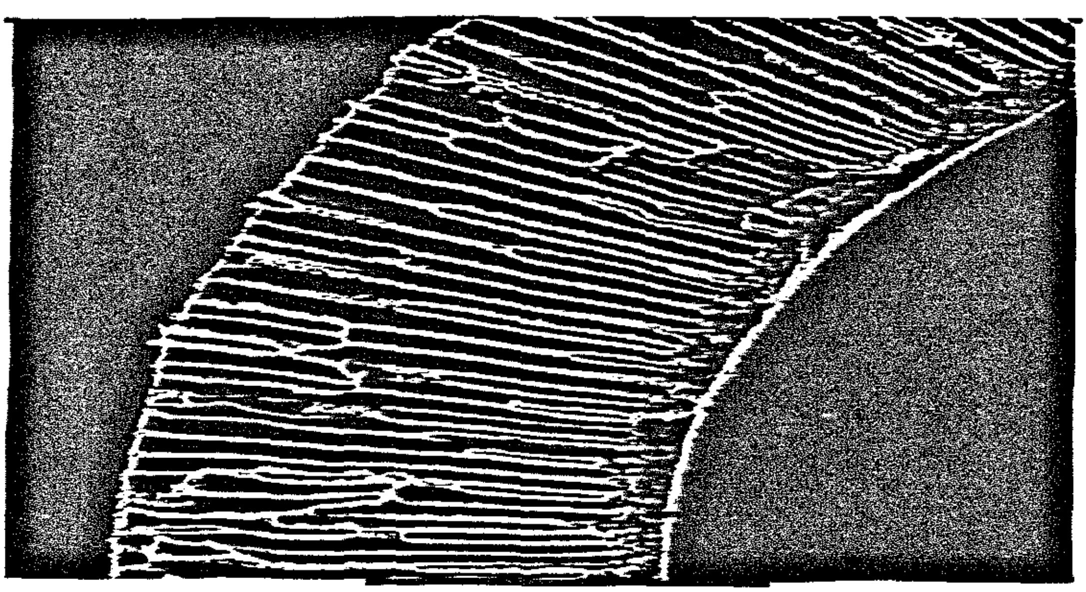


Figure 3.1-3 Electron micrograph of the cross-section of an externally unskinned PSf membrane (Jacobs E.P. et al, 2000)

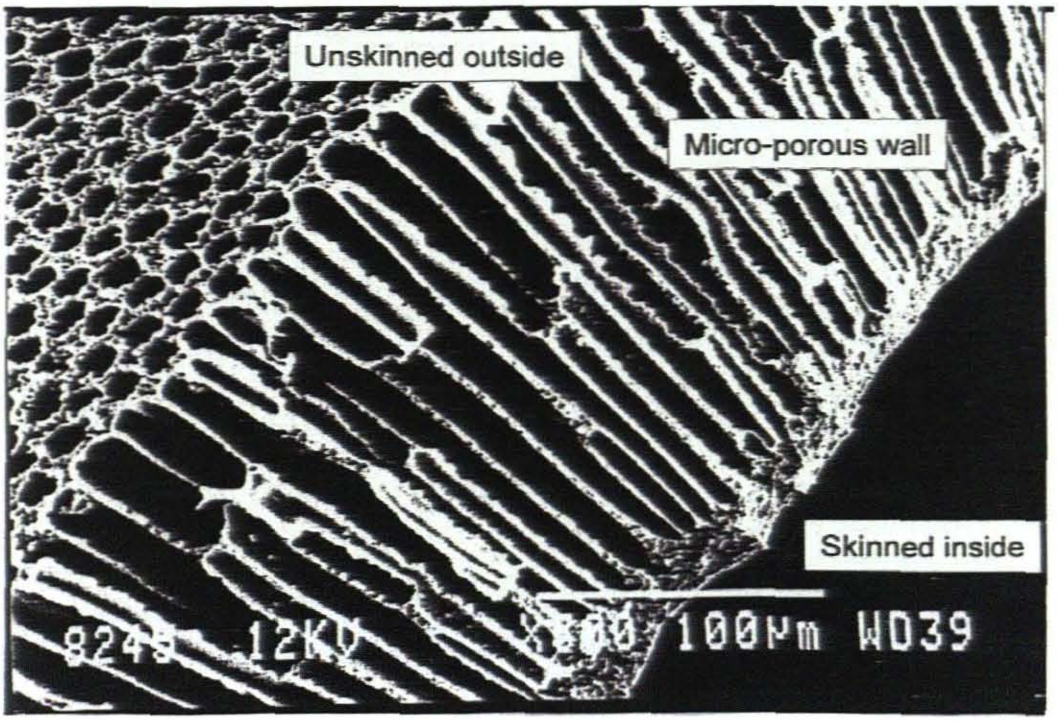


Figure 3.1-4 Clean and fouled ultrafiltration membranes used in the study

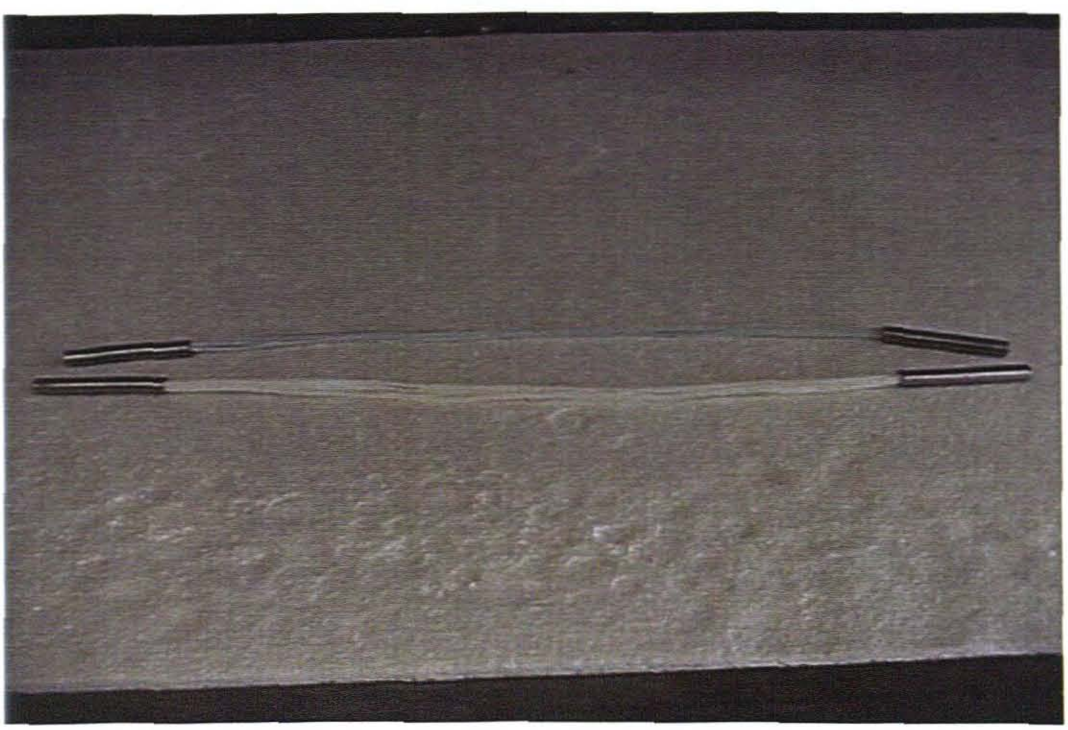


Figure 3.1-5 *Assembled test cell used in the study*

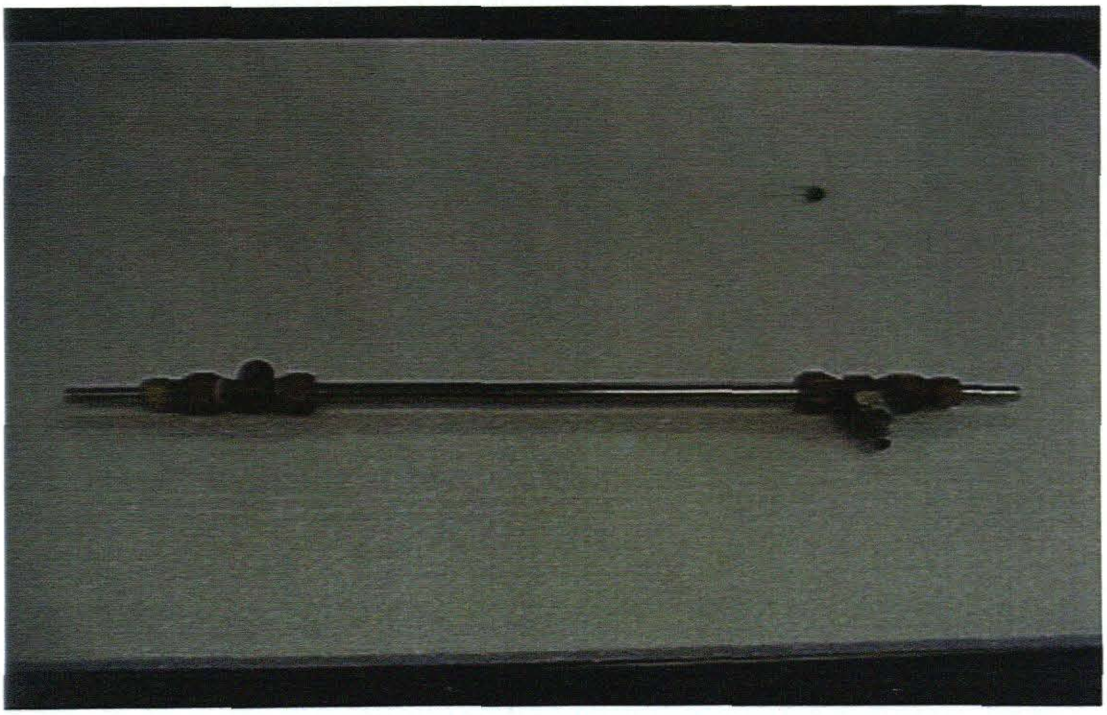
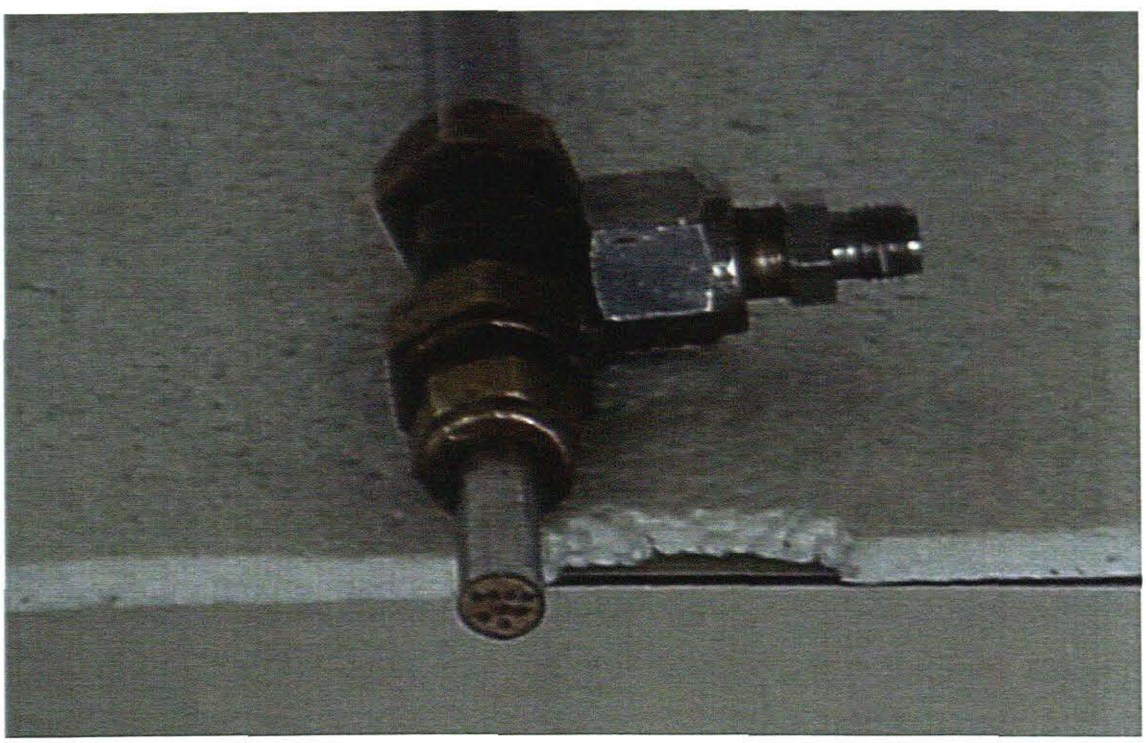


Figure 3.1-6 *Assembled test cell showing eight numbers of membranes and permeate outlet.*



3.1.3 Experimental Waters

The following raw waters were tested in the project.

- Ground water
- Tertiary wastewater effluent
- Eutrophic water
- Coloured water

(a) Ground water

The ground water was obtainable from Peninsula Technikon Lake. The water is pumped directly from the borehole to the lake. Iron was present in fairly high concentrations in the raw water (~ 1.67 mg/L). *Typical raw water qualities were as follows:*

Determinant	Raw	Determinant	Raw
pH	6.78	Sodium (*mg/l Na*)	177
Conductivity (*mS/m*)	152	Potassium (*mg/l K*)	4.48
Alkalinity (*mg/l* $CaCO_3$)	214	Sulphate (*mg/l* SO_4)	123.2
Chloride (*mg/l Cl*)	nd	UV 4cm at 300nm	nd
Colour (*mg/l as Pt/Co*)	120	Total Dissolved Solids *(mg/l)*	1000
Calcium (*mg/l Ca*)	73.5	Nitrate/Nitrite (*mg/l* NO_3/NO_2)	nd
Magnesium (*mg/l Mg*)	37.0	Turbidity (*NTU*)	11.9
Aluminum (*mg/l Al*)	0.182		
Iron (*mg/l Fe*)	1.667		
Manganese (*mg/l Mn*)	0.014		

nd: not determined

(b) Tertiary wastewater effluent

Tertiary wastewater effluent used for the study was from Bellville South Wastewater Treatment Plant (BWWTP). A number of analyses were conducted on the level of microbiological contamination in the feed. High concentration of *feacal coliform* and *Escherichia Coli* were present in the raw water before chlorine dosage and the results were as follows: *Feacal coliform* (per 100 ml) = 12×10^4 and *Escherichia Coli* (per 100 ml) = 10×10^4. Despite this, the *Feacal coliform* and *Escherichia Coli* bacteria present in the product remained < 10.

- **Primary treatment** – improving the influent quality and making it acceptable for subsequent biological treatment.
- **Secondary treatment** – biological and chemical processes such as activated sludge, and extentended aeration were used for the removal of biodegradable organics and suspended solids.
- **Tertiary/Advanced** – additional combinations of unit operations and processes (reverse osmosis, carbon adsorption, chemical coagulation filtration and disinfection) are used to remove the nutrients, dissolved inorganic and pathogens that are not reduced significantly by secondary treatment.

(c) Eutrophic water

Eutrophic water was collected from the Voēlvlei dam. The Voēlvlei dam is used to supply the adjacent areas after treatment in the Voēlvlei water treatment works .The dam is situated approximately 87 km from Cape Town. No blue green algae found in the raw water. The raw water contained substantial concentrations of algae species and are as follows; *carteria* at 98 cells/*ml*, *centric diatoms* at 49 cells/*ml*, *melosira* at 685 filaments/*ml* and trachledomonas at 49 cells/*ml*. Table 4.2.7 shows product water results.

(d) Coloured water

The coloured water sampled from Duivenhoks River, which normally has water with high levels of colour and high turbidity water during rainy seasons. The river runs through Heidelberg in the Western Cape. This river is being used by Overberg Water treatment plant to supply potable water to Heidelberg and surrounding areas. The water is usually reasonably clear, but has a typical brown colour ranging from 330 – 360 mg/l as Pt/Co, and fairly high iron concentrations of up to 1,3 mg/l. *Typical raw water qualities were as follows:*

Determinant	**Raw**	**Determinant**	**Raw**
pH	6.82	Sodium (*mg/l Na*)	36.8
Conductivity (*mS/m*)	25.0	Potassium (*mg/l K*)	5.77
Alkalinity (*mg/l* $CaCo_3$)	9.5	Sulphate (*mg/l* SO_4)	10.0
Chloride (*mg/l Cl*)	61.0	UV 4cm at 300nm	2.418
Colour (*mg/l as Pt/Co*)	160	Total Dissolved Solids (*mg/l*)	162.50
Calcium (*mg/l Ca*)	5.49	Nitrate/Nitrite (*mg/l* NO_3/NO_2)	0.359
Magnesium (*mg/l Mg*)	5.70	Turbidity (*NTU*)	12.3
Aluminum (*mg/l Al*)	nd		
Iron (*mg/l Fe*)	1.286		
Manganese (*mg/l Mn*)	nd		

nd: not determined

3.2 Methods

3.2.1 Experimental procedure

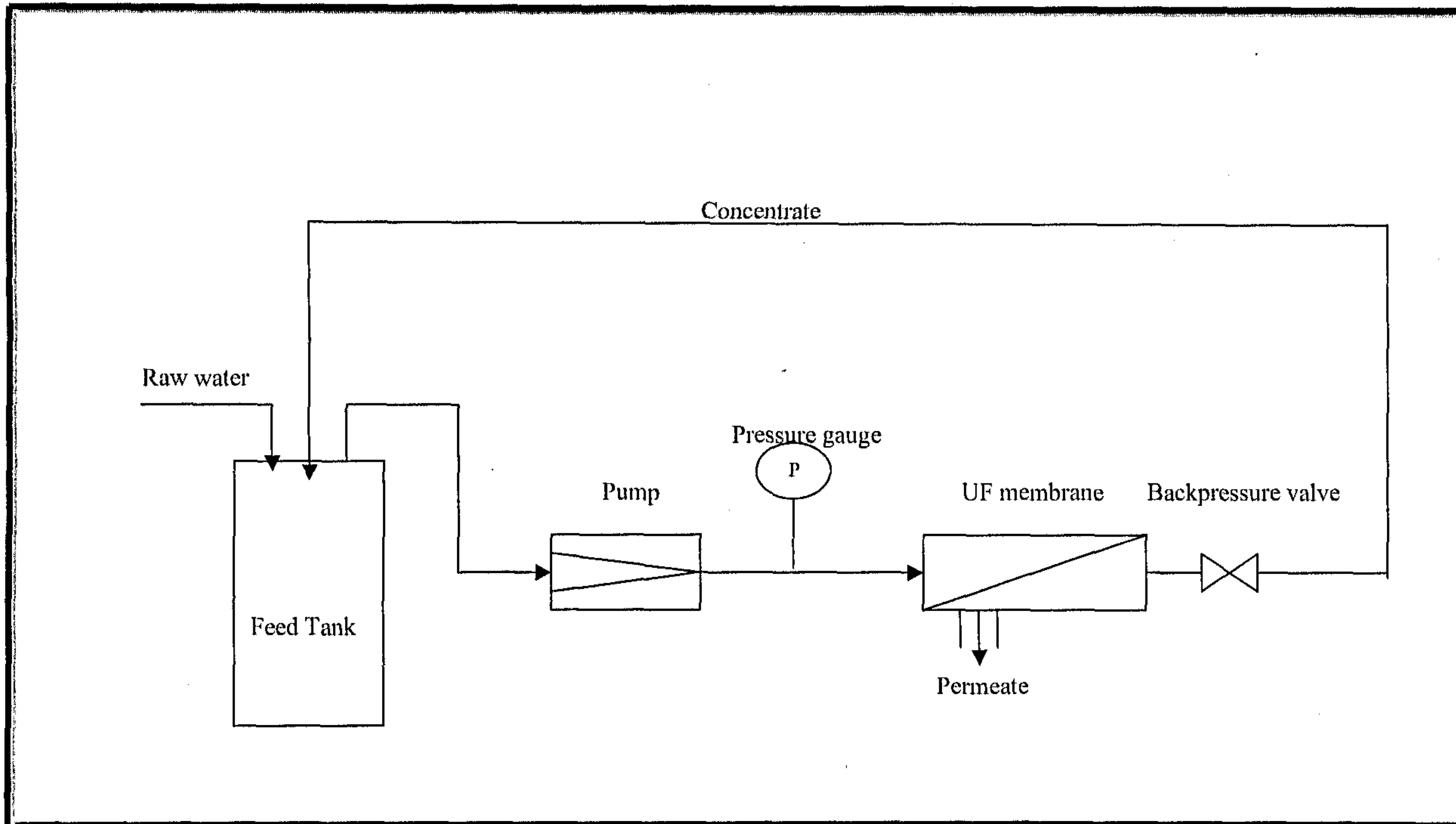
The flow diagram for this experimental set-up using different experimental waters is presented in figure 3.2.1. For all the experiments, the ultrafiltration process was operated in a cross-flow mode, with one permeate outlet opened.

Figure 3.2.1 shows the flow diagram of the laboratory bench scale ultrafiltration unit, which was operated at Peninsula Technikon Laboratory. Feed waters were sampled from four different raw water sources and brought to the laboratory.

The feed water was pumped from the feed tank using a peristaltic pump. The pumping rate was set to allow the flow rate of one liter in two minutes and this was done manually. The pressure gauge was used to measure the pressure during the filtration process and the pressure was constantly set at 1 bar using the backpressure valve. During the filtration process, permeate flow rate was recorded and the retentate was allowed to recycle back into the feed tank.

At the start of each evaluation, 10 liters of raw water was used in the feed tank and the experiment was allowed to run for 10 minutes before the first reading was recorded. After 10 minutes the first reading was recorded and there after at 30 min interval until the last reading is recorded. For every reading recorded, the turbidity of the permeate, retentate and feed tank were also recorded. The permeate volume recorded was measured manually. It was measured at a constant volume of 100ml against the time taken, hence, the permeate fluxes could be calculated.

***Figure 3.2-1 Schematic** diagram of the experimental set up*



3.2.2 Determination of Water Percentage Recoveries

(i) At 0 percentage recovery

At 0% recovery, the turbidity of permeate, retentate and feed tank were recorded at 30 min interval until the last reading is recorded. The permeate and brine was circulated back into the feed tank.

(ii) At 10 percentage recovery

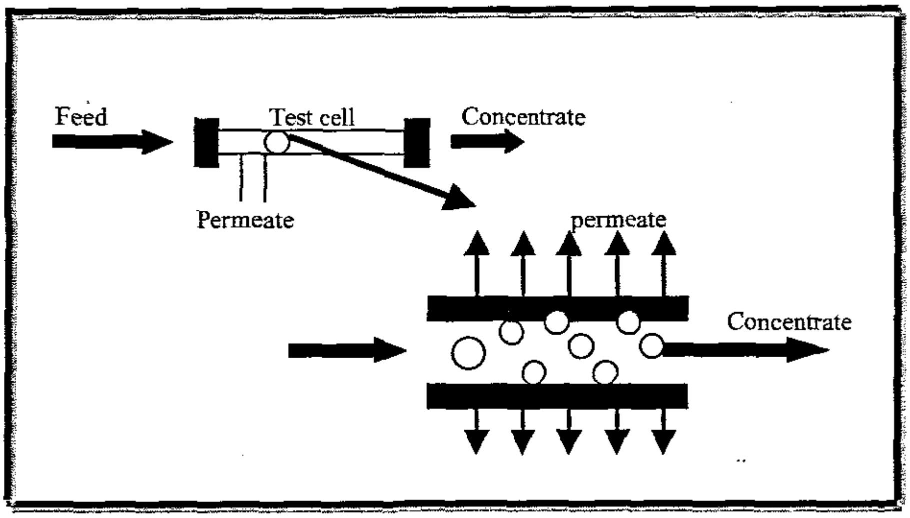
At 10% recovery, ten percent of the total volume in the feed tank (10 liters) is measured and collected as permeate. This 1000 ml permeate is not circulated back into the feed tank and the feed water is now 10% concentrated and the raw water in the feed tank is now reduced to 9 liters. Then the readings are recorded at 30 min intervals until the last results are recorded.

(iii) At 20 percentage recovery

At 20% recovery, twenty percent of the total volume in the feed tank (10 liters) is measured and collected as permeate. This 2000 ml permeate is not circulated back into the feed tank and the feed water is now 20% concentrated and the raw water in the feed tank is now reduced to 8 liters. Then the readings are recorded at 30 min intervals until the last results are recorded.

Then the same procedure was done until the recorded and desired percentage recovery depending on the raw water was achieved. The flux decline during the filtration was manually calculated from the readings recorded during the filtration process. All filtration tests were carried out at constant pressure of 1 bar in a cross flow mode as shown in figure 3.2.2.

***Figure 3.2-2** Representation of the Filtration Process (Cabassud et al, 1997)*



3.2.3 Fresh Water Flux Measurement (FWF)

Before each filtration test with the experimental waters, the FWF of the membrane was obtained by filtering clean tap water through the membrane at the pressure of 1 bar. Prior to the start of the FWF measurement the flow rate is manually set at one liter in two minutes. The experiment is let to run for 10 minutes after which the first reading is recorded and then at 30 minutes intervals until the constant results are recorded.

Clean water and permeate fluxes are calculated using the following equation:

$$F = 3.6\left(\frac{V}{A * t}\right) \tag{3.2.1}$$

where:

F = flux through membranes (l/m^2.h)

V = filtrate volume (ml)

A = membrane surface area (m^2)

t = filtration time (sec)

3.2.4 Membrane Flux

Throughout the whole study, the bench scale unit was operated in a cross flow mode at a constant TMP of 1 bar to test the integrity of the experimental membranes. The membrane performance was studied at different percentage recoveries i.e. from 0% to 60% recovery. This continually increased the load on the membrane during the filtration cycle. In most instances, it was found that on fairly high NOM concentration in the feed, water caused precipitation on the memebrane surface which restricted the lumen flow path and eventually decreased the process flux.

3.2.5 Turbidity Reduction

Regular measurements of the raw water, feed tank, retentate and permeate turbidities were performed using a portable HACH turbidity meter. The turbidity was measured in nephelometric turbidity units (NTU). The feed tank samples were taken from different raw water sources and these would represent the actual turbidity the raw water source is expected to have. Due to the concentration effect during operation, the feed tank and the retentate turbidities increased with filtration time, while the raw water did not change significantly.

3.2.6 Colour and Iron Reduction

Highly coloured water was sampled from Duivenhoks River. A portable HACH calorimeter was acquired to determine the colour in PtCo units, and regular measurements were done on the raw water, feed tank, retentate and the permeate.

Although the raw water had a fairly high colour, low colour concetrations were found in the permeate.

3.2.7 Microbial Analysis

Microbial analysis were done on the tertiary waste water effluent to determine the level of microbilogical contamination in the feed and most importantly to evaluate the removal efficiency of the membranes. Microbiologicaly analyses were done by Cape Metropolitian Council (CMC) Scientific Servicers Department.

3.2.8 Algae Reduction

Voëlvlei Dam water is characterised by a high amount of algae species. The raw water quality from this dam varies from time to time and during heavy rain falls, the algae in the water drops extremely low. The algae species identified in the raw water include, *Carteria* species; *Centric* species; *Trachledomonas* species and *Melosira* species (table 4.2.5) No blue green algae was detected in the raw samples. The analyses were done at CMC Scientific Servicers Department. All the procedures and the methods used to determine the algae were kept confidential by the Scientific Service Department.

4 RESULTS AND DISCUSSIONS

In order to evaluate the feasibility of ultrafiltration for the treatment of different raw waters at different percentage recoveries, the same operating conditions were used. Because the main problem of ultrafiltration systems when applied to potable water treatment is represented by fouling, the susceptibility to fouling of the UF capillary membranes were analysed by means of membrane behaviour during the filtration process. The whole idea of operating the membranes at different water recovery percentages means in fact measurement of the length of time necessary for fouling of the membranes and the removal efficiency at different concentrations.

4.1 Influence of the Operating Conditions on the Rate of Fouling and Process Efficiency.

The operating conditions have a great influence on membrane fouling, by influencing the hydrodynamic conditions and the filtration mechanism directly or indirectly (Howell and Finnigan, 1990). In this study, the influence of the temperature variation can be neglected, because the usual temperature variation of the feed water was not more than 5°C (17°C - 23°C). However, in order to be able to compare fluxes, all fluxes values have been corrected for 25°C.

Clean water and permeate fluxes are calculated and corrected for 25°C, using the following formulas (Koprowski, 1995)

$$F = \frac{\eta_t}{\eta_{25}} \times \frac{Q_{avg}}{A}$$

Where:

F = flux ($l/m^2.h$)
Q_{avg} = average clean water flow at temperature t, (l/h)
A = membrane surface area (m^2)

As water temperature differed from test to test, the flux is corrected for water temperature t = 25°C.

Viscosity of water at different temperatures was calculated using the following formula:

$$\eta_t = \frac{\eta_0}{\left(1 + 0.0337t + 0.000221t^2\right)}$$

Where:

η_0 = water viscosity at temperature 0°C (Ns/m^2)
$\eta_0 = 1.7799 \times 10^{-3}$ (Ns/m^2)
η_t = water viscosity at temperature t (Ns/m^2)
t = water temperature (°C)

4.1.1 Raw water characterization

Four raw waters were used for the purpose of this study. To verify the raw water qualities, full characterization of the waters were done at the City of Cape Town Scientific Services. Samples were collected at various source points and quality measurements conducted in accordance with the standard methods for water and wastewater analysis. The following raw waters were characterized:

- Ground water
- Tertiary wastewater effluent
- Eutrophic water
- Coloured water.

4.1.2 Pressure and Concentration effects

For low-pressure systems, flux increases as the pressure increases. As pressure increases further, concentration polarization takes over and the flux may become independent of pressure: this is known as the region of mass transfer. This phenomenon is more important for ***cross flow*** systems. If the systems are not cleaned frequently, the boundary layer builds up, thus having a strong influence on flux decline. However, in ***dead-end*** mode systems, fluxes are lower and the modules are backwashed frequently so that the boundary layer formation is not so dominant, only cake is frequently removed.

For the experiments the pressure was kept at 1 bar keeping the percentage loss of the flux, and no flux enhancement method used. Two sets of trials were done from 0% to 60% recovery on each water analysed (the results are summarized in Figures 4.1.1 – 4.1.4). The first set represents the results obtained from the clean membrane (from 0% to 60% recovery) and the second set represents the results obtained from the fouled membrane due to deposition of foulants on the membrane surface or its pores during filtration process in the first set (figure 3.1.4) - being the same membrane used on the first set. The initial flux represents the first process flux achieved at the beginning of the experiment at different percentage recoveries. The final flux represents the final process flux achieved by the fouled membrane for the duration (the time required to reach certain percentage loss of flux during filtration processes at different percentage recoveries) of the filtration process. The difference between initial and final membrane flux represents flux decline over time due to membrane fouling.

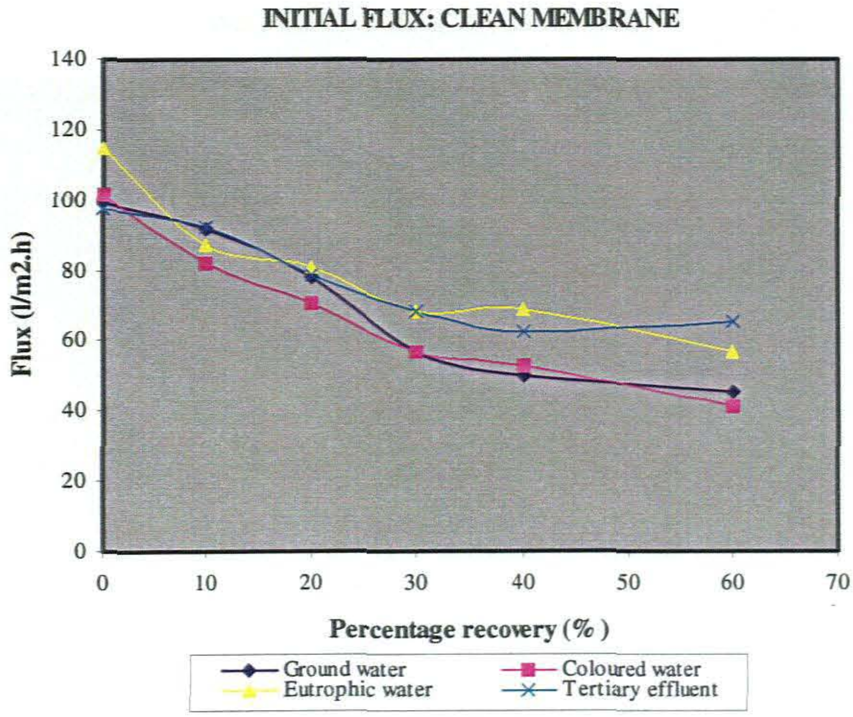


Figure 4.1-1 *First set (clean membrane) showing initial process fluxes at different water percentage recoveries*

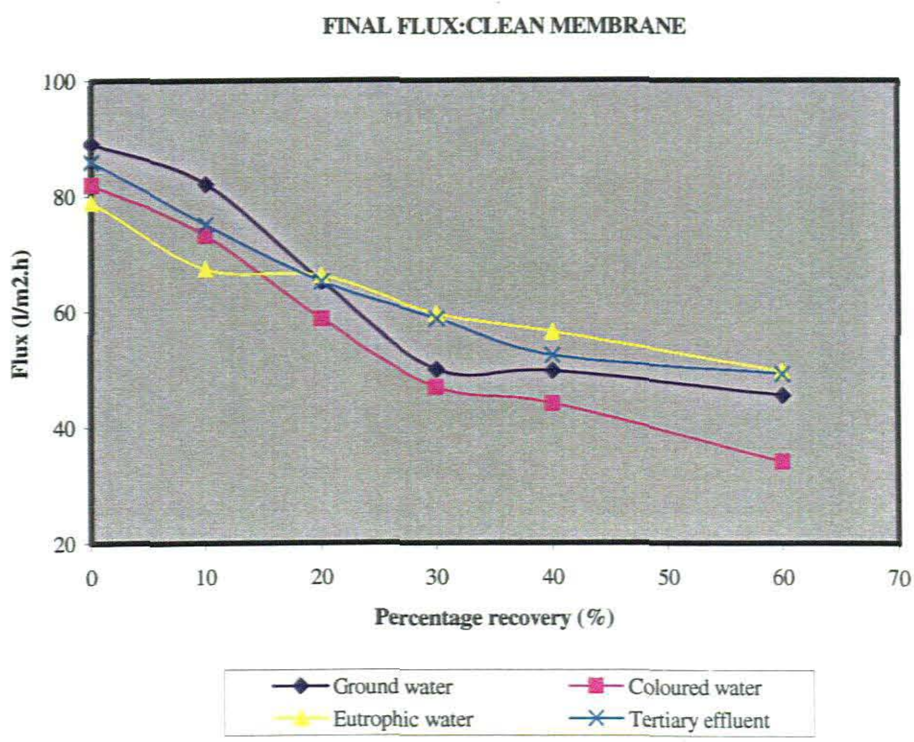


Figure 4.1-2 *First set (clean membrane) showing final process fluxes at different water percentage recoveries.*

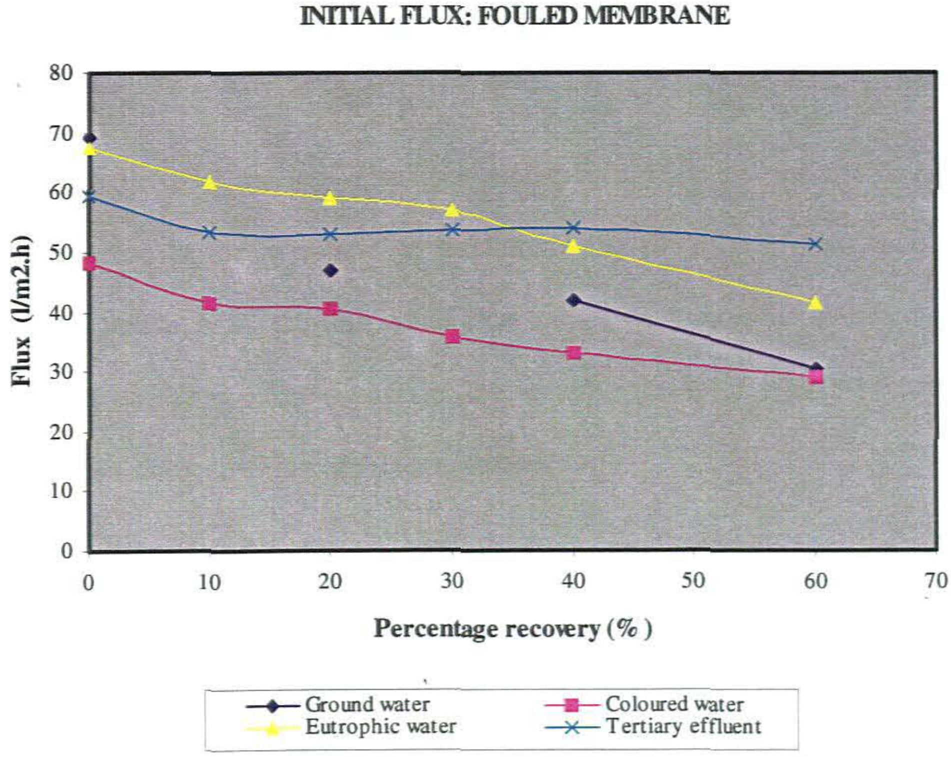


Figure 4.1-3 *Second set (fouled membrane) showing initial process fluxes at different water percentage recoveries.*

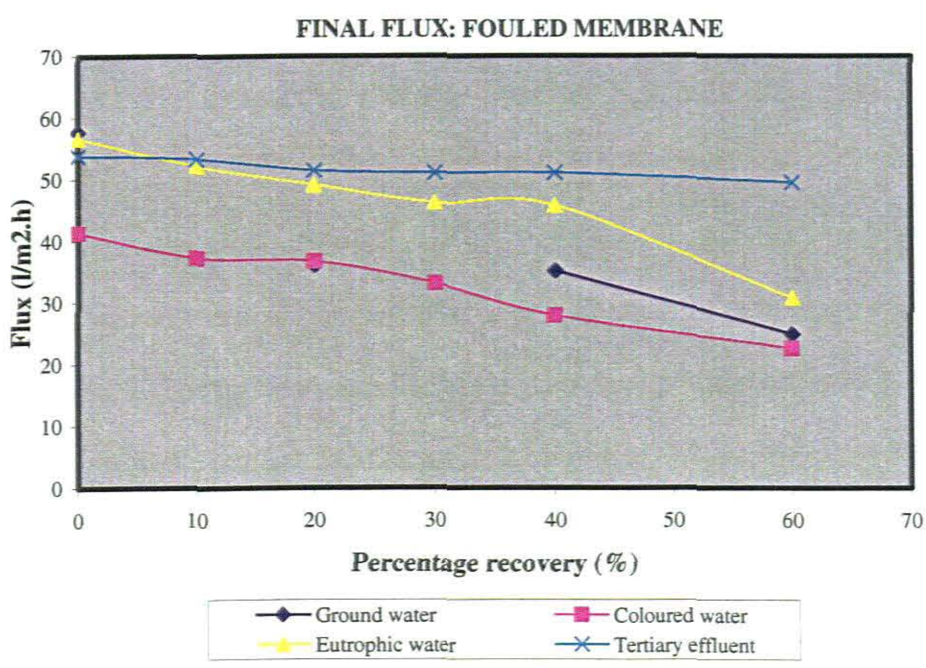


Figure 4.1-4 *Second set (fouled membrane) showing final process fluxes at different water percentage recoveries*

Permeate fluxes as a function of percentage water recovery is shown in figures 4.1.4 – 4.1.4. The individual figures are further discussed below.

The specific fluxes of the individual percentage recoveries are not similar. There is a gradual decrease in the average flux throughout the filtration process, and it is note worthy that although all the individual flux values decline with time as the foulants accumulated on the membrane surface, the specific fluxes of higher flux membranes decline at the same rate as lower flux membranes.

Figure 4.1.1 shows initial permeate fluxes as a function of percentage water recoveries in the first set of results. Eutrophic water had the highest initial permeate flux at 0% recovery of 114.47 $l/m^2.h$, and finally at 78.96 $l/m^2.h$ at 60% recovery. Both the ground water and tertiary effluent had more or less the same initial permeate flux of 99.36 and 97.73 $l/m^2.h$, respectively at 0% recovery. The coloured water had the lowest permeate flux of 41.50 $l/m^2.h$ at 60% recovery due to high turbidities and high colour concentrations.

Figure 4.1.2 shows the final permeate fluxes as a function of percentage water recovery from 0% to 60%. The ground water had the highest final permeate flux of 89.10 $l/m^2.h$ at 0% recovery with the gradual decrease of 39,22 $l/m^2.h$ at 60% recovery. At 20% recovery ground water, eutrophic water and tertiary effluent had more or less the same decrease in permeate flux of 65.19, 66.24 and 65.16 respectively at 20% recovery. There was a great loss of permeate flux in ground water between 10% and 30% recovery.

The average percentage loss of permeate flux during the filtration process in figure 4.1.1 and 4.1.2 was:

- At 0 % recovery = 18.2%
- At 10 % recovery = 15.7%
- At 20 % recovery = 15.2%
- At 30 % recovery = 14.1%
- At 40 % recovery = 17.2%
- At 60 % recovery = 17.3%

Figure 4.1.3 and 4.1.4 shows initial and final permeate flux as a function of percentage water recovery in the second set of results (fouled membrane). The membrane is fouled due to accumulation of foulants onto the membrane surface during the filtration processes in the first set from 0% to 60% recoveries. So the same membranes are used without any flux enhancement to get the second set of results.

In both figures (4.1.3 and 4.1.4) ground water was analysed at 0%, 20%, 40% and 60% recoveries due to the time constraints. In fig 4.1.3, both the ground water and Eutrophic water had more or less the same initial permeate fluxes at 0% recovery of 69.12 $l/m^2.h$ and 67.50 $l/m^2.h$, respectively. There was little loss of permeate flux in both sets on tertiary effluent. In figure 4.1.3 the initial permeate flux at 0% recovery was 59.40 $l/m^2.h$ and finally 51.40 $l/m^2.h$ at 60% recovery. This shows a 13% loss of permeate flux, while in figure 4.1.4 the final permeate flux at 0% recovery was 53.83 $l/m^2.h$ and finally 49.50 $l/m^2.h$ at 60% recovery and this shows 8% loss of permeate flux.

The average percentage loss of permeate flux during the filtration process in figure 4.1.3 and 4.1.4 was:

- At 0 % recovery = 14.09%
- At 10 % recovery = 7.56%
- At 20 % recovery = 12.13%
- At 30 % recovery = 7.31%
- At 40 % recovery = 15.76%
- At 60 % recovery = 17.39%

The comparison between the two sets indicated that the first set of results has better permeate fluxes and a higher efficiency of production and operation than the second set of results.

4.2 Evaluation of Different Waters

The results are now following, and they are presented separately for each of the raw waters. The overall removal efficiency results are given in tables 4.3.1 – 4.3.4 and summurised in figures 4.3.1 – 4.3.8.

4.2.1 Ground Water

Ground water used was pumped from a borehole at the Peninsula Technikon Lake on the main campus. The results of the full analysis done is, as follows:

***Table 4.2-1** Typical Water quality of the Ground Water at Peninsula Technikon Lake*

Determinant	Raw	Final Product		
		0% Recovery	**30% Recovery**	**60% Recovery**
pH	6.78	7.71	8.20	8.72
Conductivity (*mS/m*)	152	148	155	150
Alkalinity (*mg/l* $CaCO_3$)	214	167.8	259.4	261.20
Chloride (*mg/l Cl*)	nd	281	315	307
Colour (*mg/l as Pt/Co*)	120	30	40	40
Calcium (*mg/l Ca*)	73.5	74.3	72.6	71.8
Magnesium (*mg/l Mg*)	37.0	36.5	36.2	35.8
Aluminum (*mg/l Al*)	0.182	0.027	0.033	0.060
Iron (*mg/l Fe*)	1.667	0.450	0.057	0.046
Manganese (*mg/l Mn*)	0.014	0.20	0.017	0.012
Sodium (*mg/l Na*)	177	185	180	178
Potassium (*mg/l K*)	4.48	6.80	6.97	7.74
Sulphate (*mg/l* SO_4)	123.2	105	121	120
UV 4cm at 300nm	nd	0.590	0.661	0.732
Total Dissolved Solids (*mg/l*)	1000	1000	1100	1000
Nitrate/Nitrite (*mg/l* NO_3/NO_2)	nd	0.08	0.08	0.09
Turbidity (*NTU*)	11.9	0.31	0.29	0.2

nd: not determined

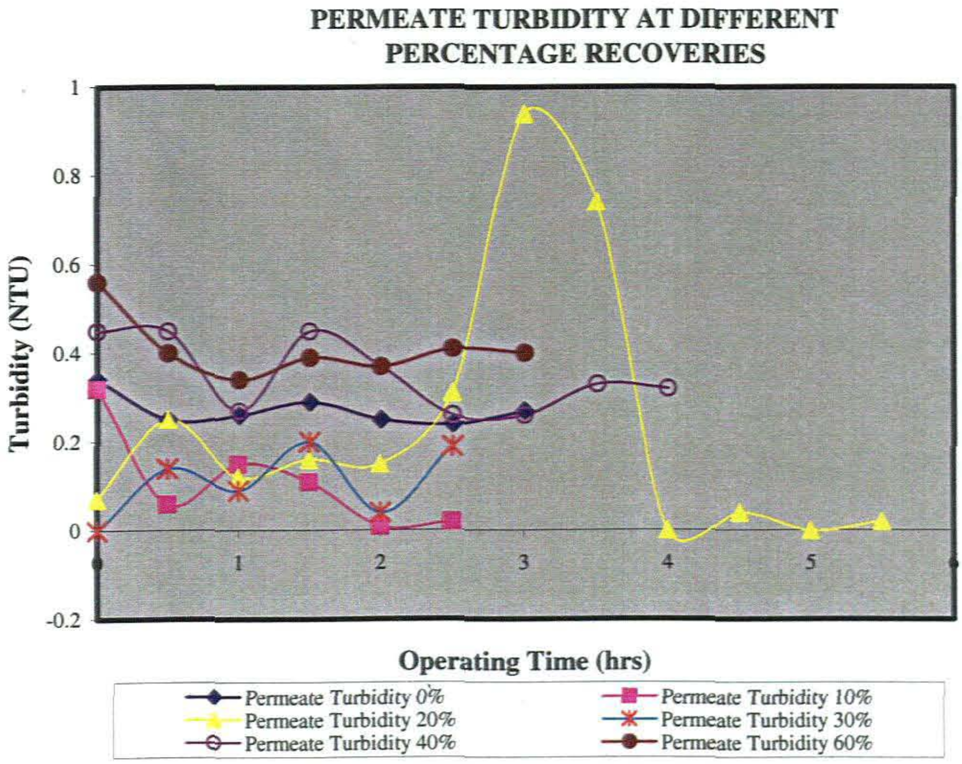


Figure 4.2-1 *First set showing permeate turbidities at different percentage recoveries over the operating period*

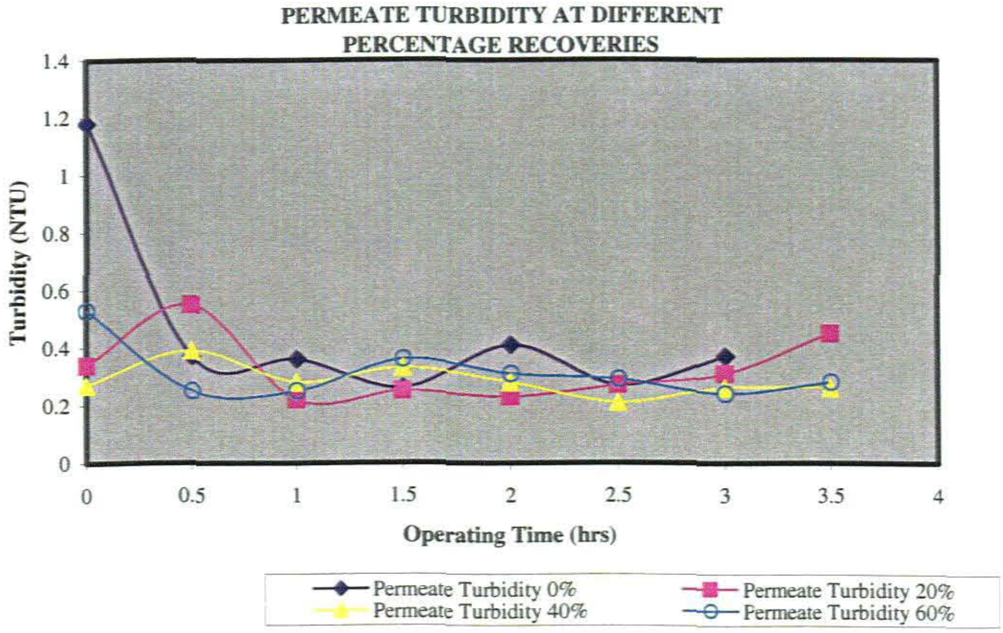


Figure 4.2-2 *Second set showing permeate turbidities at different percentage recoveries over the operating period*

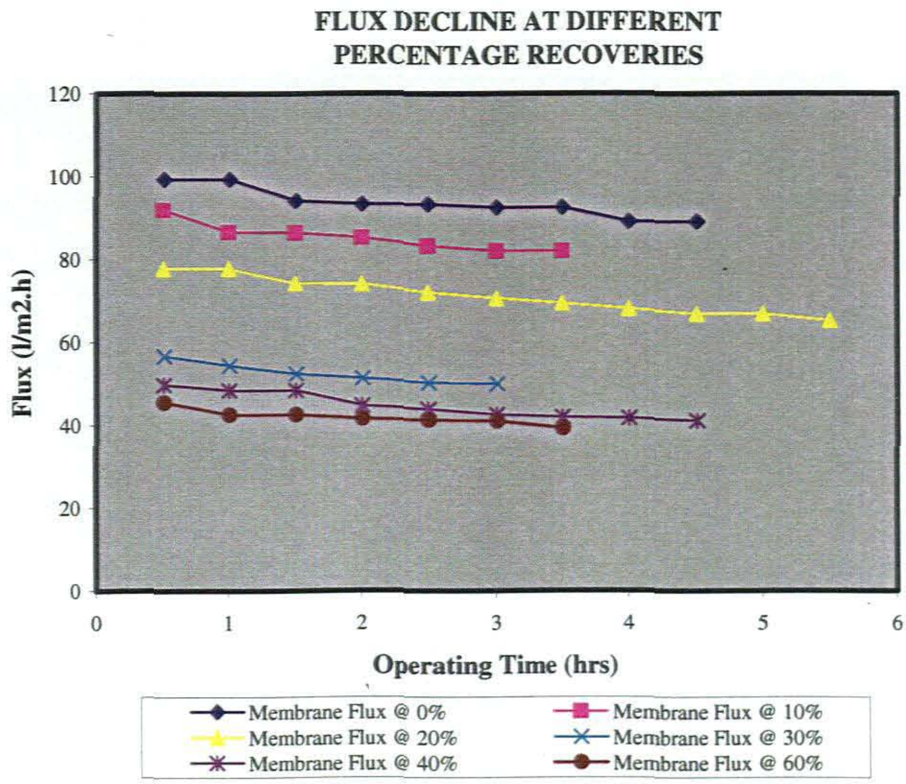


Figure 4.2-3 *First set showing flux decline over time at different percentage recoveries.*

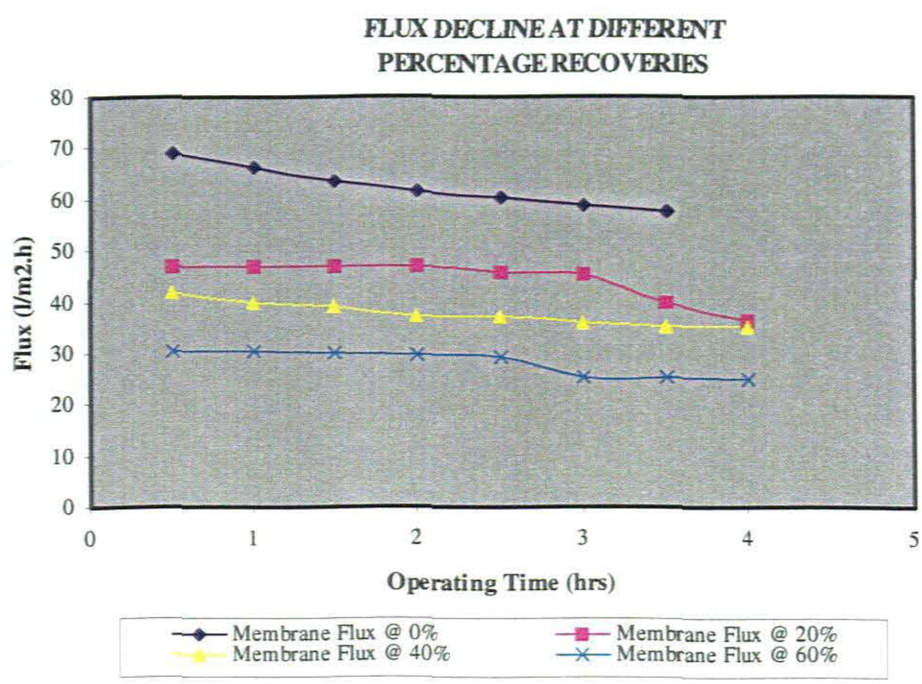


Figure 4.2-4 *Second set showing flux decline over time at different percentage recoveries*

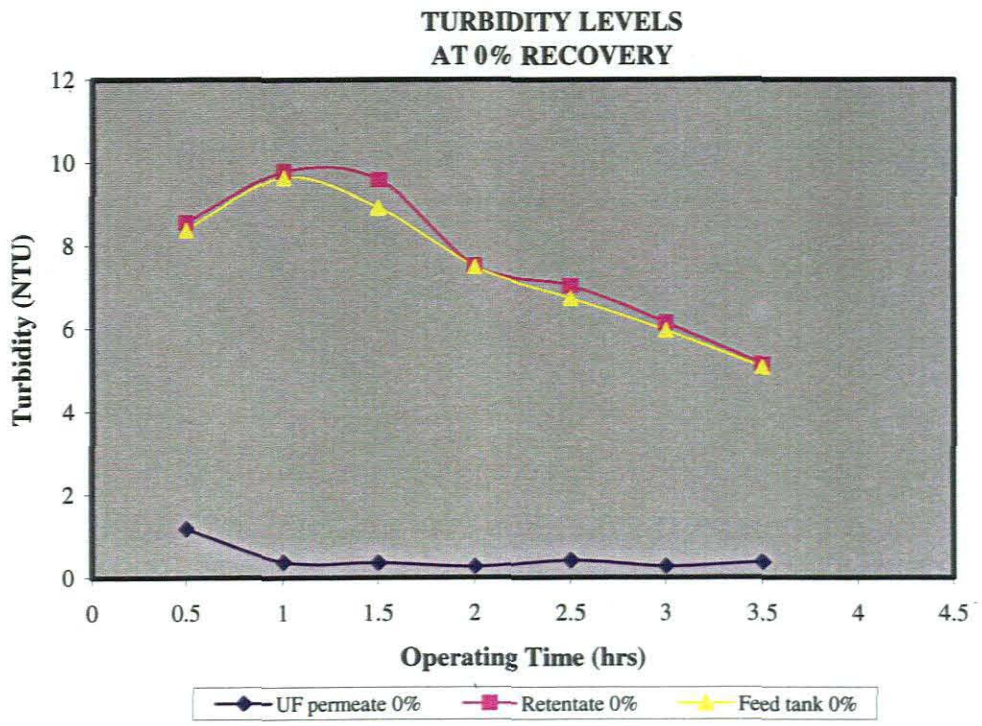


Figure 4.2-5 First set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 0 percentage recovery.

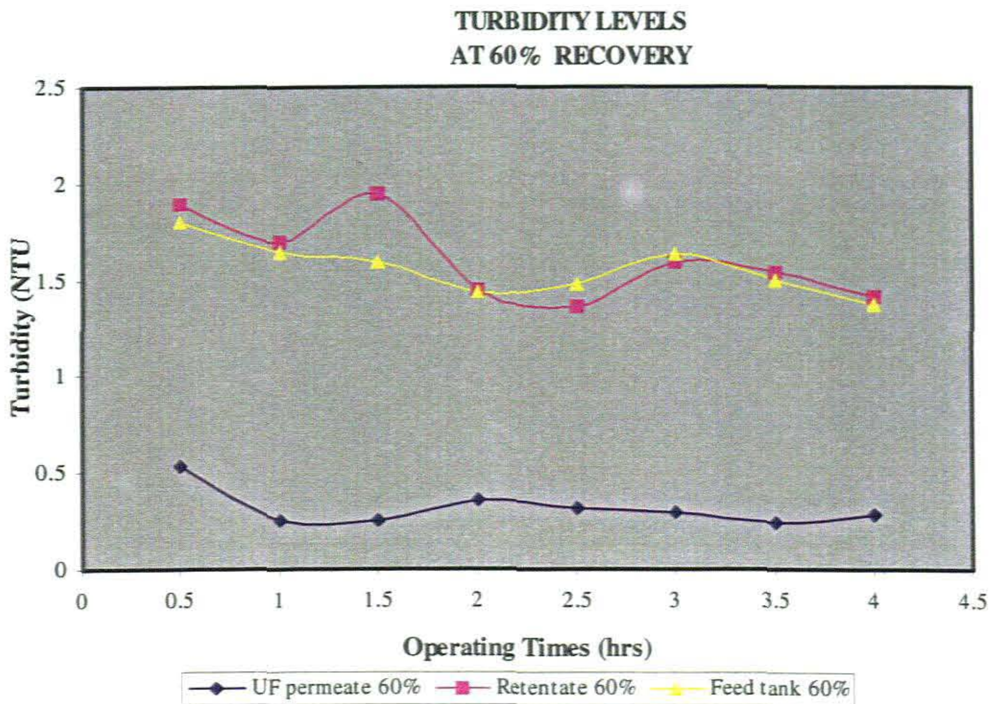


Figure 4.2-6 First set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 60 percentage recovery

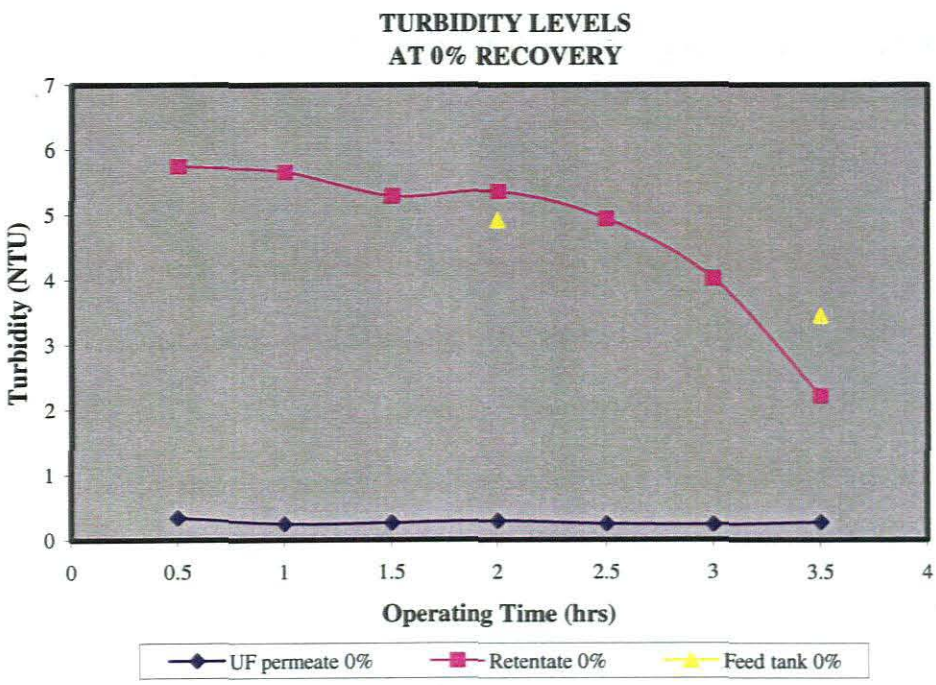


Figure 4.2-7 *Second set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 0 percentage recovery*

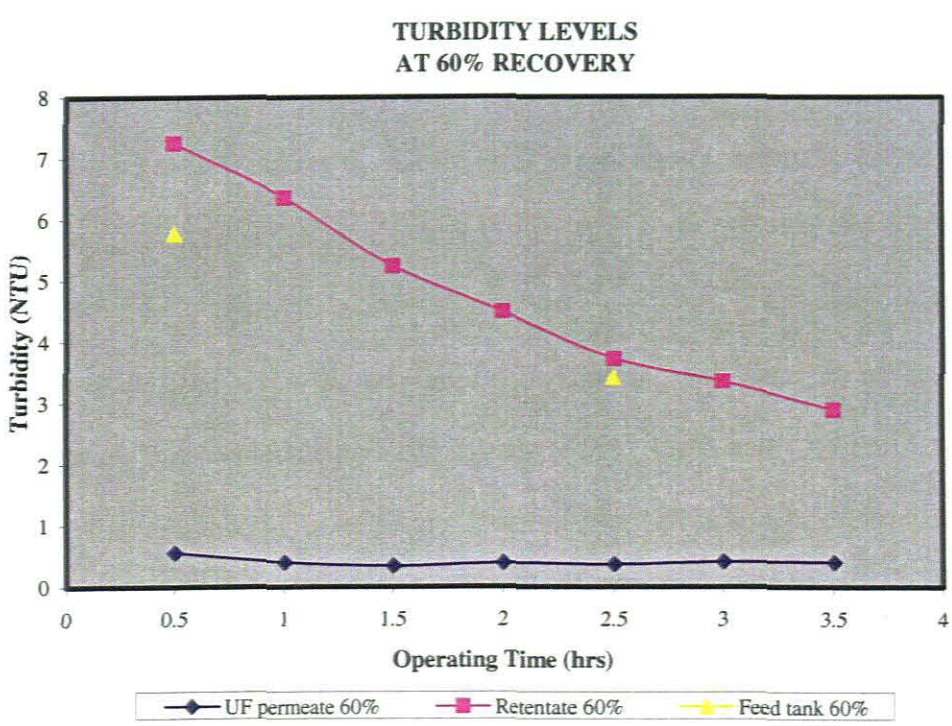


Figure 4.2-8 *Second set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 60 percentage recovery*

For the entire experimental study, turbidity was mainly used to monitor the membrane removal efficiency. Figures 4.2.1 and 4.2.2 shows the reduction in turbidity effected by membrane filtration process.

Turbidity of the raw water, feed tank, retentate and permeate were recorded at 30min intervals. The raw water turbidity ranges between 5 - 9 NTU and individual product turbities of < 0,5 NTU were recorded. Figure 4.2.1 and 4.2.2 show the permeate turbidities at different percentage recoveries for both the first and the second set of results. An average turbidities of less than 0,4 NTU were recorded in both the first and second set. The results show that there is no difference in turbidity reduction in both sets, although some spikes were observed in both sets. In figure 4.2.1 permeate turbidity level at 20% recovery at 3 – 3.5 hours of operating time was more than 0.8 NTU, and in figure 4.2.2 the permeate turbdity of more than 1 NTU was recorded at 0% recovery and this could be due to the contamination in the sampling bottles and due to the foulants from the previous set which affects the turbidity of the permeate stream at the beginning of the each set. It can further be concluded that the reduction in turbidity was > 96%.

Figure 4.2.3 and 4.2.4 shows the flux variation with time at different percentage recoveries. Initial average permeate fluxes of 70,2 l/m^2h and 47,0 l/m^2h were achieved on the first and second set of results, respectively. Initial and final permeate flux of 99,4 and 89,1 l/m^2h were achieved respectively after 5,36 hrs of operation at 0% recovery in the first set. The average flux decline for the different percentage recoveries is 13,14% on the first set and 18,4% on the second set.

Figure 4.2.5 – 4.2.8 shows the turbidity of the feed, retentate and permeate streams at 0% and 60% recoveries, for both sets of results. The turbidity of the retentate and the feed at 0% for the first set and second set ranges between 3 – 6 and 5 – 9 NTU, respectively. At 60%, the turbidity of the feed and the retentate at the first and the second set ranges between 2,8 – 7,3 and 1,3 – 1,9 NTU, respectively. The difference in turbidity at 0% and 60% is due to the cake layer on the membrane caused by the colloidal and suspended matter in the feed.

4.2.2 Coloured Water

The Coloured water used for this study was sampled from Duivenhoks River. The water from this river is characterized by a high amount of colour and a relatively high amount of iron. Typical raw and ultrafiltered water analyses results are presented in table 4.2.2

Table 4.2-2 Typical raw and ultrafiltered water qualities of the coloured water from Duivenhoks River.

Determinant	Raw	Ultrafiltered water		
		0% Recovery	**30% Recovery**	**60% Recovery**
pH	6.82	6.83	6.74	6.76
Conductivity (*mS/m*)	25.0	16.20	16.50	17.80
Alkalinity (*mg/l $CaCo_3$*)	9.5	5.80	6.60	6.8
Chloride (*mg/l Cl*)	61.0	46.0	45.0	49
Colour (*mg/l as Pt/Co*)	160	10	20	30
Calcium (*mg/l Ca*)	5.49	1.99	2.00	2.34
Magnesium (*mg/l Mg*)	5.70	3.42	3.42	3.74
Aluminum (*mg/l Al*)	nd	0.034	0.038	0.042
Iron (*mg/l Fe*)	1.286	0.031	0.025	0.031
Manganese (*mg/l Mn*)	nd	0.003	0.003	0.015
Sodium (*mg/l Na*)	36.8	22.9	23.70	25.50
Potassium (*mg/l K*)	5.77	1.00	1.70	1.37
Sulphate (*mg/l SO_4*)	10.0	5.90	7.07	7.47
UV 4cm at 300nm	2.418	0.301	0.364	0.531
Total Dissolved Solids (*mg/l*)	162.50	100	100	100
Nitrate/Nitrite (*mg/l NO_3/NO_2*)	0.359	0.123	0.178	0.065
Turbidity (*NTU*)	12.3	0.25	0.15	0.28

nd: not determined

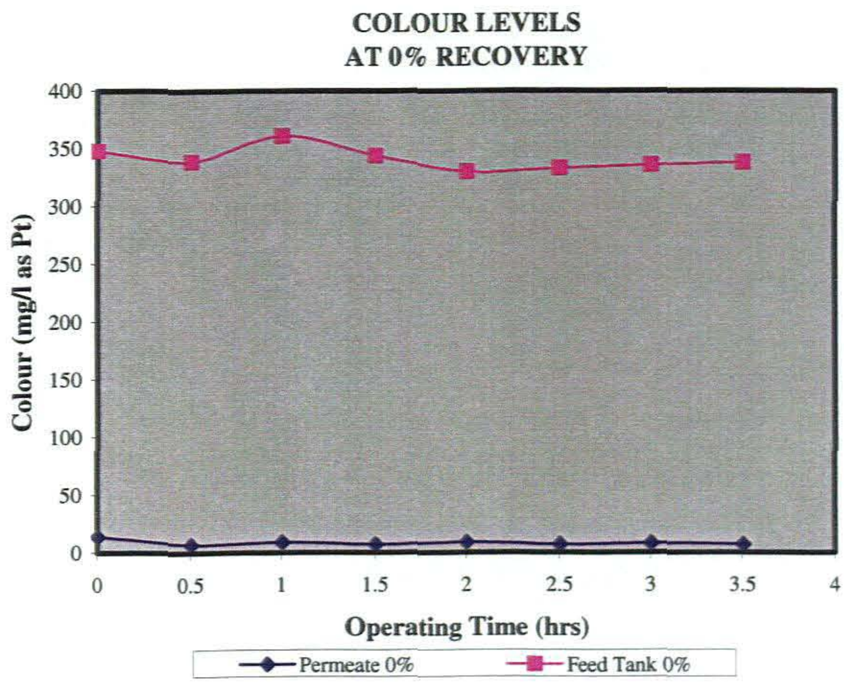


Figure 4.2-9 *First set showing colour retention capabilities of the UF membranes over the operating time at 0 percentage recovery*

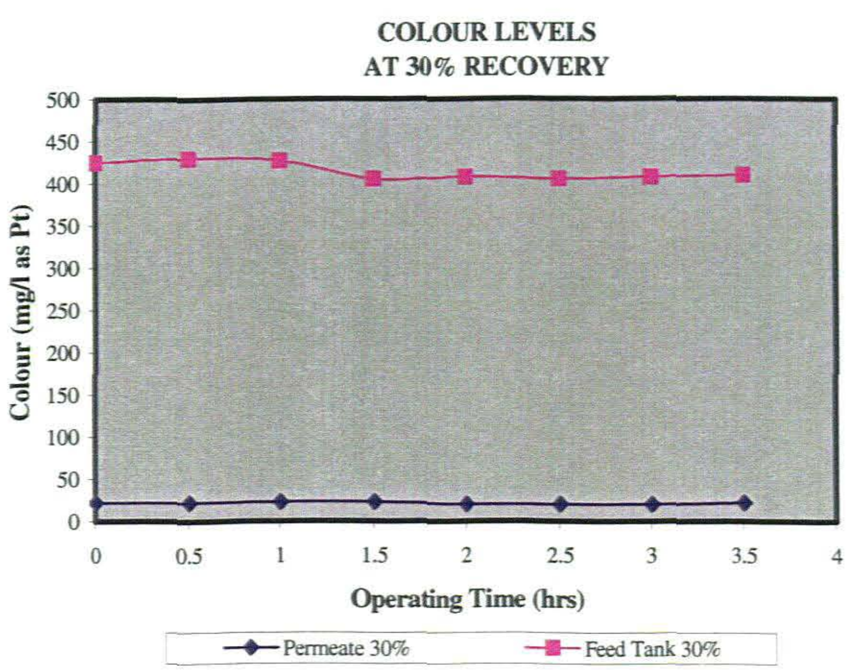


Figure 4.2-10 *First set showing colour retention capabilities of the UF membranes over the operating time at 30 percentage recovery.*

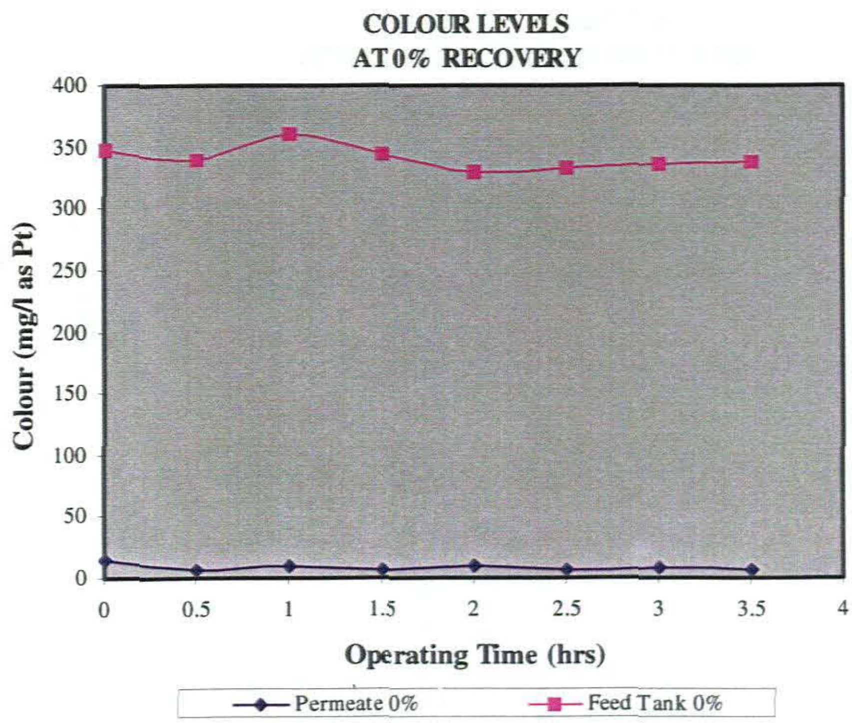


Figure 4.2-11 *Second set showing colour retention capabilities of the UF membranes over the operating time at 0 percentage recovery*

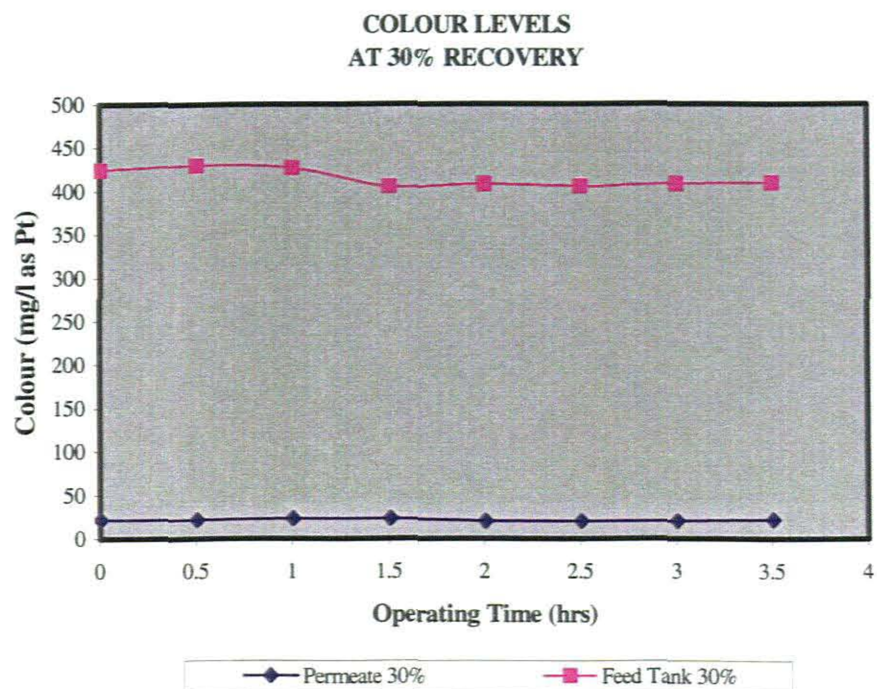


Figure 4.2-12 *Second set showing colour retention capabilities of the UF membranes over the operating time at 30 percentage recovery.*

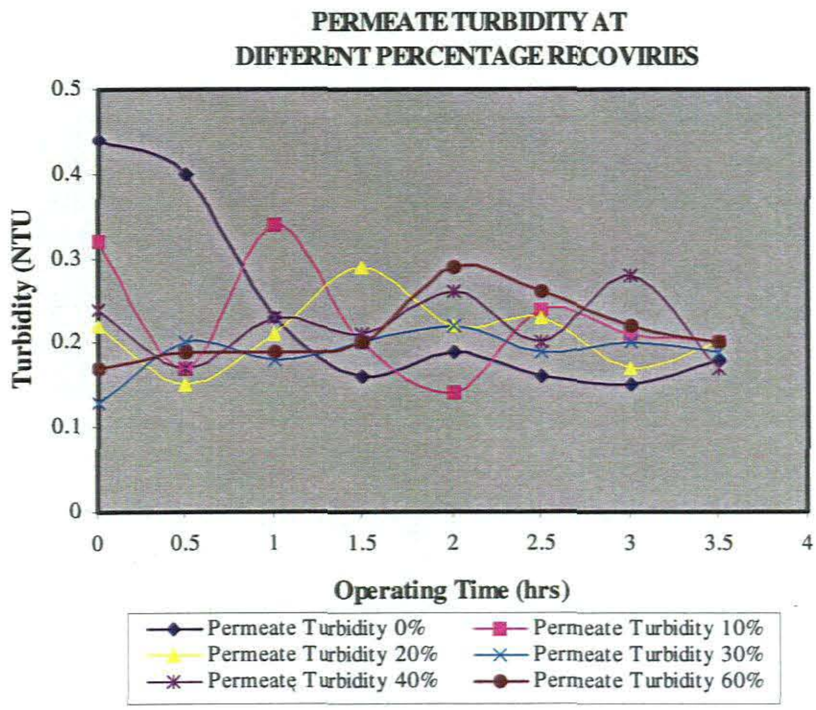


Figure 4.2-13 *First set showing permeate turbidities at different percentage recoveries over the operating period*

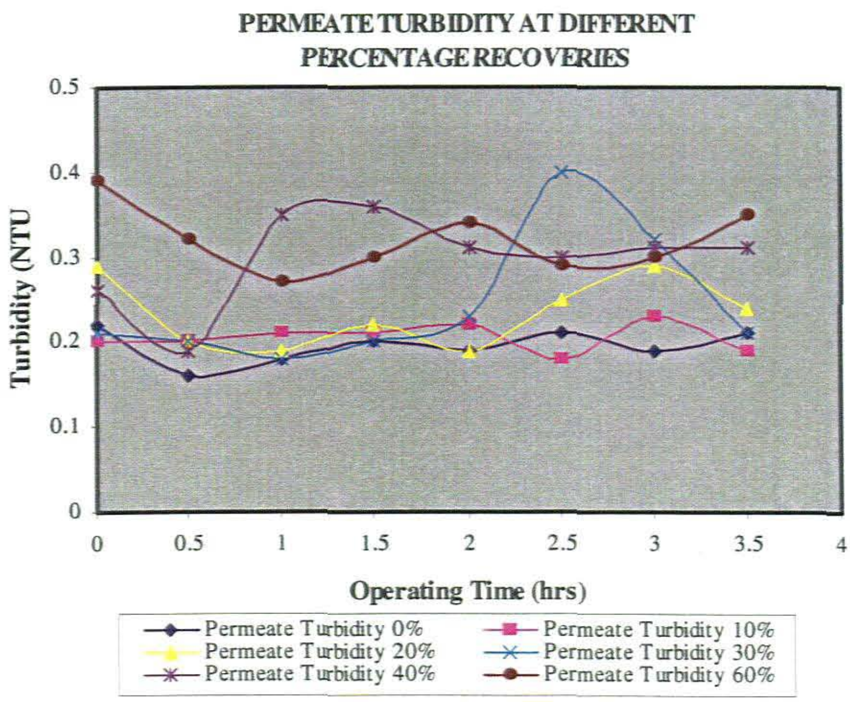


Figure 4.2-14 *Second set showing permeate turbidities at different percentage recoveries over the operating period*

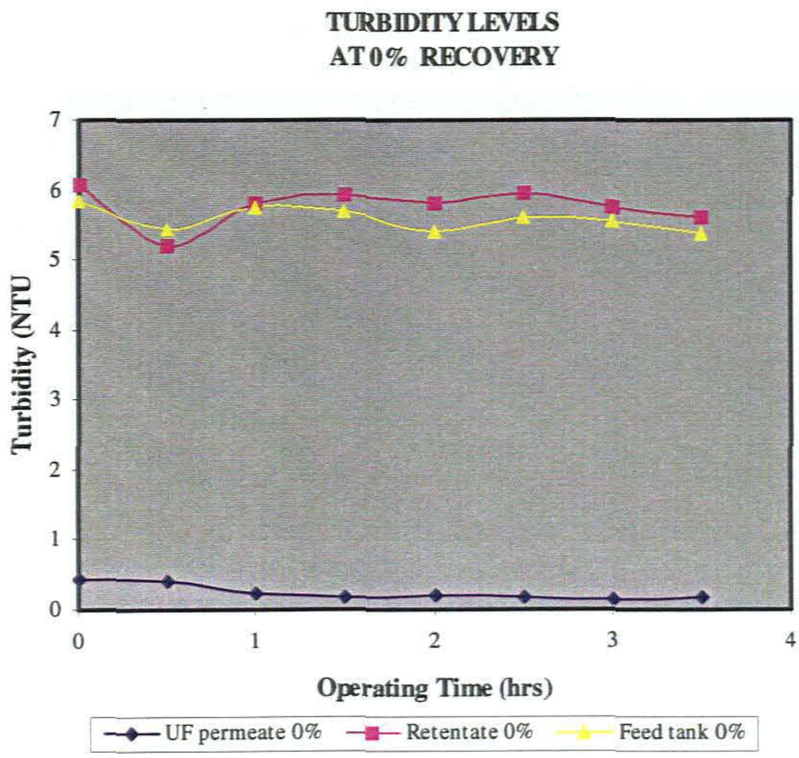


Figure 4.2-15 *First set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 0 percentage recovery*

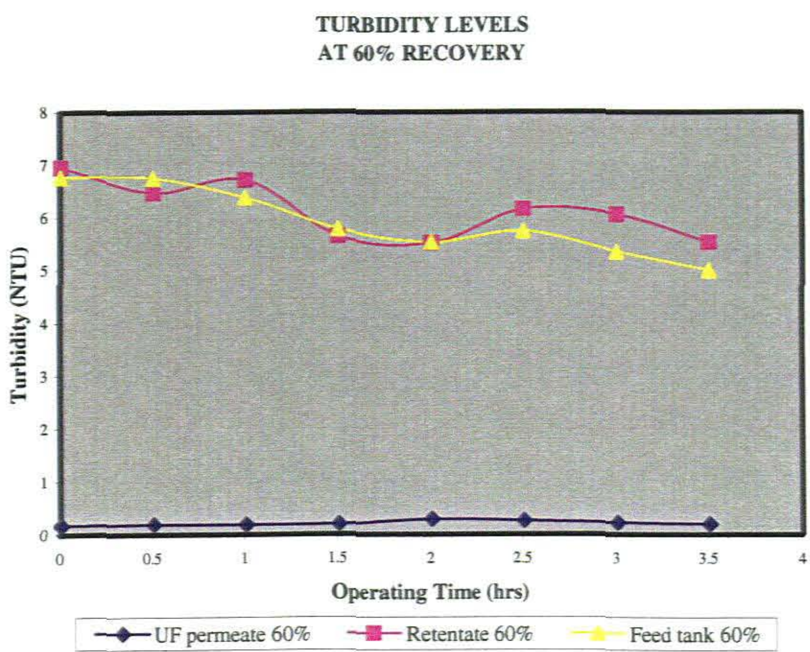


Figure 4.2-16 *First set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 60 percentage recovery*

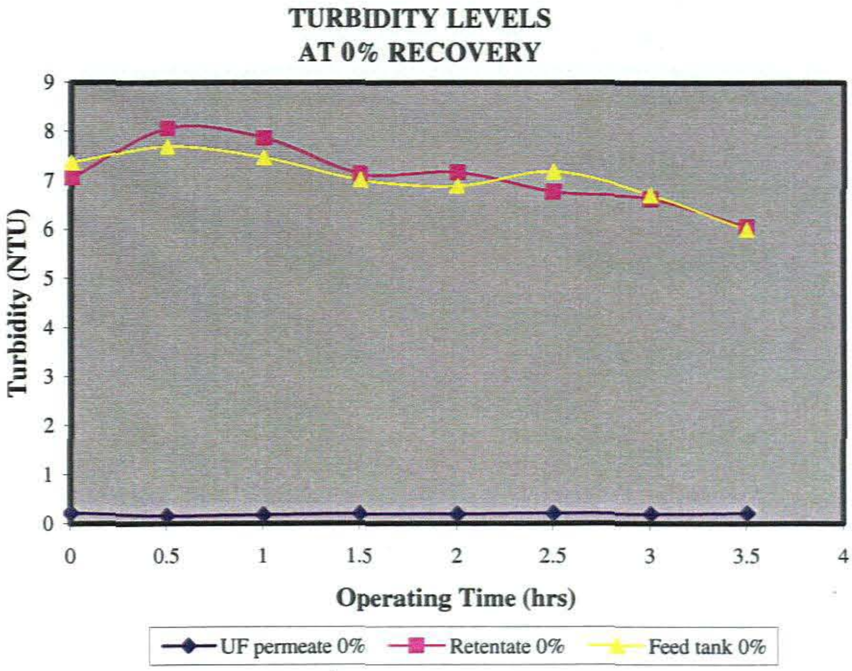


Figure 4.2-17 *Second set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 0 percentage recovery*

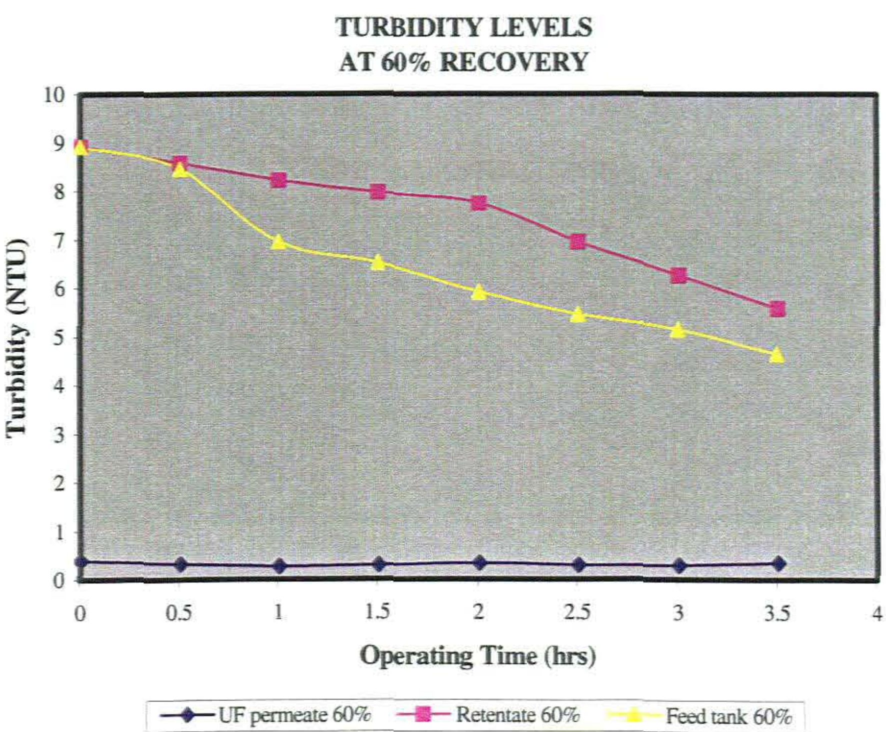


Figure 4.2-18 *Second set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 60 percentage recovery*

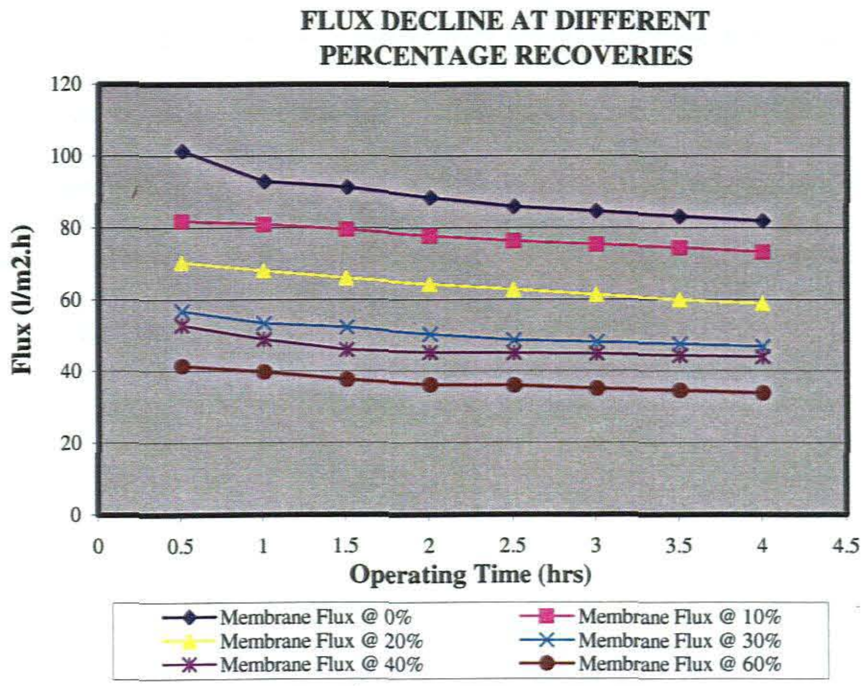


Figure 4.2-19 *First set showing flux decline over time due to fouling at different percentage recoveries*

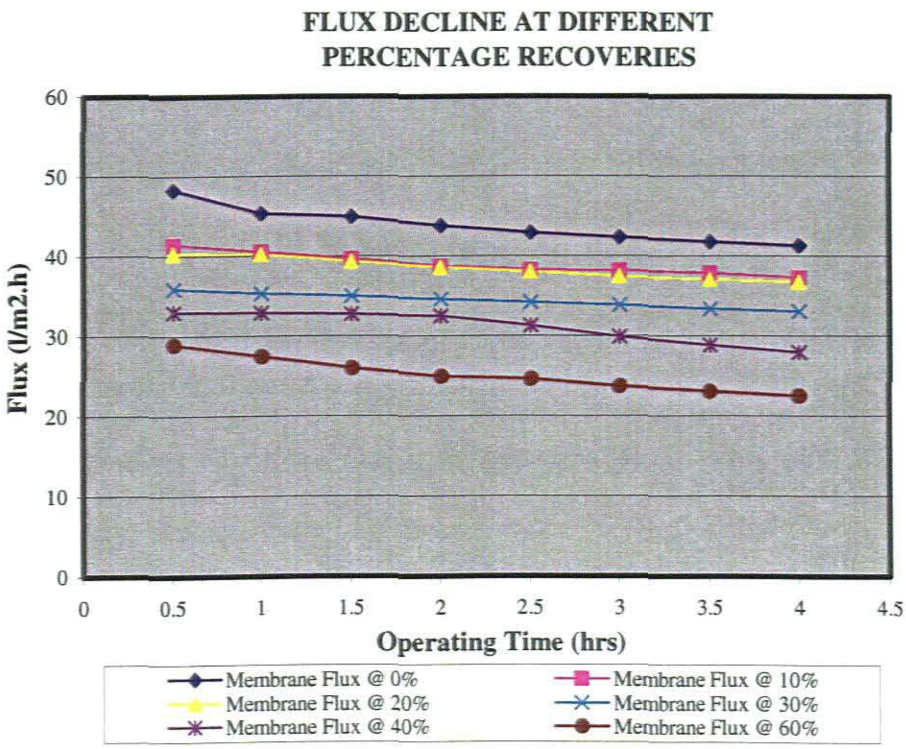


Figure 4.2-20 *Second set showing flux decline over time due to fouling at different percentage recoveries*

The raw water for this study is characterised with high concentrations in colour content and moderate concentrations in iron content of >1.3 mg/l. Figure 4.2.9 – 4.2.12 shows the true colour levels of the permeate in relation to the feed stream over the operating period at different percentage recoveries. Although high colour concentrations between 330 – 360 mg/L as Pt were recorded for the feed , the UF membranes shows consistency in producing product water with very low colour content between 7 – 24 mg/L as Pt. This shows a colour reduction between 81 and 97% for the entire filtration process.

The iron in the water was reduced by 97 to 99% at which permeate iron concentrations levels below 0.03 mg/l were recorded.

Figure 4.2.13 and 4.2.14 presents UF product turbidities at different percentage recoveries. Similar to the previous results an excellent permeate turbidity is obtained from the start of the filtration cycle in both sets. Permeate turbidity ranged from 0,13 – 0,44 NTU, and was generally around 0,3 NTU. Average permeate turbidity of 0,3 NTU were recorded in both sets of results, but few points arise from the graphs. In figure 4.2.13 permeate turbidity value of more than 0.4 NTU at 0% recovery was recorded at the start of the analyses and in figure 4.1.14 permeate turbidity value of more than 0.35 NTU at 2,5 hours of operating time at 30% recovery was recorded. However, this increase my be due to the same problem found in ground water, being that the product water is contaminated in the sampling bottles, which affect their turbidity. The two sets do not show much difference in their permeate turbidity in comparison.

Figure 4.2.15 and 4.2.18 also presents turbidity levels of permeate in relation to the feed and retentate streams over the operating period at 0% and 60% for both sets of results. The results shows fairly good constant permeate tubidities ranging between 0,13 – 0,40 NTU. Turbidity for both the feed and retentate ranged between 4 NTU and 9 NTUs, respectively, for the entire filtration process. The turbidity of the retentate is higher than that of the feed. This indicates good retention of suspended solids.

The average flux per cycle and the system productivity can be used as a tool to asses the removal effeciency of the UF systems. The filtration period for different percentage recoveries was normally between 4,5 – 6 hrs. Figure 4.2.19 and 4.2.20 shows flux variations with time which result in flux decline. In the first set, initial and final average permeate flux of 67,51 l/m^2hr and 56,49 l/m^2hr were achieved, respectively. And in the second set initial and final average permeate flux of 38,00 and 33,16 l/m^2hr were achieved respectively. The average flux decline in the first set is 16,45% and 13,13% in the second set. Initial permeate flux of 101,44 l/m^2hr and final permeate flux of 81,99 l/m^2hr were achieved in the first set after 4,81 hours of operation at 0% recovery and the flux decline for the entire operation period is 19,17% .

4.2.3 Tertiary Wastewater Effluent.

The raw water is treated at the plant to a quality that permits discharge into the Elsies River and to adjacent industries for further treatment and re-use. The table below gives the full analysis done on the tertiary wastewater effluent.

***Table 4.2-3** Full analysis and characterization results of tertiary treated wastewater effluent.*

Determinant	Tertiary treated wastewater effluent
Total Suspended Solids *(mg/l)*	1
COD *(mg/l)*	31
TKN *(mgN/l)*	12.4
NH_3 *(mgN/l)*	11.9
Organic Nitrogen *(mgN/l)*	0.5
NO_3/NO_2 *(mgN/l)*	6.6
Ortho-phosphate *(mgP/l)*	4.7
pH	7.0
Conductivity *(mS/m)*	66
Cl^- *(mg/l)*	79
Alkalinity *(mgCaCo$_3$/l)*	118

Microbiological results of the tertiary treated wastewater and ultrafiltered tertiary wastewater effluent are presented below.

***Table 4.2-4** Microbiological results of the raw and ultrafiltered tertiary wastewater effluent.*

Determinant	**Tertiary treated wastewater effluent**	**Ultrafiltered tertiary wastewater effluent**
Feacal Coliform (*per 100 ml*)	12×10^4	<10
Escherichia Coli (*per 100 ml*)	10×10^4	<10

NB. No chlorine dosage to the raw water.

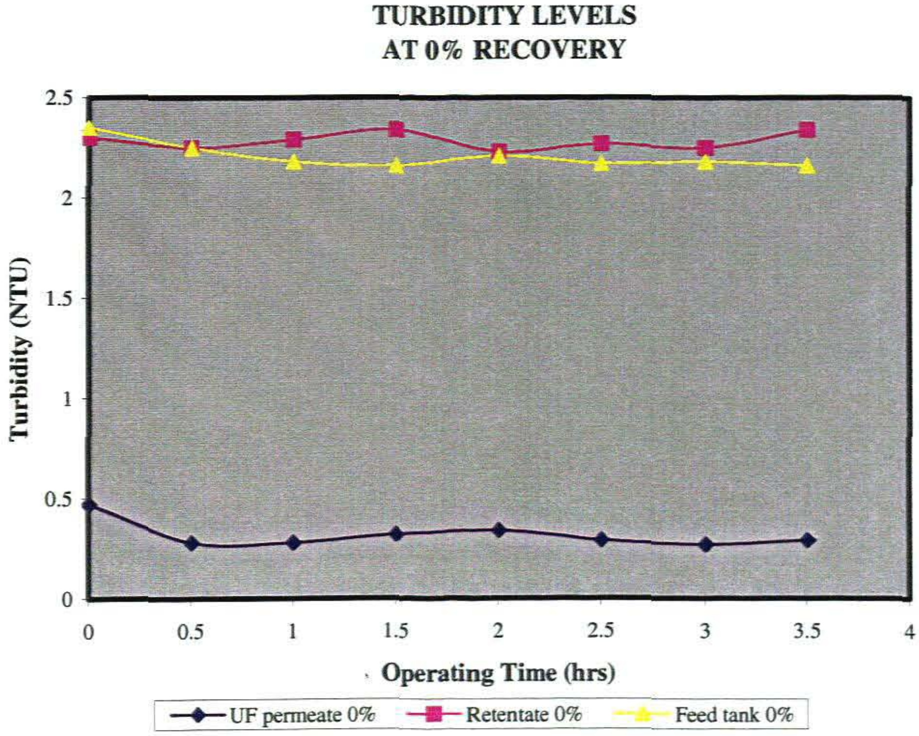


Figure 4.2-21 *First set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 0 percentage recovery*

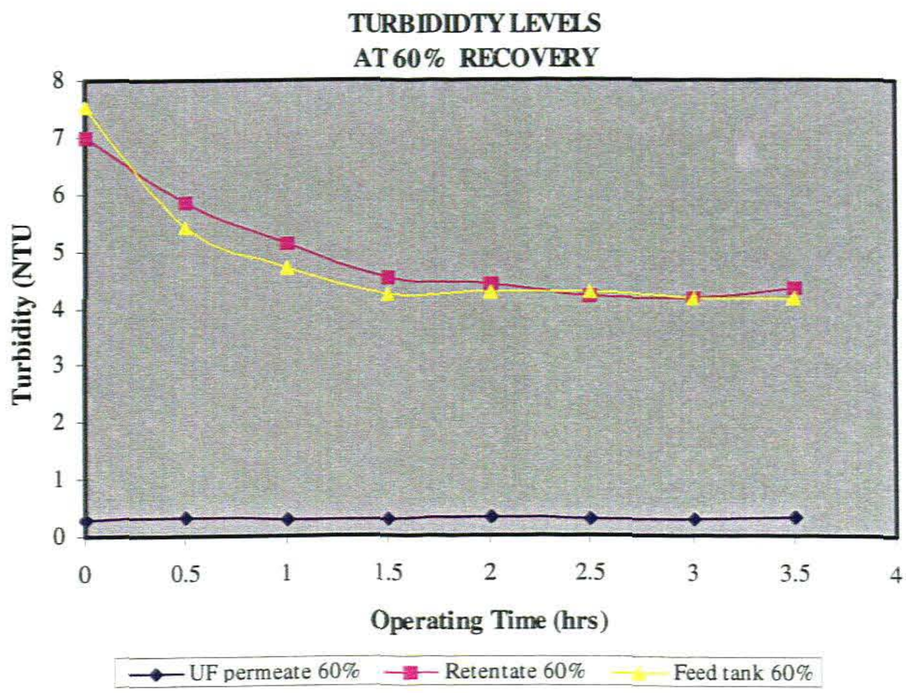


Figure 4.2-22 *First set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 60 percentage recovery*

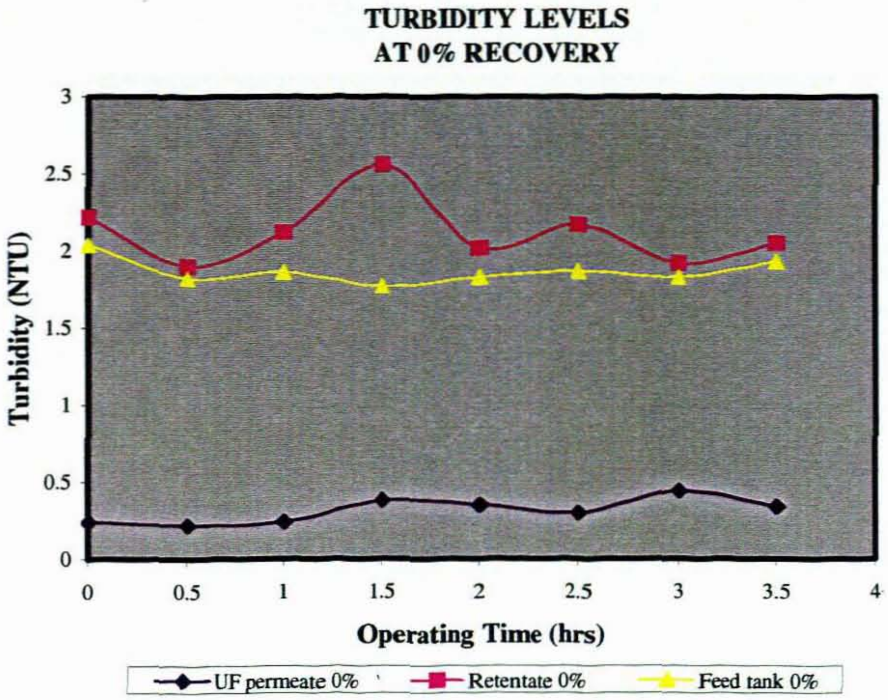


Figure 4.2-23 *Second set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 0 percentage recovery*

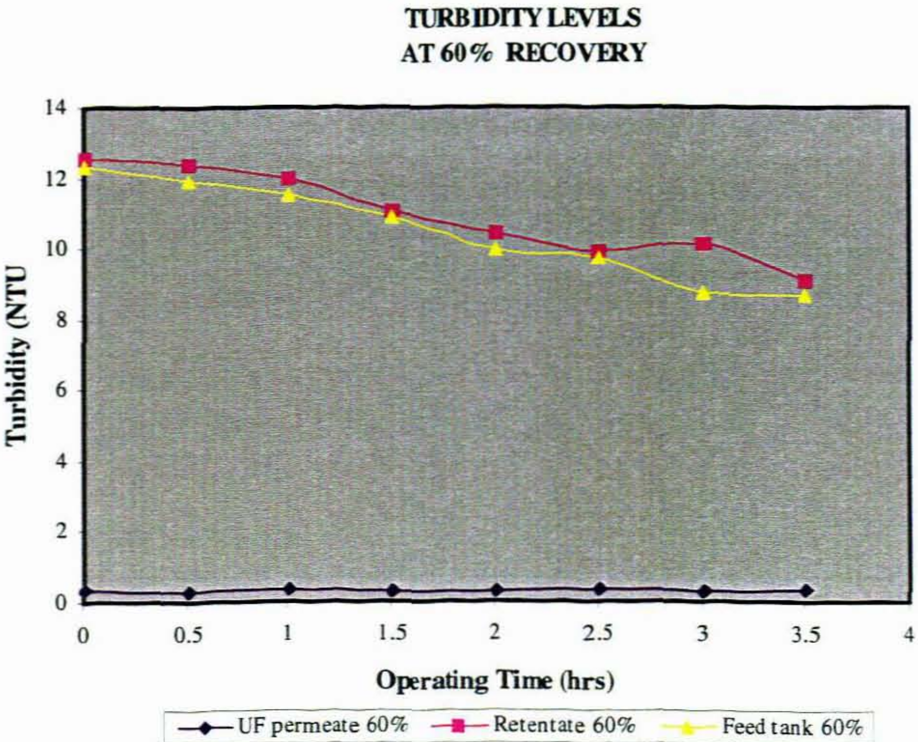


Figure 4.2-24 *Second set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 60 percentage recovery*

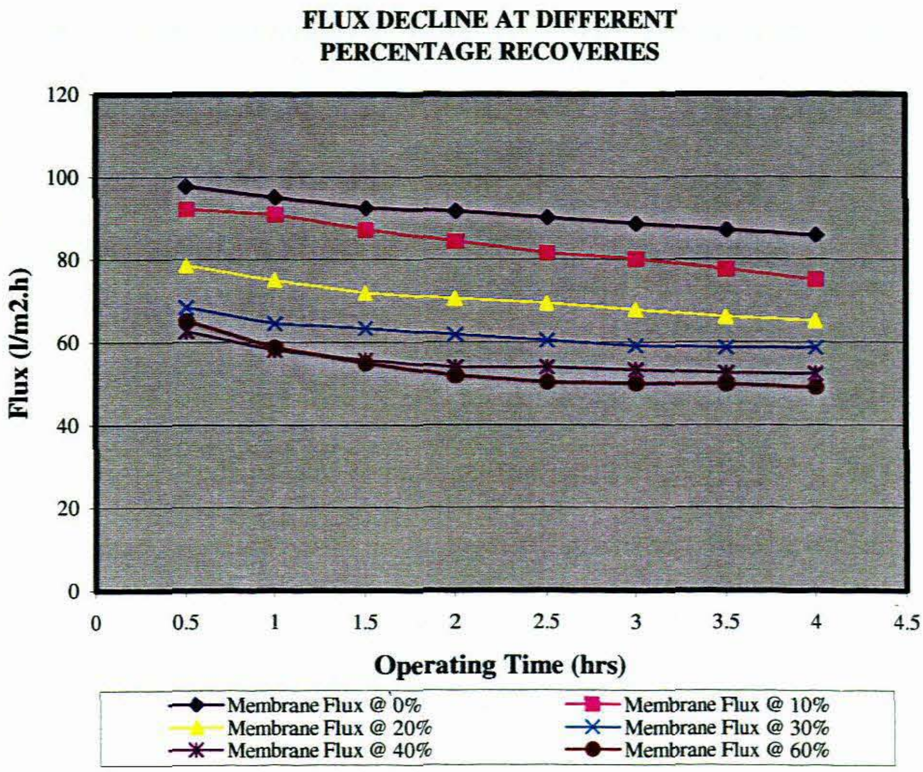


Figure 4.2-25 *First set showing flux decline over time due to fouling at different percentage recoveries*

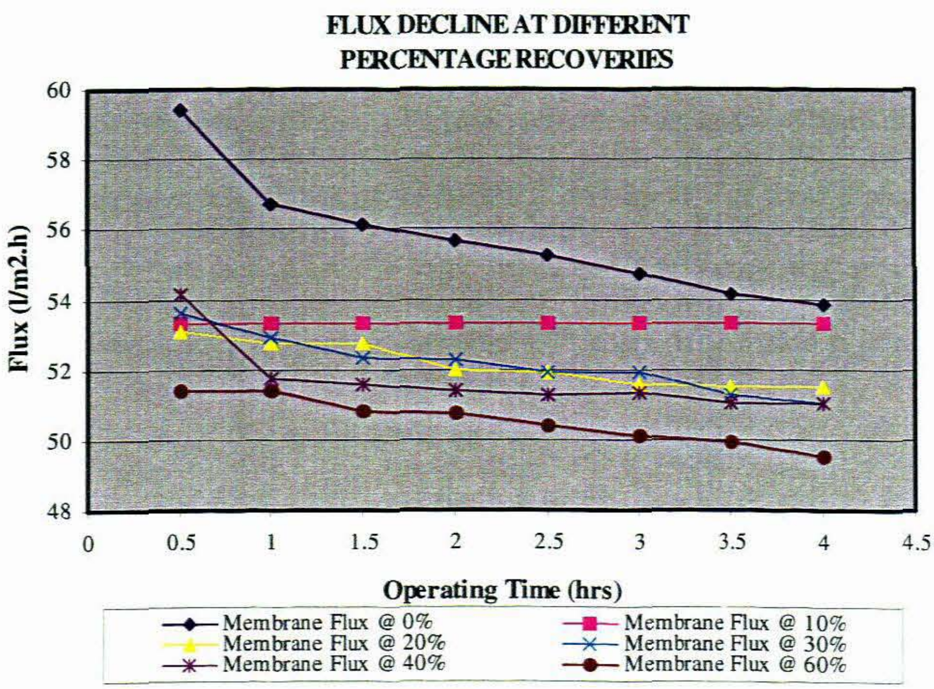


Figure 4.2-26 Second *set showing flux decline over time due to fouling at different percentage recoveries*

The influent into the Bellville South Wastewater Treatment Plant, consisted of surface water run-off, domestic and industrial waste water. Three main treatment processes are used at the plant and these are:Primary, secondary and tertiary treatment processes. Chlorine is dosed into the clear water sump as a disinfectant before the effluent is discharged into the environment.

A number of analyses were conducted to determine the level of microbiological contamination in the feed and also to evaluate the removal effeciency of the membranes. Because of the cost associated with an analyses of this nature and the limited number of samples to the Scientific Services, the analyses were done on *Escherichia Coli* (*E.Coli*) and Feacal Coliform (FC) only. The overall turbidities of the raw water were fairly low, ranging from 1 – 1.6 NTU. Turbidity levels of feed, retentate and permeate are depicted in Figures 4.2.21 – 4.2.24.

Figures 4.2.25 and 4.2.26 present flux variation with time, where the average flux decline for the different percentage recoveries is 17,16% on the first set and 4,45% on the second set. Initial average permeate fluxes of 77,50 l/m^2h and 54,17 l/m^2h were respectively identified in the first and second set of results. Initial and final permeate fluxes of 97,73 and 85,95 l/m^2h were achieved, respectively, after 4,78 hours of operation at 0% recovery in the first set.

Based on microbial analysis the raw water is by far unsuitable for human consumption, (see table 4.2.4),because of the high amount of Feacal Coliform and *Escherichia Coli* bacteria in the feed. The turbidity of the product water was on average below 0,35 NTU. The analyses were done on the raw water, the retentate and the permeate as indicated in figures 4.2.21 – 4.2.24. It is very intresting to note that, the concentration of microbes in the raw water feed and the retentate streams do not differ much. It is possible that the microbial cells are damaged in the recirculation loop. This which may be as a result of shear in the narrow flow paths of the membrane.

The raw water used for the study was sampled before the dosing of the chlorine to find the true concentration of microbes in the water. The product waters at different water percentage recoveries were then taken to the lab for analysis. The analyses show high amount of FC and *Ec* as 12×10^4 per 100ml and 10×10^4 per 100ml, respectively, in the raw water. An excellent reduction in FC and *Ec* bacteria was observed with the product water reaching less than 10 per 100ml concentrations. This shows that the UF membranes have disinfection capabilities, and with a final disinfection using chlorine, for example, the membrane process is effective for potable water treatment.

4.2.4 Eutrophic Water

Eutrophic water used in this study comes from the Voëlvlei dam. The raw water is characterized with a high number of algae species. The full raw water characterization, algae identification and enumeration determinations were done by CMC Scientific services. The results are presented below.

***Table 4.2-5** Physico-chemical results of Eutrophic water from Voëlvlei Dam.*

Determinant	Raw
pH	7.16
Conductivity (*mS/m*)	7.4
Alkalinity (*mg/l* $CaCO_3$)	12.0
Chloride (*mg/l Cl*)	19.9
Colour (*mg/l as Pt/Co*)	10
Calcium (*mg/l Ca*)	4.14
Magnesium (*mg/l Mg*)	nd
Aluminum (*mg/l Al*)	nd
Iron (*mg/l Fe*)	nd
Manganese (*mg/l Mn*)	nd
Sodium (*mg/l Na*)	nd
Potassium (*mg/l K*)	nd
Sulphate (*mg/l* SO_4)	3.20
UV 4cm at 300nm	0.19
Total Dissolved Solids (*mg/l*)	48.1
Nitrate/Nitrite (*mg/l* NO_3/NO_2)	0.007
Turbidity (*NTU*)	13.5

nd: not determined

ALGAE IDENTIFICATION AND ENUMERATION DETERMINATIONS

Table 4.2-6 *Raw water results on algae identification and enumeration determinations on Eutrophic water*

Sample sites	Identified Algae Species	Concentration
Voēlvlei Raw Dam	*Carteria sp.*	98 cells/ml
	Centric Diatoms	49 cells/ml
	Melosira sp.	685 filaments/ml
	Trachledomonas sp.	49 cells/ml

Sample type: Raw water
Raw water source: Voēlvlei dam
REMARKS: No Blue-green algae were detected in the sample.

Table 4.2-7 *Ultrafiltered water results on algae identification and enumeration determinations on Eutrophic water*

Sample sites	Percentage Recovery	Identified Algae Species	Concentration
Voēlvlei Treated	0%	*Melosira sp.*	98 filaments/ml
	20%	*Chlamydomonas sp.*	49 cells/ml
	40%	*No algae present*	-
	60%	*No algae present*	-

Sample type: Ultrafiltered water
Raw water source: Voēlvlei dam
REMARKS: No algae were detected in the 40% and 60% samples.

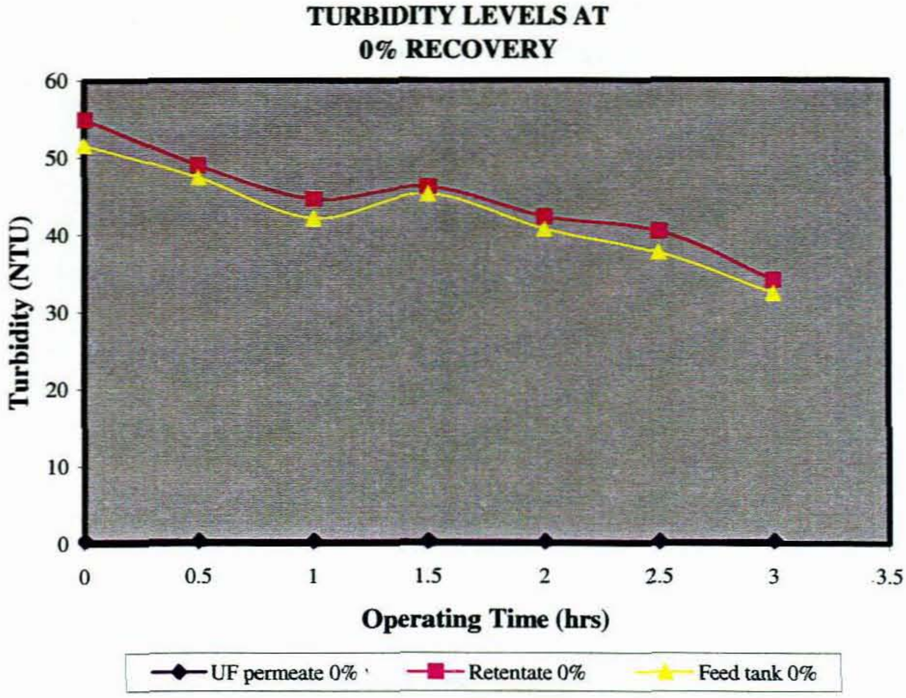


Figure 4.2-27 *First set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 0 percentage recovery.*

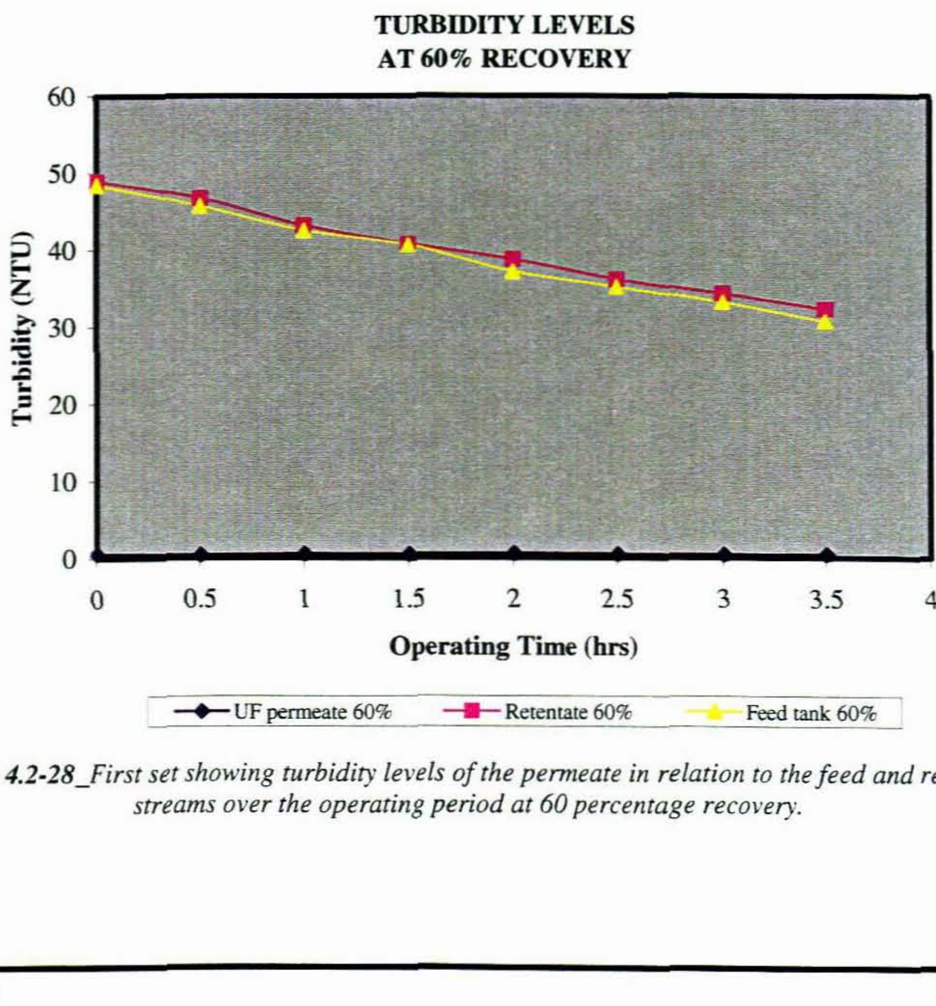


Figure 4.2-28*_First set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 60 percentage recovery.*

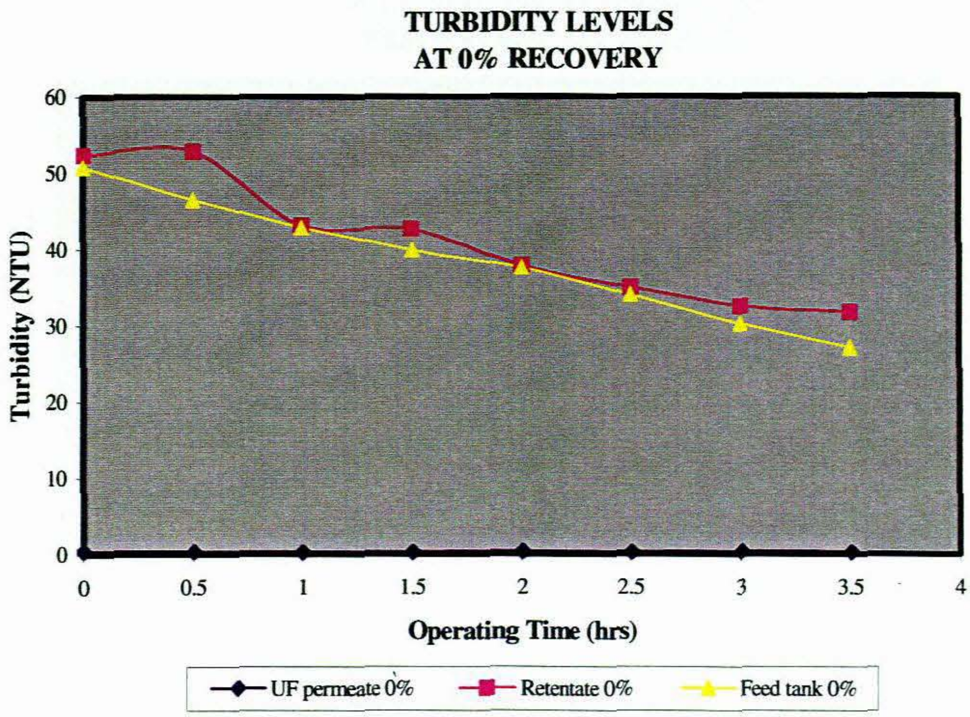


Figure 4.2-29 *Second set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 0 percentage recovery*

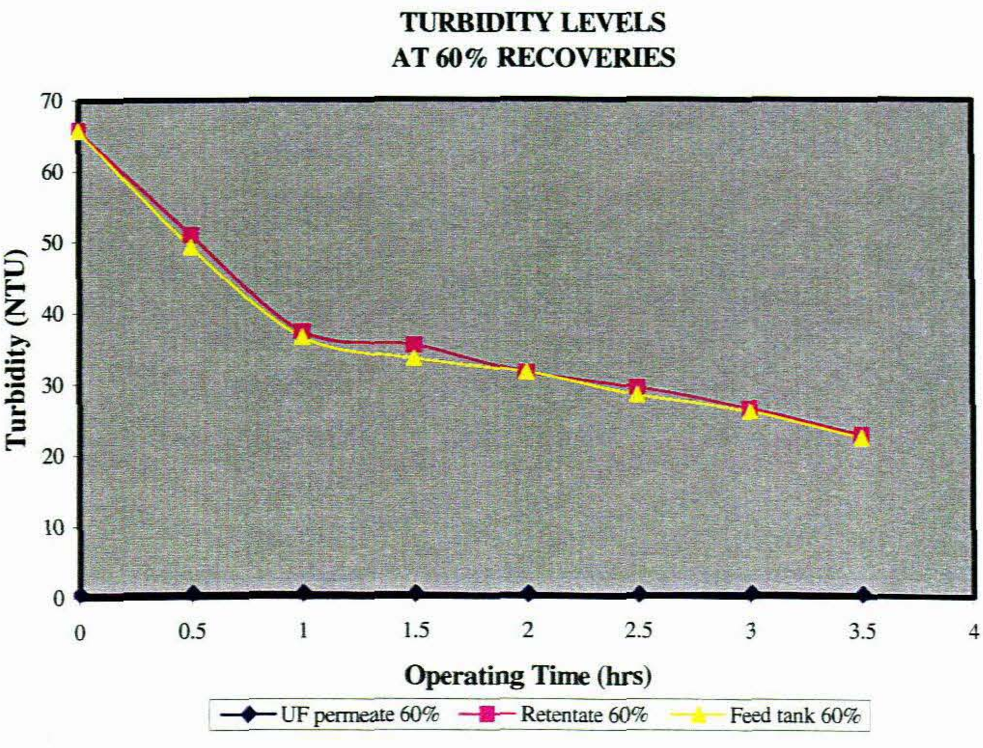


Figure 4.2-30 *Second set showing turbidity levels of the permeate in relation to the feed and retentate streams over the operating period at 60 percentage recovery.*

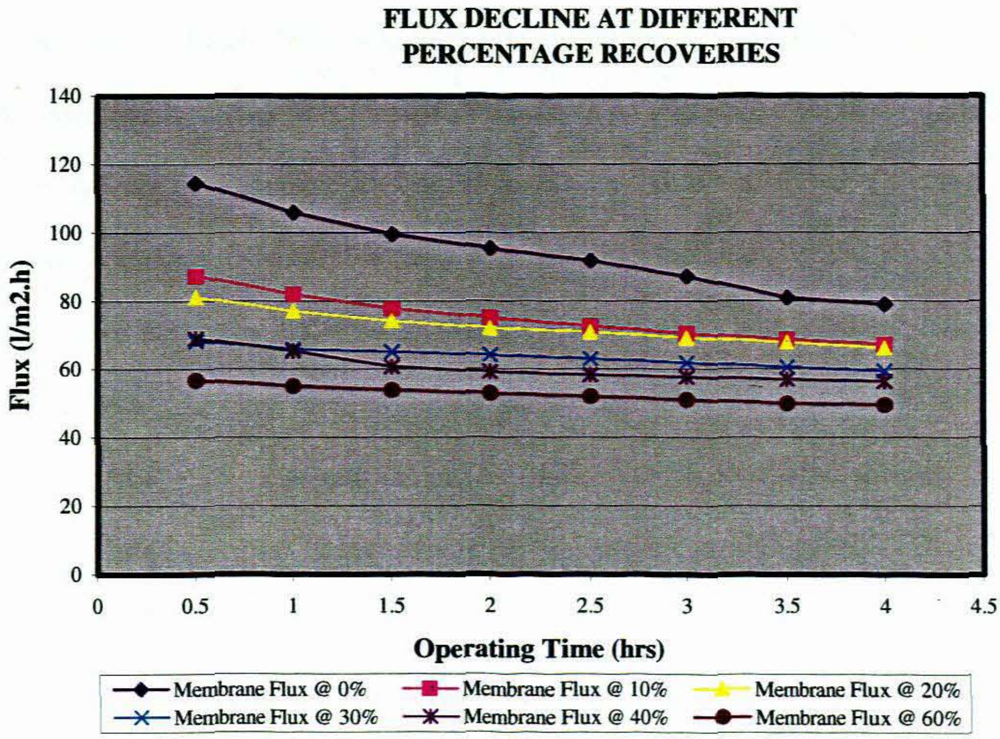


Figure 4.2-31 *First set showing flux decline over time due to fouling at different percentage recoveries*

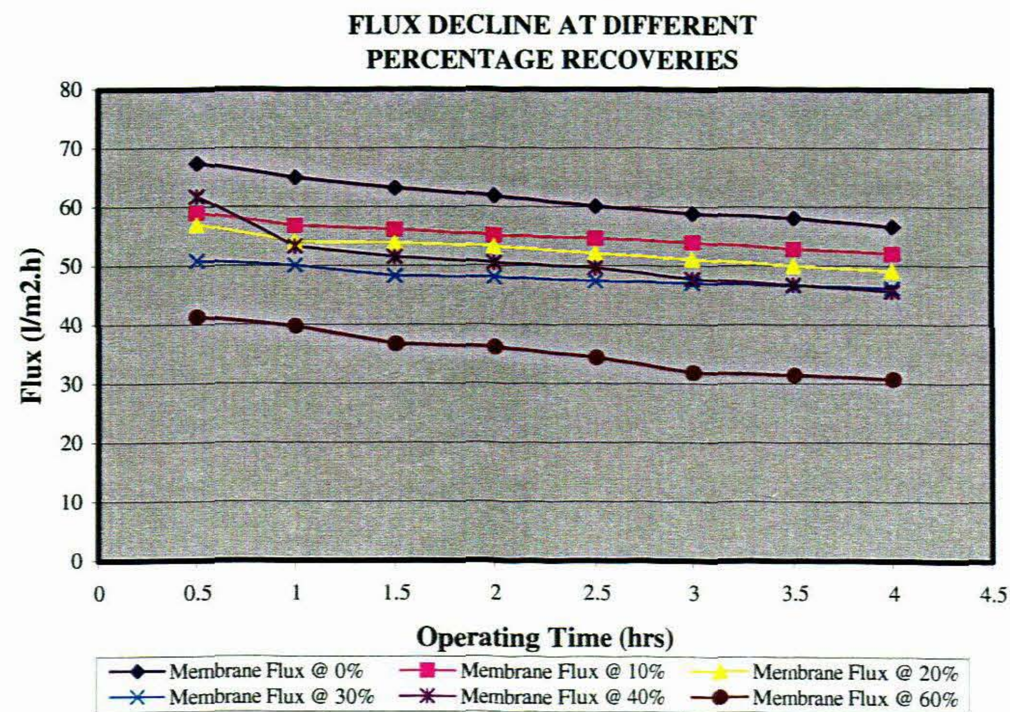


Figure 4.2-32 *Second set showing flux decline over time due to fouling at different percentage recoveries*

The Voëlvlei treatment plant uses the water from the Voëlvlei dam to supply the nearby areas. The water is characterised with high concentrations of algae species with melosira species sometimes reaching as high as 867 filaments/ml (Scientific Services, CMC). The water quality from the dam changes from time to time and the analyses of the raw water sampled for the study did not show any concentrations of blue-green algae. The algae species detected in the raw water sample were Carteria species with a concentration of 98 cells/ml; Centric diatoms with a concentration of 49 cells/ml; Melosira with a concentration of 685 filaments/ml and lastly Trachledomonas species with a concentration of 49 cells/ml. The raw water turbidities were as high as 47 NTU.

Irrespective of the high raw water turbidities the filtration process was able to remove around 99% of the turbidity content in the feed. Figures 4.2.27 – 4.2.30 shows the turbidity of the feed, retentate and permeate at 0% and 60% recoveries. The overall turbidities of the raw water feed is high. Turbidities of both the feed and retentate are getting lower and lower during the filtration process. Initial and final turbidities in the feed water at 0% recovery are 51,63 and 30,90 NTU respectively. This is due to the cake layer build upon the membrane. Product water turbidities between 0,20 – 0,60 NTU were recorded.

Initially before the start of the experiment on the algae water, it was thought that the membrane was easily going to be fouled due to the high concentrations of the melosira species in the water. For the two sets of results, there was a relatively decline in the membrane flux during the filtration process. Figure 4.2.31 and 4.2.32 show flux variation with time at different percentage recoveries for the fisrt and the second set of results. In the first set the initial and final permeate fluxes are 114,47 and 78,96 l/m^2h, respectively, at 0% recovery. At 60% recovery the initial and final permeate fluxes are 56,75 and 49,64 l/m^2h respectively. It is clearly observed from the results that the cake layer actually builds up as filtration goes on, thus showing an influence on the membrane performance.

Analyses done on the product water shows a relatively high reduction in the algae species in the raw water. The analyses were done on samples at different percentage recoveries and the results were as follows (see table 4.2.7)

- 0% recovery *melosira* species with up to 98 cells/ml concentrations.
- 20% recovery *chlamydonomas* species with 49 cells/ml concentrations.
- 40% recovery, No algae present in the water.
- 60% recovery, No algae present in the water

4.3 Evaluation of the Removal Efficiencies

Ultrafiltration is a proven technology for the removal of suspended solids and colloids as well as bacteria , thus enabling a good pretreatment for the use of reverse osmosis membranes. Organic compounds attached to suspended solids can also be removed by ultrafiltration. Turbidity, colour, iron, magnesium, algae species, Feacal Coliform and *Escherichia Coli* were monitored in this study in order to assess the removal efficiency of suspended solids and organic content.

Two sets of evaluations were done on each experimental water. The evaluations were done at different water recoveries starting from 0 percent to 60 percent recovery. The first set of evaluation was done using a new clean membrane at 0% recovery up to 60% recovery and the second set of evaluation was done using the same membrane used in the first set of evaluation. The results of the analysis are presented in the tables 4.3.1 – 4.3.4. In the second set of results, removal efficiency was only done on turbidity except on the coloured water due to financial constrains.

Considering the removal efficiencies calculated for each experiment (table 4.3.1 – 4.3.4) the overall results are summarized in Figures 4.3.1 – 4.3.8

A. GROUND WATER RESULTS

Table 4.3-1 A and B: *Results of the analysis on ground water for both first and second set.*

A - First Set

% Recovery	Operating Conditions	Initial Permeate Flux (l/m^2h)	Final Permeate Flux (l/m^2h)	% Removal
0%	P = 1bar, T = nd Δt = 5.36h, pH = nd	99.36	89.10	Turbidity = 97.4 Iron = 73.0 Mg = 1.40
10%	P = 1bar, T = nd Δt = 4.23h, pH = nd	92.01	82.07	Turbidity = 98.0 Iron = nd Mg = nd
20%	P = 1bar, T = nd Δt = 7.52h, pH = nd	77.81	65.19	Turbidity = 96.1 Iron = nd Mg = nd
30%	P = 1bar, T = nd Δt = 4.02h, pH = nd	56.69	49.96	Turbidity = 97.6 Iron = 91.5 Mg = 2.10
40%	P = 1bar, T = nd Δt = 6.30h, pH = nd	49.73	41.03	Turbidity = 94.6 Iron = nd Mg = nd
60%	P = 1bar, T = nd Δt = 4.99h, pH = nd	45.50	39.22	Turbidity = 98.3 Iron = 94.0 Mg = 3.40

P= Pressure, T = Temperature, Δt = time taken, nd = not determined, Mg = Magnesium

B - Second Set

% Recovery	Operating Conditions	Initial Permeate Flux (l/m^2h)	Final Permeate Flux (l/m^2h)	% Removal
0%	P = 1bar, T = nd Δt = 4.50h, pH = nd	69.12	57.67	Turbidity = 94.47
20%	P = 1bar, T = nd Δt = 5.62h, pH = nd	46.77	36.12	Turbidity = 94.21
40%	P = 1bar, T = nd Δt = 5.91h, pH = nd	41.76	35.12	Turbidity = 95.12
60%	P = 1bar, T = nd Δt = 6.56h, pH = nd	30.37	24.86	Turbidity = 93.82

P= Pressure, T = Temperature, Δt = time taken, nd = not determined

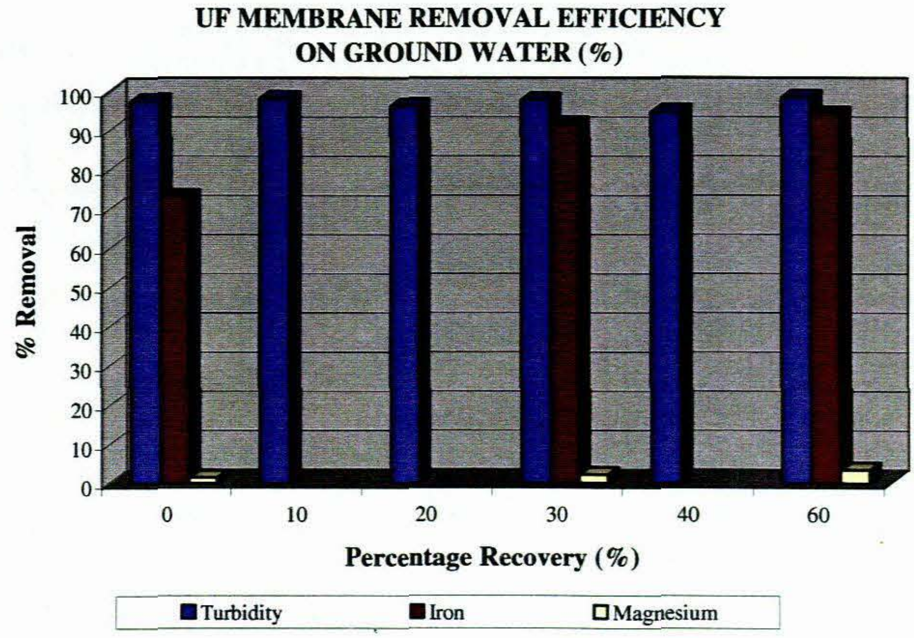


Figure 4.3-1 *First set showing turbidity, iron and magnesium removal at different percentage recoveries.*

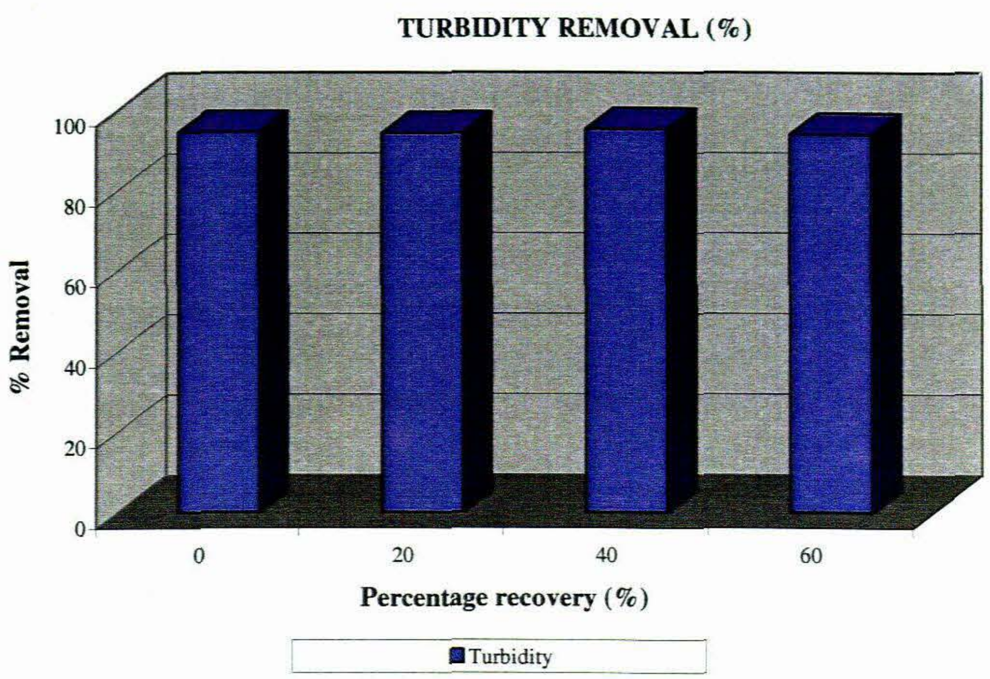


***Figure 4.3-2**_Second set showing turbidity removal at different percentage recoveries.*

B. COLOURED WATER RESULTS

Table 4.3-2 A and B: *Results of the analysis on coloured water for both first and second set.*

A - First set

% Recovery	Operating Conditions	Initial Permeate Flux (l/m^2h)	Final Permeate Flux (l/m^2h)	% Removal
0%	P = 1bar, T = 21.9°C Δt = 4.81h, pH = 6.80	101.44	81.99	Turbidity = 96.5 Iron = 97.6 Colour = 97.2
10%	P = 1bar, T = 22.1°C Δt = 4.92h, pH = 6.91	81.99	73.23	Turbidity = 96.4 Iron = 98.4 Colour = 97.3
20%	P = 1bar, T = 22.8°C Δt = 5.12h, pH = 7.14	70.34	58.75	Turbidity = 97.2 Iron = 98.4 Colour = 93.6
30%	P = 1bar, T = 23.0°C Δt = 5.42h, pH = 7.25	56.87	46.89	Turbidity = 97.1 Iron = 98.6 Colour = 87.5
40%	P = 1bar, T = 22.4°C Δt = 5.54h, pH = 7.49	52.93	44.07	Turbidity = 96.6 Iron = 99.2 Colour = 93.1
60%	P = 1bar, T = 22.9°C Δt = 4.5h, pH = 7.49	41.50	34.01	Turbidity = 96.5 Iron = 97.6 Colour = 81.2

P= Pressure, T = Temperature, Δt = time taken, nd = not determined

B - Second Set

% Recovery	Operating Conditions	Initial Permeate Flux (l/m^2h)	Final Permeate Flux (l/m^2h)	% Removal
0%	P = 1bar, T = 18.7°C Δt = 5.63h, pH = 7.37	48.29	41.34	Turbidity = 97.2 Iron = 98.4 Colour = 96.9
10%	P = 1bar, T = 22.1°C Δt = 5.83h, pH = 7.42	41.50	37.30	Turbidity = 97.1 Iron = 99.0 Colour = 96.8
20%	P = 1bar, T = 23.0°C Δt = 5.85h, pH = 7.48	40.35	36.74	Turbidity = 96.8 Iron = 99.2 Colour = 96.8
30%	P = 1bar, T = 22.9°C Δt = 6.07h, pH = 7.45	35.93	33.10	Turbidity = 96.8 Iron = 99.2 Colour = 96.9
40%	P = 1bar, T = 23.50°C Δt = 6.30h, pH = 7.36	33.00	27.94	Turbidity = 96.1 Iron = 99.2 Colour = 93.7
60%	P = 1bar, T = 21.9 °C Δt = 6.85h, pH = 7.36	28.94	22.54	Turbidity = 95.5 Iron = 99.2 Colour = 88.3

P= Pressure, T = Temperature, Δt = time taken, nd = not determined

P= Pressure, T = Temperature, Δt = time taken, nd = not determined

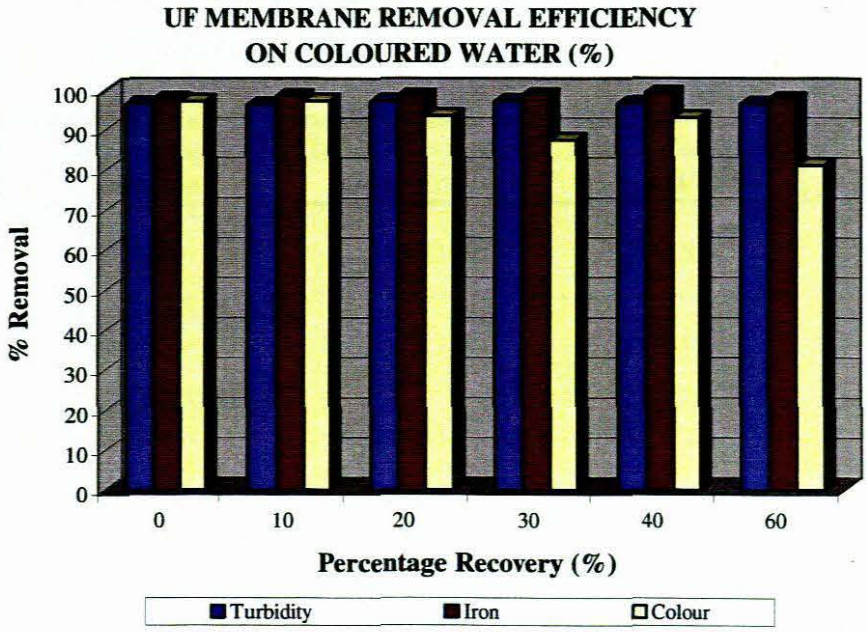


Figure 4.3-3 *First set showing turbidity, iron and colour removal at different percentage recoveries.*

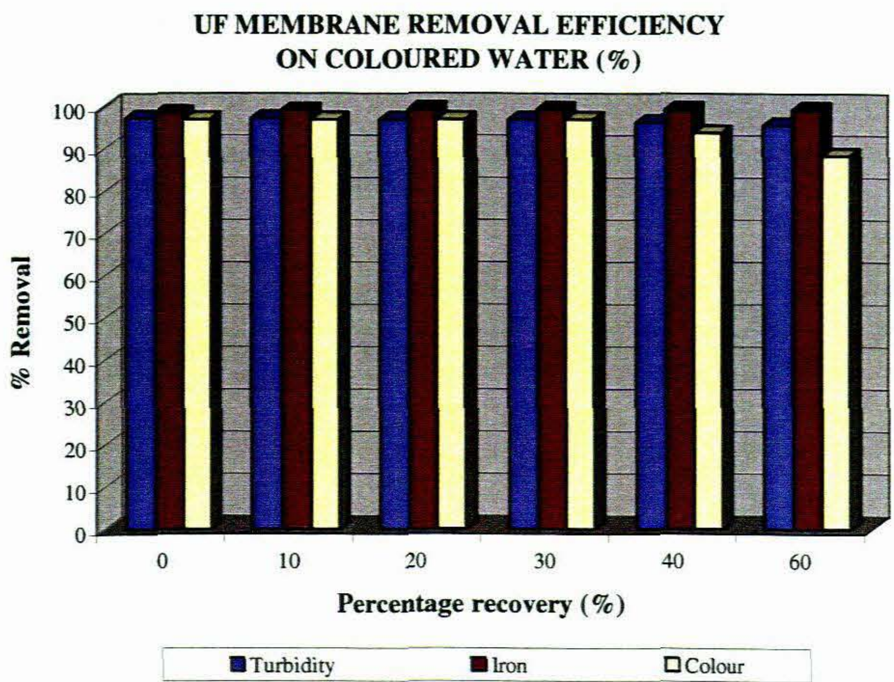


Figure 4.3-4 *Second set showing turbidity, iron and colour removal at different percentage recoveries.*

C. TERTIARY WASTEWATER EFFLUENT RESULTS

Table 4.3-3 A and B: *Results of the analysis on tertiary wastewater effluent for both first and second set.*

A - First Set

% Recovery	Operating Conditions	Initial Permeate Flux (l/m^2h)	Final Permeate Flux (l/m^2h)	% Removal
0%	P = 1bar, T = 21.9°C Δt = 4.77h, pH = 7.56	97.73	85.95	Turbidity = 78.5 FC = 99.9 *E.Ccli* = 99.9
10%	P = 1bar, T = 20.4°C Δt = 4.95h, pH = 8.01	92.17	75.08	Turbidity = 80.9 FC = 99.9 *E.Ccli* = 99.9
20%	P = 1bar, T = 20.6°C Δt = 5.00h, pH = 7.83	78.61	65.16	Turbidity = 80.0 FC = 99.9 *E.Ccli* = 99.9
30%	P = 1bar, T = 21.2°C Δt = 5.12h, pH = 7.82	68.34	58.75	Turbidity = 76.0 FC = 99.9 *E.Ccli* = 99.9
40%	P = 1bar, T = 20.1°C Δt = 5.18h, pH = 7.92	62.74	52.41	Turbidity = 74.6 FC = 99.9 *E.Ccli* = 99.9
60%	P = 1bar, T = 19.5°C Δt = 5.36h, pH =7.83	65.19	49.18	Turbidity = 79.9 FC = 99.9 *E.Ccli* = 99.9

P= Pressure, T = Temperature, Δt = time taken, nd = not determined

B - Second Set

% Recovery	Operating Conditions	Initial Permeate Flux (l/m^2h)	Final Permeate Flux (l/m^2h)	% Removal
0%	P = 1bar, T = 19.9°C Δt = 5.16h, pH = 8.06	59.40	53.83	Turbidity = 71.68
10%	P = 1bar, T = 20.8°C Δt = 5.30h, pH = 7.56	53.35	53.30	Turbidity = 71.07
20%	P = 1bar, T = 20.0°C Δt = 5.36h, pH = 7.72	53.09	51.50	Turbidity = 66.95
30%	P = 1bar, T = 20.2 °C Δt = 5.29h, pH = 7.87	53.64	51.06	Turbidity = 79.07
40%	P = 1bar, T = 20.9°C Δt = 5.43h, pH = 8.03	54.16	51.06	Turbidity = 76.67
60%	P = 1bar, T = 22.0 °C Δt = 6.04h, pH = 7.88	51.40	49.50	Turbidity = 76.38

P= Pressure, T = Temperature, Δt = time taken, nd = not determined

P= Pressure, T = Temperature, Δt = time taken, nd = not determined

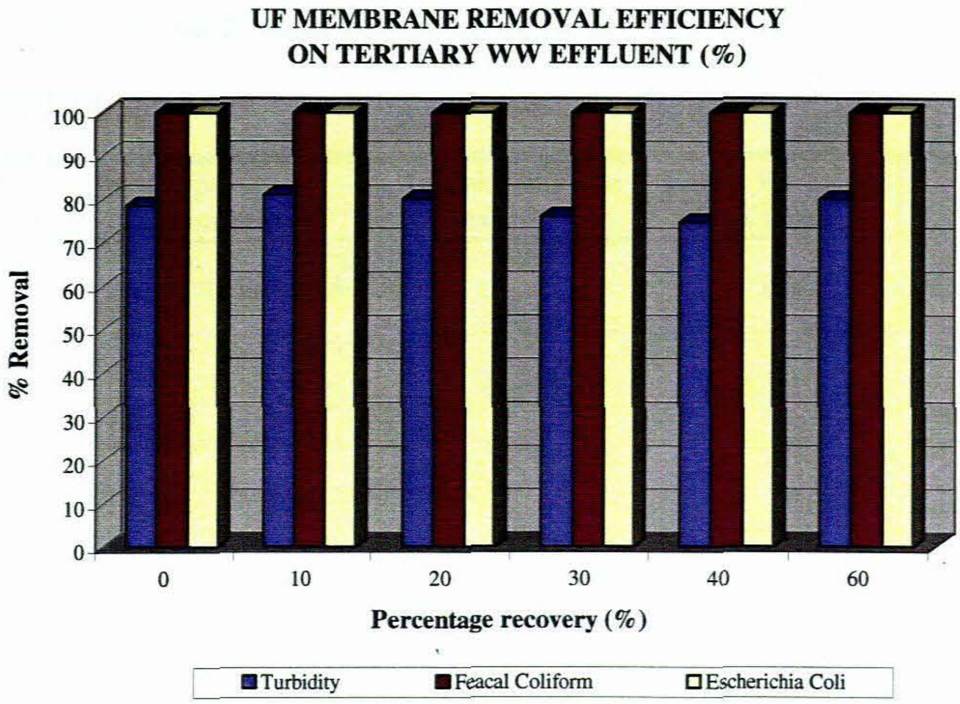


Figure 4.3-5 *First set showing turbidity, Feacal Coliform and Escherichia Coli removal at different percentage recoveries.*

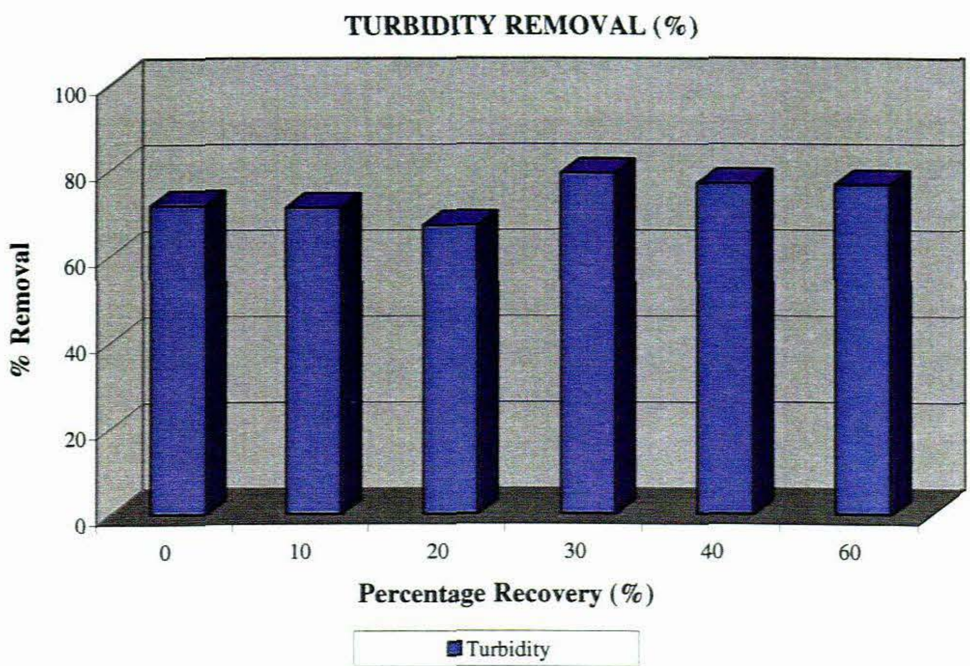


Figure 4.3-6 *Second set showing turbidity removal at different percentage recoveries*

D. EUTROPHIC WATER RESULTS

***Table 4.3-4 A and B:** Results of the analysis on Eutrophic water for both first and second set*

A - First Set

% Recovery	Operating Conditions	Initial Permeate Flux (l/m^2h)	Final Permeate Flux (l/m^2h)	% Removal
0%	P = 1bar, T = 21.9°C Δt = 4.77h, pH = 7.56	114.47	78.96	Turbidity = 99.2 Algae = 85.7
10%	P = 1bar, T = 20.4°C Δt = 4.95h, pH = 8.01	87.35	67.41	Turbidity = 99.09 Algae = nd
20%	P = 1bar, T = 20.6°C Δt = 5.00h, pH = 7.83	81.00	66.24	Turbidity = 99.0 Algae = 92.8
30%	P = 1bar, T = 21.2°C Δt = 5.12h, pH = 7.82	68.36	59.60	Turbidity = 99.0 Algae = nd
40%	P = 1bar, T = 20.1°C Δt = 5.18h, pH = 7.92	68.98	56.47	Turbidity = 98.9 Algae = 99.9
60%	P = 1bar, T = 19.5°C Δt = 5.36h, pH =7.83	56.75	49.64	Turbidity = 99.0 Algae = 99.9

P= Pressure, T = Temperature, Δt = time taken, nd = not determined

B - Second Set

% Recovery	Operating Conditions	Initial Permeate Flux (l/m^2h)	Final Permeate Flux (l/m^2h)	% Removal
0%	P = 1bar, T = 19.9°C Δt = 5.16h, pH = 8.06	67.50	56.69	Turbidity = 99.3
10%	P = 1bar, T = 20.8°C Δt = 5.30h, pH = 7.56	59.00	52.15	Turbidity = 99.3
20%	P = 1bar, T = 20.0°C Δt = 5.36h, pH = 7.72	57.00	49.13	Turbidity = 99.3
30%	P = 1bar, T = 20.2 °C Δt = 5.29h, pH = 7.87	50.91	46.20	Turbidity = 99.3
40%	P = 1bar, T = 20.9°C Δt = 5.43h, pH = 8.03	61.80	45.69	Turbidity = 99.4
60%	P = 1bar, T = 22.0 °C Δt = 6.04h, pH = 7.88	41.34	30.76	Turbidity = 99.0

P= Pressure, T = Temperature, Δt = time taken, nd = not determined

P= Pressure, T = Temperature, Δt = time taken, nd = not determined

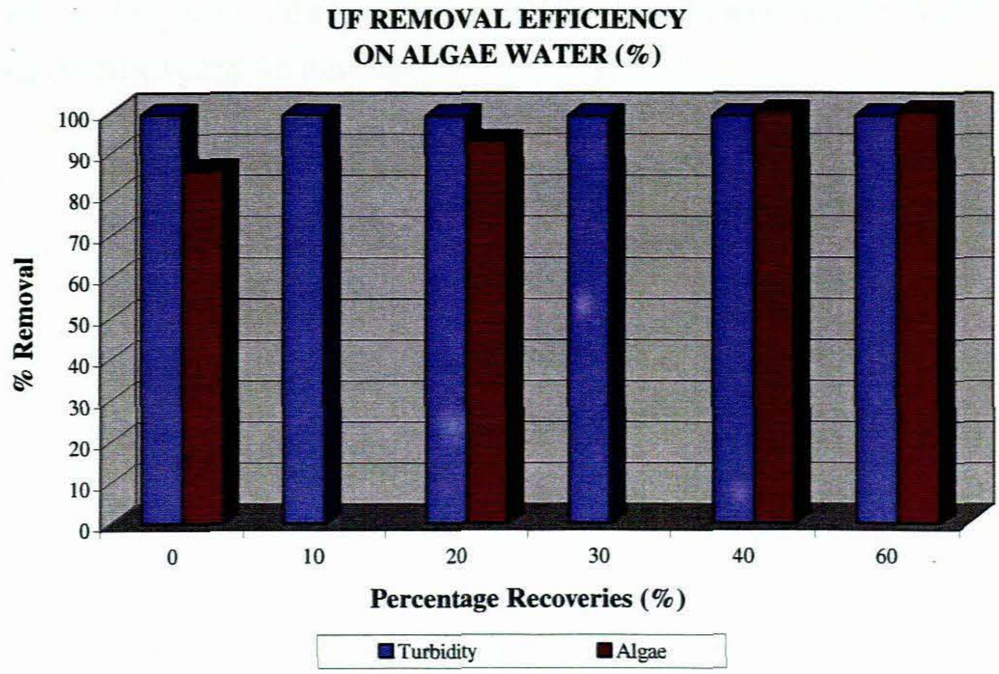


Figure 4.3-7 *First set showing turbidity and algae removal at different percentage recoveries.*

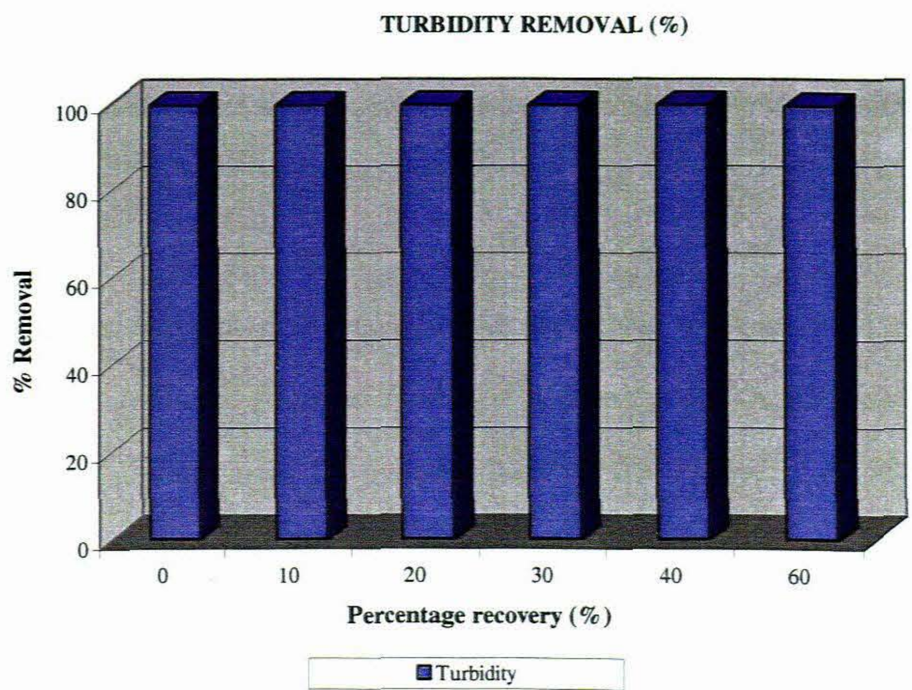


Figure 4.3-8 *Second set showing turbidity removal at different percentage recoveries*

Note:

- Removal efficiencies of the low-pressure capillary ultrafiltration membranes have been calculated using the formula:

$$E\% = \left(\frac{A-B}{A}\right) \tag{4.3.1}$$

where:

A = initial value of the parameter analyzed
B = final value of the parameter analyzed.

As it was expected, the removal of suspended and colloidal solids on the UF membranes were excellent, *i.e.* **99%** as turbidity, for the majority of the experiments. It was also observed that the suspended solids removal efficiency is constant, depending on the operating conditions. Certain differences observed in removal efficiencies of turbidity can be correlated with the change of the feed waters i.e. each raw water used in the study had different percentage removal on turbidity due to different raw water turbidities and characteristics.

Organic compounds attached to suspended solids, have also not been removed to a certain extent. Dissolved organic materials can easily pass through the UF membranes depending on the molecular mass. On the other hand the UF membranes do not retain dissolved inorganic compounds and these compounds can further be retained by the reverse osmosis system.

5 SOCIO-ECONOMIC STUDY ON ACCEPTANCE OF MEMBRANE TECHNOLOGIES BY RURAL COMMUNITIES.

5.1 Introduction

This chapter discusses the issues of social acceptance as a critical factor for water supply project success and long-term sustainability. The study is based on literature studies done in South Africa and on preparations that are being made for the socio-economic study of this project. The actual social study for this project on membrane technology has not been completed yet due to delayed commencement of the project. The social study is currently been conducted by the Rural Support Services (RSS).

The government has rightly placed themselves under much pressure to achieve better water and sanitation coverage. Thousands of people die every year from lack of access to safe water and adequate sanitation (Pergrum *et al,* 1998). Most of the water projects have failed to consistently deliver affordable water and sanitation to developing communities. The involvement of local communities is often lacking in the planners and developers reform programs, and in this case the local communities are seen mainly as recipients, rather than contributors to the development.

The local communities in particular do not usually have access to contract information. In small-scale water supply projects, poor communities do not even decide on technology options and locating of water points. Social mobilization and community participation have been proven from time to time as prerequisites for sustainable development.

5.2 General Acceptance of Rural Water Supply Projects by the Communities.

Monitoring and evaluation of rural water supply projects during the implementation and after completion of certain stages is not sufficient enough to ensure the long-term sustainability and acceptance of the project. The ways to ensure the future sustainability of water projects is to involve the local communities right from the start of the project, so that there can be an active community participation in planning, evaluating and implementation of the project. The project should further be monitored and evaluated after the final implementation stage (Joubert E, 1998)

From the studies done by James Rivett – Carnac – (Rivett, 2002), on the sustainability of community water supply systems, several factors are cited as necessary to ensure sustainable out comes for the development of water systems. These factors include:

- Ecologically sustainable supplies, which refers to water supply source ability to be recharged from the environment. It is very important that the introduction of the water supply scheme is user friendly to the environment.
- Social sustainability – the local communities should be empowered and have a sense of ownership on the water supply scheme. The community should be given what they want so that the technology can be easily accepted.
- Technologically sustainable – the system should be operated and maintained to high standards by the local communities and therefore the new technology employed must be appropriate to the needs and the skills of the communities. A higher level of technology requires higher levels of skills and management to operate and maintain.

- Financial sustainability – this mainly refers to the full cost recovery for the operational, maintenance and replacement costs of the system.

5.2.1 Social acceptance factors

Social acceptance factors are very critical in ensuring the success and long-term sustainability of the water projects. Most of the effective water treatment plants in South Africa are failing as a result of either socio-political or financial non-sustainability. The way to ensure future sustainability of water supply projects is to ensure that all the social acceptance factors for the rural communities are fully known and taken care of.

(a) Importance of social acceptance factors (Mackintosh G. *et al.*, 2000)

- The new technology to be fully accepted and owned by the community.
- Proper technology transfer.
- Community empowerment, which will have a direct influence on the sustainability of the water supply systems.
- Ownership, which goes hand in hand with responsibility and acceptance of the technology by the community, will have a direct influence on the operating and maintenance of the system and avoiding any sort of vandalism to the system.
- The community receives the full benefit of the new technology and the systems will be operated and maintained to high standards to ensure long-term sustainability of the scheme.

5.3 Monitoring, evaluation and mentorship to rural water projects.

The main purpose of monitoring, evaluating and mentoring water supply projects is a well-known factor in the rural water supply projects (Joubert E, 1998).

- **Monitoring** of the projects ensure that the progress is well kept
- **Evaluation** measures the outcomes of the project and whether the pre-determined objectives have been reached
- **Mentorship** period is very important in ensuring the sustainability of the project. It ensures that the project is operational in the long future.

With reference to water projects, current government policy, states that the local water committees are responsible for operation and maintenance of their own infrastructure. It should be noted that the implementation agent is only available during the construction period, and the role played by the committee is different during operation and maintenance. Therefore, it is necessary to have a Mentorship Programme to assist the committee after the completion of the project (Joubert E, 1998).

According to the Rural Support Services in the Eastern Cape (Joubert E, 1998), there are two main benefits of monitoring and evaluating the water projects after completion. With their experience in the Eastern Cape from previous and current water projects, they simply found out that there are some of the factors that work or not in ensuring the sustainability of future community based water supply projects. This will assist in the adjustments of the designs, community development facilitation processes or training programmers. The beneficiary community will benefit since there will be a lot of adjustments to suit the current water project.

After the completion of the project, the major task is the operation of the plant. Therefore, necessary training of the local community is very important. Regular visits after the mentorship Programme are also very important (once a month) even in spite of excellent training and community facilitation.

5.3.1 Social component

Since rural projects are people oriented and dependent on the full commitment of the whole community, this social factor is crucial for sustainability of the project. Most of the technical problems during the operation of the systems usual have a related social cause. The main problem to date is vandalism of the water system and it is very crucial that the communities are well trained and aware of the importance of the water supply systems. They should be aware of the negative consequences caused by vandalism of the water supply system and how badly they can be affected to their social life as far as water usage is concerned.

The social key issues relating to the sustainability of a rural water project includes (Joubert E, 1998):

- Full community commitment towards the project
- Correct usage of technology
- People awareness of the water communities and various responsibilities of the water committees.

- Impact of the project in general on people livelihoods and to their health especially women and children.
- Women involvement in maintenance and operation of the project.
- Children behavior around tapstands and other infrastructure.
- Political stability in the community.

All this information can be possibly obtained by observation, structured or formal interviews and questionnaires with the community members. Despite getting the information from the community members as a whole, it is very important to conduct more interviews with the women, since they are the main users of the water in the rural areas. Always important to find the extent to which the women are involved in the water committees and decision taking regarding the usage of the water.

5.3.2 Training of rural communities (Joubert E, 1998)

Training is recognised as a very important component of a successful water supply project. Through training, community members are equipped with certain skills that are crucial for the sustainability of the project. The community members would be able to achieve various skills so that they can be able to manage, operate and maintain the water supply systems. The community is trained on how to collect funds for day-to-day operations of the project as well as holding community meetings to spread awareness of the benefits of clean water for their health.

Training of the community and their water committees is conducted before and during the early stages of the project implementation so that enough time can be credited. The quality of the water depends highly on the application and maintenance of the technology and it is very important that the community members that were trained for operation and maintenance apply their skills appropriately. The women must always take part in the training sessions, because they are so closely involved in water usages, as well as the small possibility of leaving an area to go and live elsewhere after being trained.

Many of the rural communities use groundwater as the main source of water supply. Most of the borehole waters in rural areas in South Africa are not fit for human consumption because of the high levels of nitrate-nitrogen and salinity (Schoeman and Steyn, 2000).

Schoeman *et al,* (2000) have done a lot of studies in South Africa on the application on membrane technologies especially in the rural communities. He did a study on the demonstration of reverse osmosis technology for nitrate removal from borehole water in the rural areas of South Africa. The main objectives of this study were:

- Proper RO technology transfer through process demonstration to people living in the rural areas.
- Capacity building regarding the operation and maintenance of the RO application in rural areas.
- Produce a maintenance and operation manual for the use of RO in rural areas as well as training of local operators.

From the results of this study it was demonstrated that the RO processes if applied correctly could be effectively applied for treatment of borehole water in the rural areas to produce excellent quality water for drinking purposes. It mentioned that, there are various water treatment methods that can be used for the removal of nitrate for the borehole waters, but the key challenge between the use of these various technologies depends on several factors which includes; plant capacity, water quality, process automation and access to manpower of suitable skills (Schoeman, 2002).

(a) Capacity building and training of operators

When considering the South African rural scenarios to water supply projects, capacity building and operators training are the prerequisites for the long-term sustainability of the water projects. Most of the water projects are non-sustainable because the systems cannot be properly operated or there is lack of commitment from the local community.

From this project done by Schoeman, capacity was built to the technical people of the Department of Water and Forestry, which will help the rural community in continually receiving quality water. DWAF technical team will help in solving electrical and mechanical problems during the operation of the plant.

The plant also demonstrated that modern technology could be successfully applied in the rural areas if the technology is social accepted, if operators are reliable, committed, well trained and under constant supervision. The two local operators were also taught how to operate and maintain the plant. It is however very important that these two local operators form part of the local water committee and should also share the skills to other committee members so that, incase one die or decides to use the skills some where in town, there would be someone to take over.

5.4 Evaluation Questionnaire checklist for water schemes

Most of the information on socio-economic studies for local communities is conducted by having formal interviews or by distributing questionnaires to the community involved. The formulation of the questionnaires requires thought, planning and testing. The researcher must formulate clear questions and arrange them accordingly. It should be in such a way that taking data from it, is very easy, and, as accurate as possible.

The questionnaires should comprise of a covering letter, instructions to respondents, questions, response categories and preceding, demographic data and inducements to respond.

The covering letter has to comprise the identification of the sponsoring institution and the researcher. A research project under the name of a highly respected person or agency is worthwhile and that data has been entered in a database. In general terms, the letter must explain why the research is being done, how the respondents were selected for the study, and why their contribution is important. The respondent must always be guaranteed anonymity and confidentiality of the responses given.

The questions are the pillar of the questionnaires in which the researcher depends upon in collecting information of the research problem. Therefore, it is very necessary that questions be examined carefully and tested for appropriateness, content and wording. Here is a typical socio-economic study questionnaire for rural water schemes. This questionnaire is based on the socio-study done by the department of health sciences at Peninsula Technikon.

1. DEMOGRAPHY

1.1 What is your Name?..

1.2 Gender:

M		F	

1.3 How old are you?.......................................

1.4 Who is the head of the household?...

1.5 How many people live in this household?...

Ages	Male	Female	Level of Education	Total
Less than 6yrs				
6 – 13yrs				
14 – 18yrs				
19 – 30yrs				
31 – 45yrs				
46 – 60yrs				
Older than 60				

Do you expect the number of people in this household to increase?

YES		NO	

1.7 If YES, by how many?................................

2. ECONOMIC ANALYSIS

2.1 How many people in this household are currently unemployed?..........................

2.2 How many people in this household are currently employed?..........................

2.3 Is the employment:

Fulltime		Part-time		Casual	

2.4 What type of work do they do?...

....

2.5 Apart from the above, what types of work can you or any person in this household

do?...

....

3 INCOME AND EXPENDITURE

3.1 Does the household have an income?

Yes		No	

3.2 If No to 3.1, how does the household survive economically?.............................

....

3.3 If Yes to 3.1, what are the main source/s or the source of income?

....

3.4 In which bracket would you place the entire monthly income of the household?

(a) Less than R 800

(b) Between R 801 and R 1 500

(c) Between R 1 501 and R 2 000

(d) Between R 2 001 and R 4 000

(e) Between R 4 001 and R 6 000

(f) Between R 6 001 and R 8 000

(g) More than R 8000

3.5 Please indicate your average household spending, per month, on each of the following

(a) Food excluding alcoholic beverages R.............

(b) Energy (electricity, candles, paraffin, etc.) R.............

(c) Clothes R.............

(d) Alcohol R.............

(e) Water R.............

(f) Education R.............

(g) Entertainment R.............

(h) Luxury items R.............

(i) Medication R............

4 CURRENT WATER SUPPLY AND USAGE PRACTICES

4.1 Which are your main sources of drinking water? ....

4.2 Are you satisfied with the existing water supply?

....

....

4.3 Are you aware that the water can be cleaned?

Yes		No	

4.4 Is the water fetched?

Yes		No	

4.5. If yes to 4.4, who decides when to fetch the water? ....

4.6. If yes to 4.4 who decides who must fetch the water? ....

4.7 Who decides how much water to be fetched? ....

4.8 What are the Likes and Dislikes of fetching water? ....

....

Likes	Dislikes
....	....
....	....
....	....

4.9 How do you feel about fetched vs. piped water?..

....

4.10 Who in the house decides how water is used?...

....

4.11 What is the water mainly used for?

Cooking		Drinking		Laundry	
Bathing		Dishwashing		Garden	

4.12 What influences the amount of water used per day?......................................

....

4.13 Amount of water provided by the existing source (l/c/d)................................

4.14 Minimum water needs (l/c/d)...

4.15 Are you ever short of water? **Yes, when?**.................. | **No** | |

4.16 What do you do if and when running short of water?......................................

....

....

5. DISTANCE TO THE POINT OF WATER SOURCE

5.1 Average distance from household.

Less than 50m		50 – 100m		100 – 150m		150 – 200m		More than 200m	

5.2 Maximum distance from the household.

Less than 50m		50 – 100m		100 – 150m		150 – 200m		More than 200m	

5.3 Conditions of access paths to water collection.

Path steep, uneven, dangerous		Path steep, uneven, safe		Path even but safe even when wet		Good path and accessible		Completely good paths	

5.4 Is the community willing to maintain the paths to water collection? | Yes | | No | |

6 WILLINGNESS TO PAY

6.1 Do you pay for water? | Yes | | No | |

6.2 If yes to 6.1,why do you pay for water and how long have you been paying?

....

6.3 If yes to 6.1, what are the principles of payments?

....

....

6.4 Do you know about the 6 kl/d free water per household per month?

....

....

6.5 If No to 6.1, why not and how long have you not been

paying?...........................

....

6.6 What do we need to do to encourage people to pay for water?............................

....

7. TECHNOLOGY IMPLEMENTATION

7.1 Do you think the existing water source needs to be replaced or upgraded?

Yes		No	

7.2 What do you think are the important issues about what the community will feel about

treatment system?

....

....

7.3 Are you aware of any water project/machine in this area?

Yes		No	

7.4 If yes to 7.3, how did you come to know about it?

....

....

7.5 Who participated in the implementation of the water project/machine?

....

7.6 How long did it take to implement/install?..

7.7 Did the water project create any employment opportunities?

YES		NO	

7.8 Do you understand any water project/machine?

YES		NO	

7.9 If yes, what do you understand?

....

....

7.10 If No, would you like to understand something about it?

YES		NO	

7.11 How do you think this community could participate in the implementation of water Projects/machines?

....

....

7.12 How reliable is the Project/machine in producing water?

Highly Reliable		Moderately Reliable		Moderately Unreliable		Highly Unreliable	

7.13 Are you satisfied with the water?

YES		NO	

7.14 Why do you say so?

....

....

8. COMMUNITY COHESIVENESS

8.1 Which recreational activities/facilities are in your area?

....

....

8.2 Which organisations are in your area?

....

....

8.3 How active are they?

Highly active		Moderately active		Inactive	

8.4 If active. How do you know they are active?

....

....

8.5 How are problems in the community handled?

....

....

Is there anything else you want to tell us?

....

5.5 Community Involvement and Transparency in Rural Water Supply

Since 1994, a great deal of resource has gone into implementing community water supply in the previously under-developed rural and peri-urban areas of South Africa (Cain J, 2000). The major concern is the serious problem of high rate of non-sustainability of community water supply projects. One of the main reasons to this failure is lack of community participation in the water projects. Without community involvement in decision making for the type of the service that will be delivered and the long and medium-term maintenance of the installations, it has been shown that the services will only last in the short-term. This may be due to the plant being badly installed in the first place, and the communities not knowing whom to approach to take responsibility for shoddy workmanship, or if spare parts or expertise in fixing the problem is needed, the problem is that the necessary social preparation for such tasks has not been implemented.

5.5.1 Community participation and mobilization

Community participation and mobilization is defined as the involvement of people in the community projects that are meant to improve their well being within and around their respective areas (Daniel X, 2002).

In the process of involvement the community defines their own problems, decides which are higher priority, and organizes itself to address the priority problems. The community involvement is considered successful if their needs and decisions are fully considered by the developers. The community should also be included in the decision-making relating to the project.

All the people in the community are expected to participate irrespective of their social status or political affiliation. The community as a whole should be fully motivated and encouraged so that all the people (skilled, unskilled, poor or rich) should feel that they have to participate. In most projects only economically well off, educated people and people with political background participates. Efforts should be done to involve groups in the community, and should be done through consultations with opinion leaders, women's groups, youth and religious groups (Daniel X, 2002)

The team members (community facilitators) should include men and women, some with technical and others with social science backgrounds and should be able to provide information about community attitudes, perceptions, preferences and doubts.

5.5.2 Procedure for community participation

Community participation may take all different forms depending on the socio-economic situations and political backgrounds of people. The main important thing is to highlight and represents the community needs during the participation process (Daniel X, 2002).

(a) The need for the technology implementation

This is the preliminary stage where the developer and planners identity the needs for technology implementation. An ideal community that needs water supply and sanitation in their area of operation is identified. The eligible communities are selected as the potential participants to the proposed water supply project.

(b) Participatory planning.

The identified community is mobilized to identify community facilitators and to form a project committee. Then the next step is to establish a line of contact with the community and to establish positive relation with the relevant community leaders. At this stage the community facilitators should receive special training from the developer with special skills in communication and social work. The community then defines the number and the form of the meetings. The purpose of these meetings is to select priorities for the implementations of the water supply works and delivery of services.

(c) Implementation of the project

Prior to implementation the key role of all parties involved in the project should be clearly defined and well understood. The community must have an input in the scheduling of the project so that their social needs can also be taken care of. The planner's role is to design and supervise the construction.

5.6 Discussions

When talking about rural water supply projects four key tasks are:

- Delivery of safe drinking water
- Ensuring that the service is acceptable, remains affordable and presents no barrier to access.
- The service is sustainable and reliable
- Channels of communication are created

Within these practical aspects, the community involvement in decision-making is the more notion of a sense of ownership. The simple theory is that if a community have a sense of ownership over its services, these are more likely to be well looked after and used properly, thus ensuring the long-term sustainability of the project. This sense of ownership and acceptance cannot be imposed, but must come from a genuine involvement of the end-users in the processing of installing the service. The developers and planners should be more community oriented and has as understanding of community dynamics and how to ensure that all the community including the poorest, are able to access the services.

Community and acceptance factors are central and the planners must encourage female participation. Social mobilization and community participation equally takes some time and money. Prior to water project implementation, acceptance by the local community should be taken care of by visiting appropriate sites.

6 ECONOMIC COMPARISON OF MEMBRANE TREATMENT TECHNOLOGIES AND CONVENTIONAL WATER TREATMEMT SYSTEMS.

6.1 General

This chapter outlines the economic comparisons of membrane water treatment technologies and convectional water treatment systems. The high quality of product water from membrane filtration processes makes them very attractive in the field of potable and wastewater treatment. In anticipation of future demands for high standards and reduced environmental impact, membrane processes are increasingly being considered as an alternative to conventional water and wastewater treatment methods. Unfortunately, the economics of these new technologies and the parameters that control costs are not well understood by researchers, process engineers and others who wish to assess the feasibility of these processes in comparison with alternative technologies or to improve the cost effectiveness of the processes (Pickering *et al*, 1993).

The operation of membrane technologies for potable and wastewater treatment is currently limited by the high capital and operating cost with which they are associated. In extensive pilot plant studies carried out by Owen G. *et al* (1995), it was found that the most significant factors influencing the overall cost in membrane process were, membrane cost, membrane replacement frequency and power consumption. The cost of membrane filtration is largely a function of the permeate flux. Therefore, estimates of the cost of membrane technologies require accurate estimates of the permeate rate. Furthermore, membrane fouling has a significant effect on the permeate flux and therefore membrane cost (Mark R. *et al*, 1994).

6.2 Cost Determination of Membrane Plants

6.2.1 Capital Cost

The capital costs can be divided into non-membrane costs and initial membrane unit costs (Owen G. *et al*, 1995).

(a) Non-Membrane Costs

Non-membrane costs include all equipment and facilities necessary to support the use of membranes, such as, pumps, monitoring equipment, automation and associated civil engineering costs. Capital costs for non-membrane plant are based on quotes from membrane plant suppliers. Costs of non-membrane plant items have been scaled according to the six-tenths power rule (Owen G. *et al*, 1995).

$$C_a = C_b \left(\frac{Q_a}{Q_b} \right)^{0.6} \tag{6.2.1}$$

Where, C_a and C_b are non-membrane capital costs of plants to treat flows of Q_a and Q_b, respectively.

(b) Membrane Costs

The membrane cost is dependent on the specific membrane cost, c_{memb}, permeate flux, J and the plant capacity, Q_{des}. For a constant permeate flux, J, the total membrane area required to produce a given flow of filtered water can be calculated by using the equation below (Weisner, 1995).

$$A_{memb} = \frac{(Q_{des} * t_{tot}) + (Q_{bw} * t_{bw})}{J\, t_o} \tag{6.2.2}$$

where:

- A_{memb} is the surface area of membrane required to provide the design capacity
- Q_{bw} is the flow rate during back flushing
- t_o is the operating time between flux enhancement cycles
- t_{tot} is total cycle time ($t_{tot} = t_{bw} + t_{cf} + t_o$)

Equation 6.2.1 takes into consideration the volume of permeate wasted in hydraulic cleaning. The capital cost can be expressed as an annualized sum. A series of equal annual payments, C_A, invested at a fractional interest rate, *I*, at the end of each year over *n* years may be used to build up a sum of money with present worth (C_{men} + C). Annualized capital cost C_A is given by:

$$C_A(Rand/year) = \frac{(C_{mem} + C)^i}{\left[1 - (1+i)^{-n}\right]}$$

(6.2.3)

where:

C_{mem} and C are capital costs of membrane and non-membrane components. An empirical expression for capital costs as a function of the number of installed membrane modules or pressure vessels, *n*, exclusive of the initial cost of the membrane modules was developed by Mark *et al*, 1994. In his estimates he included the cost of buildings, chemical feed systems, control and instrumentation, site works, storage, process piping, yard piping, site electricity, pretreatment, cleaning and booster pump. The total capital costs are then calculated as: (Mark R. *et al*, 1994).

$$CC_{tot} = \frac{\left[\left(150037\left(n_{\mathrm{mod}}\right)^{0.74}\right) + C_{\mathrm{mod}} n_{\mathrm{mod}}\right]\frac{A}{P}}{Q_{design}}$$

(6.2.4)

where:

CC_{tot} – annualized capital cost

C_{mod} – cost per module or pressure vessel of the membrane

A/P – the amortisation factor

(c) Depreciation

Allowance has been made for the cost of replacement of non-membrane plants at the end of their technical life. This cost is charged as depreciation on the equipment. This was estimated as the total end cost of non-membrane units expressed as annual cost, and is given as:

$$Depreciation = \frac{Total\ non\ memb.\cos t - memb.plant\ \cos t}{Technical\ life\ of\ the\ plant}$$

(6.2.5)

The sum of membrane and non-membrane capital costs is amortised over the design life of the plant to yield an annual cost by equation 6.2.6 below

$$C_{annual} = \left(C_{memb} + C_{non-memb}\right) * A$$

(6.2.6)

Where A is the amortization factor given by equation 6.2.7 below

$$A = \frac{(1+i)^n * i}{(1+i)^n - 1}$$

(6.2.7)

Where, I is interest rate and n is the plant life.

6.2.2 Operating Cost

Operating costs include membrane replacement cost, energy cost, labour cost, maintenance cost and the cost of cleaning chemicals. Membrane replacement costs are the total costs of all the replacement membranes distributed over the entire life of the plant as an annual costs.

(a) Membrane Replacement

Membrane replacement costs are the total costs of all the replacement membranes distributed over the entire life of the plant as an annual cost. Membrane lifetimes estimated by manufacturers range from 3-5 years for polymeric membranes and up to 10 years for ceramic membranes. The actual lifetime achieved by a membrane can have substantial effect on the operating cost.

(b) Energy

Energy costs are calculated from the applied feed pressure, the energy required to maintain a specific permeate flux and the energy required for flux enhancement or membrane cleaning. Feed pump power estimated from the equation below (Owen G. *et al,* 1995).

$$Power(kW/d) = Q_l * P * \frac{24}{100} \tag{6.2.8}$$

Where:

P = feed pressure (N/m^2)
Q = average permeate flow rate (m^3/s)

The cost of electricity depends on the locality and the supplier.

(c) Labour Cost

Initial estimates of labour requirements can be obtained from membrane system suppliers. The number of man-hours per week required to operate the plant can be assumed to be proportional to the size of the plant since a significant part of operator time is likely to be associated with membrane cleaning and maintenance (Owen G. *et al*, 1995). Labour costs are found to be low, compared to conventional treatment plants since there is much potential for automation compared with conventional process.

(d) Maintenance

The maintenance cost of a plant is related to the capital cost of mechanical and electrical items. It is assumed that an annual sum of 1,5% of initial non-membrane capital cost can be used to obtain this maintenance cost (Owen G. *et al*, 1995)

(e) Chemicals

In order to determine optimum cleaning frequencies, prolonged trials over several months have to be carried out. Information gathered by (Owen G. *et al*, 1995) from existing installations and suppliers give chemical costs as below 1 cent/m^3 of permeates produced. Concentrate disposal costs are calculated as the cost of energy and chemicals invested in the wasted concentrate.

6.3 Effect of Permeate Flux on Cost

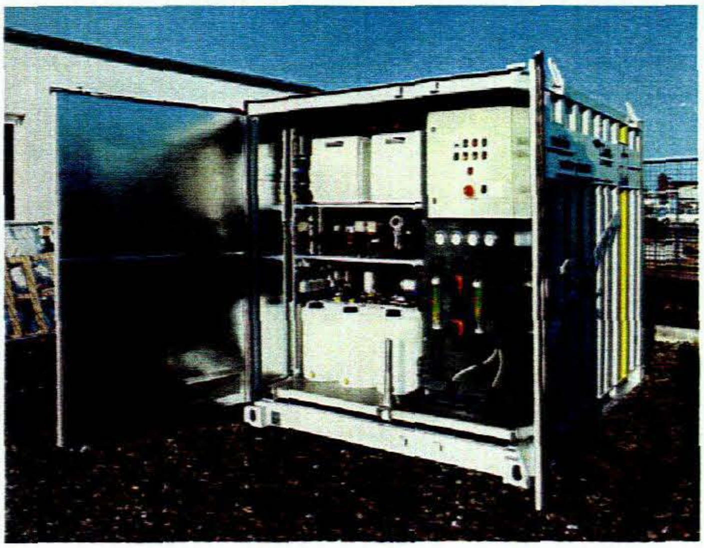
The cost of constructing and operating UF system is extremely sensitive to the permeate flux (Mark R. *et al.*, 1994). Higher permeate fluxes are achieved at higher pressure at the cost of higher energy consumption. However, less membrane area is required to produce the same design flow. Cost estimates calculated from the corresponding permeate flux data observed in pilot studies by (Mark *R. et al*, 1994) indicated that the higher energy costs associated with increased pressures should be more than offset by the savings in capital costs and membrane replacement that result from a higher permeate rate. Reductions in cost achieved by increasing pressure are constrained by the mechanical strength of the membrane and potentially by an increase in mass transport of materials to the membrane surface at a higher permeate flux.

6.4 Comparative Assessment of the Performance of Membrane Technology and Conventional Treatment System

Both the comparative assessment of the performance and the cost comparison of the two technologies are based on a study done by [Mackintosh G. *et al.,* 2000] of Cape Water Programme, CSIR, Stellenbosch.

According to Mackintosh and De Souza, 2000, the principal advantages of a membrane-based process for rural water treatment are production of good quality water, ability to neutralize pathogens and limitations of operators input during filtration processes. The membrane-based plant considered in this case study was a movable package water treatment plant designed to condition surface water. The unit treats approximately 2000 L/hr, depending on the raw water characteristics. The membrane-based water treatment plant is shown in Figure 6.4.1.

Figure 6.4-1: *Membrane based water treatment plant*

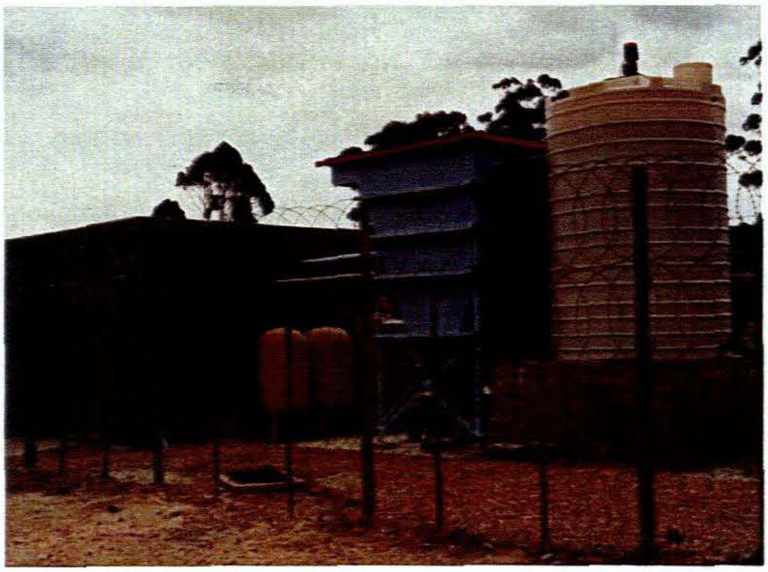


The results obtained during the trial period indicated that the plant performed well, consistently providing a high quality drinking water.

The performance of the membrane-based plant was compared to a nearby conventional plant, which treats essentially the same source. This existing water treatment system treats approximately 10 000 L/hr and employs conventional water treatment principles of coagulation, flocculation, sedimentation, sand filtration and disinfection. The conventional water treatment plant is shown in Figure 6.4.2.

The Conventional plant is highly vulnerable thereby passing on contaminated treated water to the end-user when not operating optimally. Frequent episodes of treated water quality failing *SABS 241-2001* Maximum Allowable standards (SABS, 2001) (i.e. not fit for human consumption) occurred. Both the plant operator and the community confirmed that the plant did not continuously operate at an optimal level.

Figure 6.4-2 : Conventional water treatment plant



6.5 Cost Comparison of Membrane Technology and Conventional Treatment System

Membrane units, in terms of their operational costs, have been found to be highly competitive and effective in the treatment and the provision of safe drinking water for general public consumption (Pervov *et al*, 1996). Compared to the conventional system (which includes coagulation, sedimentation and rapid sand filtration), UF is a low maintenance, simple to operate alternative for low- cost water treatment (Jacobs *et al*, 1997). Typical procedures would include pre-filtration to remove particulate solids, followed by a single step clarification and sterilisation by UF and finally, chlorine treatment against contamination.

The cost comparison was based on a water treatment plant capacity of ***10 000 L/hr*** operating for ***20 hours/day*** (i.e. providing a community of 2000 people with 100 L/person/day). Total installed capital cost estimates were obtained from manufacturers of the different water treatment technologies. Operating costs included those related to chemicals, labour, electricity and maintenance and were based on required on-site inputs and information supplied by manufacturers.

The cost comparison shown in Table 6.5.1 shows that the total installed capital cost of the membrane based plant is significantly more expensive (~ 1.9 times) than that of the conventional water treatment plant. Furthermore, the cost comparison showed that the membrane based plant shows significant operating cost savings over the conventional plant. This can mostly be attributed to lower labour and chemical requirements.

Table 6.5-1 *Cost comparison input variables (De Souza and Mackintosh, 2000)*

	Membrane		**Conventional**	
PLANT CAPACITY	10 000 L/hr		10 000 L/hr	
CAPITAL COST	R600 000		R320 000	
OPERATING COSTS	R1.12/kL		R1.54/kL	
Chemicals	***Chemical Dose***	***Cost (R/kL)***	***Chemical Dose***	***Cost (R/kL)***
PAC @ R8.96/kg	35 mg/L	0.315	60 mg/L	0.54
Polyelectrolyte @ R8.96/kg	0.1 mg/L	0.001	-	-
HTH @ R14.00/kg	0.5 mg/L	0.007	2 mg/L	0.028
Soda Ash @ 2.40/kg	50 mg/L	0.120	50 mg/L	0.12
Citric acid (membrane cleaning) @ R30.00/kg	0.1 mg/L	0.003	-	-
HTH (membrane cleaning) @ R14.00/kg	0.1 mg/L	0.001	-	-
Chlorine gas @ R14.00/kg	-	-	2 mg/L	0.028
Chemical Wastage @ 5%	-	0.022	-	0.0358
Electricity @ R0.2/kWh	*Power consumption*	*Cost (R/kL)*	*Power consumption*	*Cost (R/kL)*
Plant power consumption	8.5 kW	0.150	10 kW	0.20
Labour @ R18.75/hr	*Time*	*Cost (R/kL)*	*Time*	*Cost (R/kL)*
Plant operation, maintenance, etc	1 hr a day	0.094	4 hrs a day	0.376
Maintenance @ 5% of capital cost	*Cost (R/kL)*	0.411	*Cost (R/kL)*	0.216

Meaningful comparison of the capital and running cost figures given above is difficult. A more useful manner of comparing the two processes is to use a Net Present Value (NPV) based approach. The NPV approach relates the cash flow projection of a project over a specific time period (in this case 10 years). The NPV assessment captures both the capital and operating costs for the two alternative technologies and relates these as one financial sum in terms of today's money. An important aspect is the discount rate used. For this case study, the total discount rate included inflation: ((@7% in South Africa), required real return ((@0%, as no return on investment required by government funders) and risk ((@ 10%, as membrane based processes are less familiar for rural use in South Africa.

The NPV based cost comparison shown in Table 6.5.2 shows that the use of a membrane based plant (with higher capital costs and higher risk but lower running costs), yields a nominally negative NPV of 33 500 (and an Internal Rate or Return of 14%). This result shows that there is very little difference in financial performance between the two technologies when compared over ten years. It is important to note that this observation is contrary to conventional thinking in South Africa, where the initial significantly higher capital costs of membrane-based plants are considered to make the use thereof a non-option.

Table 6.5-2 NPV Summary table – Plant capacity 10 kL/hr [De Souza and Mackintosh]

	Conventional	**Membrane**
Capital cost (R)	320 000	600 000
Operating cost (R/kL)	1.54	1.12
Discount rate		
- Average inflation	7%	7%
- Required real return	0%	0%
- Estimated risk	0%	10%
Internal Rate of Return (IRR)		14%
Net Present Value (NPV)		- R33 500

6.5.1 Discussions

The application of membrane processes in large-scale installation for drinking water treatment is still restricted by economical factors such as membrane replacement costs and energy costs. However, from the studies done by Mackintosh G. *et al* (2000) it is very evident that the membrane processes compared favourably or even better than the conventional treatment for small facilities with a capacity of 10 000 l/hr. The study showed that the capital cost of membrane plant is more expensive than that of conventional treatment system but on the other hand the membrane based plant showed significant operating cost saving over conventional treatment plant due to labour and chemical requirements.

Considering the South African scenarios for the rural water supply schemes, anticipation of future demands for high water standards and reduced environmental impact, the membrane-based approach would be an ideal water treatment technology to be implemented to developing communities.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

- The overall objective of the study was to investigate factors for the successful technology transfer of a one-step membrane water treatment system for the production of drinking water to developing communities. A laboratory bench scale ultrafiltration unit was used for evaluation of various waters. From the results, it is evident that ultrafiltration membranes operated at low pressures between 100 and 150 kPa can produce high quality drinking water.
- The successful removal of algal suspensions from the raw water has been demonstrated by the absence of algae in the permeate, irrespective of the algal type and concentrations of the feed water.
- Membrane based treatment processes can produce superior quality drinking water consistently if operated and maintained correctly, and it is not possible for the system to pass substandard water. It should however be noted that the correct choice and application of membrane treatment technology should be done. The major limitation to membrane filtration is the fouling of the membrane, which results in flux decline. In order to enhance the flux, the foulants should be identified and a specific cleaning strategy determined.
- In South Africa, both urban and rural communities are required to pay for the operational costs of water treatment whilst funding organizations usually cover the capital costs. It is concluded from the cost comparisons that with the correct choice and application of membrane technology, it could be a feasible solution to the rural communities, based on their financial sustainability.
- Ultrafiltration is a feasible treatment for tertiary wastewater effluent, realizing almost complete removal of suspended solids and colloids (≈ 99% as turbidity), of the organic

compounds attached to suspended solids and of bacteria. In order to recycle the tertiary effluent to augment potable water supply, ultrafiltration is considered to be a good pre-treatment for the reverse osmosis process, which has to remove the dissolved inorganic compounds in order to achieve the requirements for recycling.

- Effective community participation in the water supply projects plays a crucial role in the sustainability of these projects. It ensures a trouble-free acceptance of the new technologies. The main problem is vandalism of the water supply systems and it is therefore very crucial that the water committees and the communities (including women and children) are well trained and made aware of the importance of the water supply systems.
- At the moment there is little work or research done in membrane technology in the faculty of engineering at Peninsula Technikon. Civil Engineering students are not familiar with the use of membrane-based processes. During the course of the study a sound and interactive engineering platform was established between Chemical Engineering students at Peninsula Technikon, Stellenbosch University, Institute of Polymer Science personnel and City of Cape Town Scientific Services department laboratory staff. This will in turn provide the necessary skills base to further the technology to its natural conclusion.

7.2 Recommendations

- Capillary UF membranes have shown considerable potential for the supply of potable water to small communities. Most of the effective water treatment plants are non-functional due to financial and socio-political non-sustainability and to some extent wrong choices and applications of treatment technologies. Therefore, a specific community should be identified before hand where the technology would be refined further and evaluated on site in order to increase the general applicability and acceptability thereof, ensuring sustainability of the technology in place.
- Permeate flux sometimes drops dramatically throughout the filtration process, and therefore membrane flux should be improved by a variety of flux enhancement strategies. It is, however, very important that the foulants are correctly identified so that the specific cleaning strategy is determined. These should be fully investigated and implemented so as to be most practical and cost-effective.
- It should be noted that people living in the rural areas, where these new technologies would be implemented, take it as a habit or a hobby to wake-up in the early hours of the morning and walk long distances in order to fetch the water. If the new technologies were put into place, the involved communities would now get potable water nearby, without traveling long distances and without any long queues. This in turn changes the life style and day-to-day routines of the communities by having a free-floating time. Therefore a recommendation for further studies should be done to find out what kind of activities the community would be engaging in during the free-floating time and what can be done to replace the floating time?

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