EVALUATION OF NANOFILTRATION FOR THE TREATMENT OF RURAL GROUNDWATER FOR POTABLE WATER USE

Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

Clean drinking water and sanitation, effective wastewater or industrial effluent treatment and management, and safe and efficient health care facilities and awareness are vital services to all communities around the world and in particular, South Africa. The South African government has embarked on the provision of adequate and safe water to all. This has lead to a more intensive water research than ever before to ensure increasing and continued supply of drinkable and other survival related water. As a result, a new Water Services Act evolved to ensure access to water by the many families that never had one before. Coupled to this Act, is the National Water Act 36 of 1998, which guarantees save water. The Act guards against pollution and intends to conserve and protect water.

Characterization of rural water

South African rural areas are characterized by underground water abstraction, and largely depend on this for a living. Apart from this, some areas get their water from streams, rivers, and springs. Although groundwater is normally "clean", some areas experience high levels, than is acceptable, of nitrate, fluoride and in some instances, high sulfate in their water. Salinity is also of major concern but will however not be dealt with in this study. These pollutants have their levels higher than the SABS specifications for human consumption, livestock watering and irrigation. High fluoride concentrations are experienced in borehole waters in the Mankwe (about 14ppm), Moretele (4 to 5ppm) and Taung districts (approximately 5ppm). The waters are not fit for human consumption. Nitrate concentrations are as high as 173ppm in Moretele and 130ppm in Kudumane districts [1].

High levels of nitrate (>10ppm as N) is known to easily convert the nitrite in the stomach which in turn get adsorbed in the blood stream. Nitrite hinders or defects oxygen adsorption and as a result causes oxygen depletion in the blood. Fluoride (>1ppm) causes

skeletal and dental fluorosis, and teeth mottling. It has crippling effects. Areas with high levels are usually characterized with consumers having yellow to brown-coloured or stained teeth. Sulfate in general is not known to have adverse health effects except at concentrations above 200ppm when diarrhea starts to develop. It can be a problem in areas that depend on water downstream the gold and coal mines that normally have acid mine drainage problems. This water from mines can also contaminate underground water via seepage into aquifers, subsequent health effects on consumers using groundwater. It is necessary to keep these pollutants to permissible levels and for that reason, an economic and easy to operate technology is sought to remove or keep nitrate, fluoride and sulfate to acceptable levels.

Membrane processes are gaining popularity in South Africa, especially for industrial use. It is expected that municipal use will soon become inevitable. Nanofiltration is a relatively new technique, which is looser in its polymer membrane structure than the Reverse Osmosis membrane which has dense top layer. These membranes usually having molecular weight cut-offs of 100 – 1000 Dalton, have a surface charge which can be influenced by the solution in contact with the membrane. This enable them to be discriminatory in rejecting or retaining ionic species (like water pollutants) based on weight and charge (mono- or divalent).

Aim and objectives of the study

Noting high concentrations in the North and North West Provinces, it will be worthwhile to investigate affordable and easy to use and maintain techniques that will be used in these rural areas. The aim of this study is:

1. to gain an understanding of pollution in the rural areas by sampling for pollutants for the life of this study,
2. to investigate if nanofiltration is the process suitable for application in removal of nitrate, fluoride and sulphate,
3. to construct a laboratory scale unit for ground water treatment,
4. to build and develop cross-flow nanofiltration pilot plant for study in rural areas,
5. to capacitate and empower people from the community to operate and maintain the unit.

During sampling, the areas of the greater Rustenburg region showed high levels of fluoride and to some extend of nitrate. For the other three regions (Klerksdorp, Mafikeng and Koster), the levels of these two pollutants were within the limits. The study was continued on the cross-flow unit using sampled water from selected sites.

Nine commercial NF-membranes (D11, D12, CTC1, NF70, NF90, TFC-S, TFC-SR, TFC-HR and TFC-ULP) were evaluated in this and another [2] study for their efficiency (flux and retention) using pure water, non-charged solutes, single and mixed salts as well as numerous water samples from North West rural areas. All membranes had a negative surface charge density. While D11, D12 and TFC-SR had the highest flux for all systems tested, they had the lowest retention in terms of non-charged solutes as well as single salts. NF70, NF90 and TFC-S displayed reverse osmosis (RO) properties with high reflection coefficients (σ) but low permeabilities for non-charged solutes and single salts. Membrane performance varied greatly when using mixed salts (depending on the salt combinations) and no correlation could be found.

A small laboratory scale NF unit was built to do preliminary studies in terms of screening and characterising the NF membranes. The NF unit, which could be operated up to 25bar, was built with the courtesy of Henk Veldhuis (Twente University, Holland).

For rural water treatment and testing of the high-pressure cross-flow NF unit, the best retention for fluoride and nitrate. All membranes efficiently removed sulfate due to their negative surface charge. While it was not possible to correlate membrane performance for different sample sites, TFC-S, TFC-SR, NF70 and NF90 had the best retentions on a dead-end module, and are recommended for further investigations.

The built high-pressure cross-flow unit was tested for performance by rejecting prepared solutions of sulfate, nitrate and fluoride. The results were comparable to those of the dead-end mode studies. In treating rural water, the membrane performance varied slightly from those observed during dead-end studies. Although the divalent ion (e.g.sulfate) levels were reduced greatly, monovalent ions were poorly rejected by all membranes, including the NF70 which showed promising results during the dead-end mode studies.

The backlog of the study was the failure to train and empower community people to operate the unit. This was because it was difficult to transport the unit to various sites of interest. The sampled water was instead brought on-site to where the unit was built. The ease of operation of the unit is recommended for further study.

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1 Background

1.1 Introduction

Prosperity of man is, among others, highly dependent on the availability and adequate supply of clean water. In the past, clean water supply meant clear water. If one water supply failed then another one would be easily found, as the population was small and as such water was abundantly available. The principle of the "best available source" was applied. Water-borne diseases infected some communities over time, and there had to be a way to treat water prior to drinking. Over the years man became capable of making water safe from the infectious diseases by the introduction of filtration and chlorination with subsequent development of water treatment strategies. This resulted in a shift from using the best available water to using the most economic source [1]. One of the latest strategies includes the development of membrane processes that will supplement if not substitute conventional water treatment processes. These developments result from the ever-growing need for and scarcity of water due to industrialization and the population increase, which necessitates revision and development of water regulation.

1.2 Motivation

The development of South Africa in technology advances in terms of industrial, economic, and international relations requires more cautious environmental considerations. These include air, water and soil pollution, which singly and collectively directly affect our health, wealth and prosperity. Added to industrialization are political, social, economic and demographic changes this country is experiencing. Needless to say, a decrease in water quality cannot be ignored any longer.

A major water related problem in South Africa (and probably in other countries) is that of high levels of ionic pollutants in rural water. Here, many people depend on boreholes as their source of water. Water from some of these boreholes is of low quality (high levels of nitrate, sulfate, fluoride, salinity, hardness and turbidity). It is not clear yet as to the underground geohydrological patterns and if these would be the cause of such pollutants. It is believed however, that degraded water quality is due to farming practices, polluted water seepages, and geochemical aquifer composition around the affected areas. Fluoride in the water is high in some areas and cannot go unchecked since it has chronic long-term toxicity concentrations slightly above the

beneficial level. Such high levels can cause dental and skeletal fluorosis. High levels of nitrate can cause methaemoglobinamea (blue baby syndrome) in newborn babies but is not so detrimental to adults except at exceedingly high concentrations. In addition to the nitrate and fluoride contamination the water is salty and has ions like calcium and magnesium (and hardness as $CaCO_3$), which can cause pipe scaling in industrial and household appliances. It is absolutely necessary that these nitrate, fluoride, calcium and magnesium, and salinity levels be kept to permissible limits. The purpose of this project is to investigate a nanofiltration membrane process for the treatment of rural water by specifically using a low-cost cross flow unit. Subsequently, apart from bench scale laboratory experiments, a cross-flow nanofiltration unit will be built and evaluated for performance on rural water treatment. A number of membranes that were characterized and evaluated at a laboratory scale will be further used in the large scale cross flow nanofiltration studies.

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2 Literature review

2.1 Nanofiltration – Historical background

Filtration is one of the ancient methods used for water treatment. Sir Francis Bacon, the philosopher, already used filtration in the 17th century to purify water. Water filtration for an entire town was in operation in 1804 in Praisley, Scotland. Due to these successful developments, a large water treatment plant was commissioned (in 1806) in Paris, using the River Seine as source. In this plant, water was settled for 12 hours prior to filtration then run through sponge pre-filters that were renewed every hour. The filters consisted of sand and charcoal [1].

In the late 1800's, filtration was for the first time recognised not only for straining unwanted particles, but also for removing deadly germs. During this period, rapid sand filters were developed, enabling further reduction in turbidity and bacteria. In the 1920's and 1930's the use of filtration and chlorination had virtually eliminated epidemics of major water-borne diseases such as typhoid and cholera. It was within these two decades that the dissolved air flotation, early membrane filters (primarily for analytical use), floc-blanked sedimentation and the solid-contact clarifiers were developed. A major step towards desalination came in the 1940's during the Second World War when various military establishments required water to supply troops in arid regions [2].

Presently, filtration processes are still in use and are continually being refined as more and better understanding of the complex web of physical and chemical interactions of the processes (filtration) come to the fore. Particles can now be measured in microns, compounds in parts per billion and parts per trillion levels. Regulations now require careful control of by-products of disinfecting processes. As a result, membrane filters are starting to provide the same and even better purification than conventional water treatments [1]. The latest of these membrane filtration technologies is nanofiltration (NF).

In 1988 Eriksson (of FilmTec® Corporation in Minneapolis, USA) was one of the first authors to toss the word "Nanofiltration" [3] and further gave a broad overview of the process as well as some applications of NF. NF was defined as a pressure driven membrane process between reverse osmosis (RO) and ultrafiltration (UF). It gives low

rejections of salts with monovalent anions and non-ionised organics with molecular weight (MW) below 150, and high rejection of salts with di- and multivalent ions.

It was in 1991 that Vivendi and *Syndicat des Eaux D'ile de France* (SEDIF) began experiments, using a FilmTec® NF-membrane, with a prototype unit providing water to about 5,000 people in the nearby communities [4]. This lead to a collaboration between these companies in the same year. Permission was given by the French government for the use of NF-membranes for water treatment. Today, France has up to 10 000 NF-membrane water treatment systems, which proves that NF-membranes can be used for large-scale municipality water and industrial effluent treatment [4]. At the same time, studies have been going on to understand and improve on membrane processes and applications [5, 6, 7, 8, 9, 10]. In 1997, Redondo and Lanari [11] studied membrane selection and design considerations for European potable water production based on different feed-water conditions. Today, a number of water plants both in industry and municipalities are in operation. There are more manufacturers, users and researchers [12, 13, 14, 15, 16] of membranes than before with a wide range of products to choose from.

Almost every year there are new deals with municipalities worldwide to build membrane based treatment plants. The challenge is normally that water differs from region to region and as such, more and more membrane products that suit specific water compositions are coming to the shelves. For example, in 2001 FilmTec® introduced three new products including NF90-400, NF270-400 and NF200-400 membranes. All of these have improved features compared to their predecessors [17].

2.2 Development of membranes in South Africa

Well over 20 years ago membranes were introduced to South African industries. Until recently, not much was known on possible applications and potential of membranes in this country. The South African democracy came during the same time as the information age and industry was faced with the challenge of catching up with international research and developments.

The Council for Scientific and Industrial Research (CSIR) already did some work on electrodialysis (ED) as far back as 1953. This research laid the foundation for a better understanding of the thermodynamic and physical processes involved in ED [18, 19]. Research development on polymeric membranes in 1973 at the Institute of Polymer Studies (IPS) of the Stellenbosch University (Western Cape) with subsequent

establishment of the first local membrane manufacturing company in 1979 are some of the important highlights [20]. Currently, membrane research and development are being pursued at all fronts by educational institutions and private companies, including the water and power supply institutions.

Some developments recorded include:

- Development of woven fibre MF by the Pollution Research Group (University of Natal, KwaZulu-Natal) in 1980 [21],
- Advanced research on cost-efficient manufacture of ozone using membranes and anode oxidation (University of Western Cape and IPS, Western Cape) [22],
- Extraction of metals by encapsulated supported liquid membranes (SLM) (Potchefstroom University, North West) [23],
- UF membrane bioreactors (IPS, Potchefstroom University and Rhodes University),
- Membrane fouling centering around electromagnetic, enzymatic, and chemical defouling, and surface modifications (Universiy of Stellenbosch, IPS, University of South Africa) [24, 25],
- Development of ceramic membranes by the Separation Science and Technology (Membrane Group) (Potchefstroom University, North West) [26].

Weir-Envig, a South African membrane company, has designed, manufactured and commissioned water treatment plants for both private and public sectors since 1985. Their work included desalination of brackish water and cooling tower blowdown (Sun International, Dept. Water Affairs, Bateman, Clover SA, ESKOM, Impala, Polifin, etc.), clarification and concentration of agricultural products e.g. juice, wine, etc. (SFW, CFI, KWV, Gilbeys', etc.), paper mill effluent treatment (Mondi paper), etc. [27].

It is the combination of these technological advances and the shortage of drinkable water that makes the treatment of South African rural water more urgent than before. Techniques have already been researched but need to be adapted and developed within the South African context so as to attain this goal.

2.3 Membrane processes

A membrane is a selective barrier between two phases. A membrane process is a unit operation which selectively divides a feed stream into two streams (the retentate and permeate). The retentate has a higher concentration of the entities retained by the membrane than the feed, while the other outlet stream, the permeate, has a lower concentration of the entities held back by the membrane than the feed.

Energy has to be added to the unit operation (membrane process) in order to yield a separation. This energy input, called the driving force, can be used (in a broad sense) as a means of classification of membrane processes. The driving force can be any of the following [28]:

- pressure gradient (ΔP),
- concentration gradient (Δc),
- temperature gradient (ΔT), or
- electrical potential gradient (ΔE).

2.4 Pressure driven processes

There are five pressure driven membrane processes, namely microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO) and particle filtration. The latter is not necessarily seen as a classical membrane operation. RO-membranes, which are the least permeable, are used for desalination. The disadvantage, however, is their high operational pressure. Microfiltration membranes are usually porous and are used for the removal of very small particles, for example during the clarification of fruit juices. Ultrafiltration gives a rejection of macromolecules (for example the removal of colour from dye solutions). Nanofiltration membranes are more loose in their polymer structure than RO-membranes, but have a dense top-layer. The membranes discriminate between monovalent and multivalent ions as separation takes place on the basis of both charge and particle size [29, 30].

The smaller the species to be rejected, the higher the driving force required for separation, as the osmotic pressure difference across the membrane becomes larger. Membrane processes separate mainly in two modes, i.e. dead-end and cross-flow modes. The difference between these modes can be seen in Figure 2. 1.

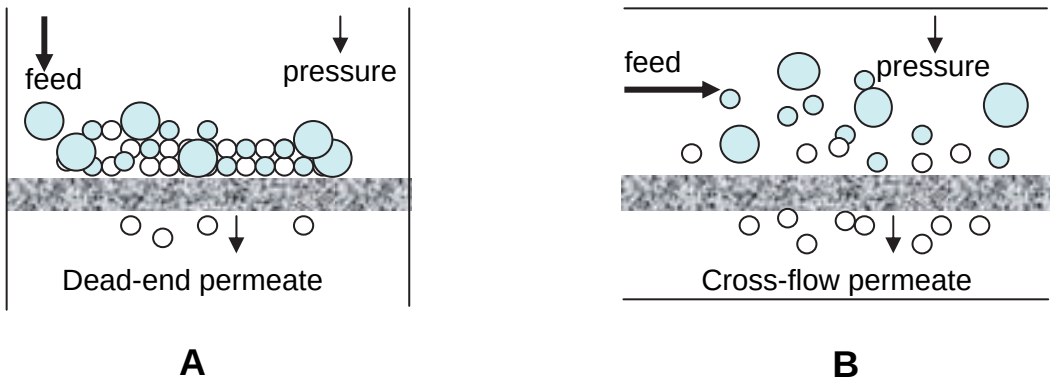

Figure 2. 1 Dead-end (A) and cross-flow (B) membrane processes

The dead-end mode (marked A) has its feed perpendicular to the membrane and as a result the retentate builds up on the membrane surface. This might lead to cake formation or fouling of the membrane surface due to pore clogging or increased adsorption. In the cross-flow mode (marked B) the feed flows parallel to the membrane surface, thereby decreasing the fouling or cake formation on the membrane surface. As a result, cross-flow can have longer sustained fluxes than the dead-end mode of transport.

2.5 Fouling

During NF, concentration polarization (CP) occurs when the solute is largely rejected by the membrane. As shown in Figure 2. 2, dissolved species are transported towards the membrane surface by convective flow during filtration. Water and species smaller than the pore radius will transport through the membrane whilst larger species are retained. As these retained species build up on the surface and membrane interface, their concentration increases until it is higher than that of the bulk stream providing a driving force for diffusion back into the bulk stream. This build-up at the interface is known as concentration polarization.

This polarization can be reduced by operating the system at high cross-flow velocities, so as to increase the shear rate at the membrane interface [31].

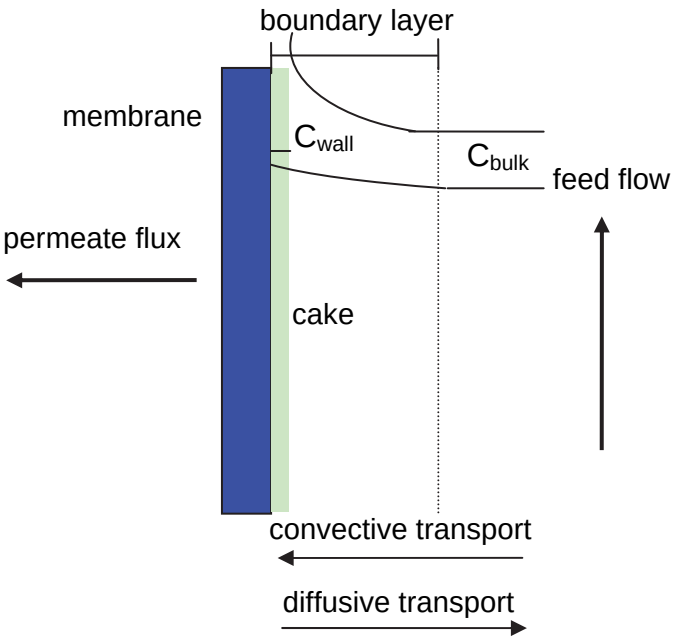

Figure 2. 2 The concentration polarization phenomenon

An irreversible or not easily reversible deposition or binding of solute or particulate onto or within the membrane is known as fouling. This results in a loss of solvent flux over time and a change in solute rejection influenced by concentration polarization (CP). This common problem of flux decline and fouling has direct implications on costs, energy and the environment during operation.

Foulants include inorganic scalants, suspended solutes and colloidal matter, metal oxides, organic matter as well as biological material [32, 33, 34]. Fouling can be divided into several phases [35, 36, 37] which result from concentration polarization, pore blocking and adsorption of hydrophobic species onto the membrane [38, 39].

Pore blocking is another fouling phenomenon (Figure 2. 3). Pores may either become clogged when species smaller than their size adsorb onto the inner walls. Chemical cleaning in place (CIP) is not very effective in removing this adsorbed material on the inside of the pores and may lead to irreversible fouling.

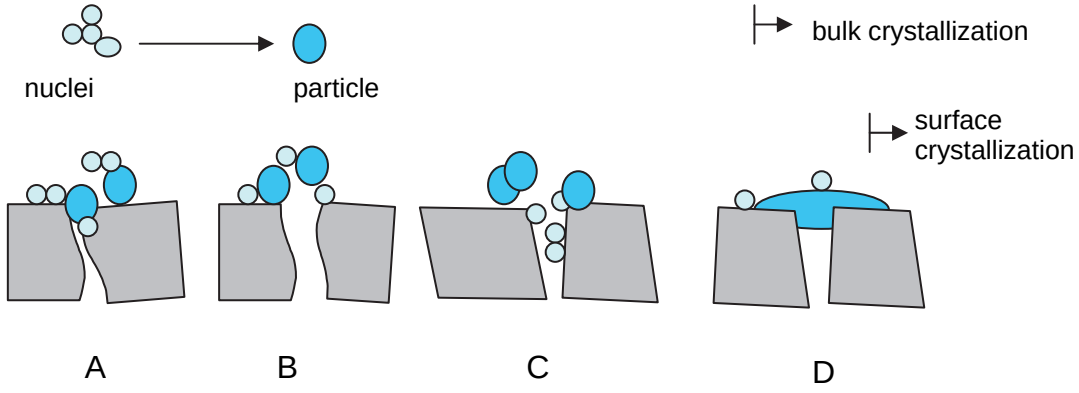

Figure 2. 3 Pore blocking mechanisms (A: complete pore blocking, entrance to pore sealed, B: pore bridging: partial obstruction to entrance, C: internal pore binding, entrapment/adsorption of non-retained species), D: lateral cake formation (Adapted from Jacobs et a*l* [31])

Apart from fouling, scaling can also occur on the membrane surface. Scaling entails the precipitation of dissolved salt in the feed water due to the increase in concentration on the adsorbent surface due to CP. This happens as soon as salts exceed their solubility product and precipitate. Compounds with a low solubility commonly present in feed water are calcium carbonate, barium sulfate, silica and calcium phosphate [40]. When scaling occurs, the permeability of the membrane decreases and the head-loss in the feed-brine channel increases. A higher feed pressure is usually applied to maintain the desired flux, causing an increase in energy consumption. Even under these conditions, scaling would still continue causing a further decrease in flux while simultaneously shortening the life expectancy of the membrane.

There are two causes of flux decline during scale formation in RO; cake formation and surface blockage [41, 42, 38]. During cake formation, crystal particles, which are formed in the bulk phase; through bulk (homogenous) or secondary crystallization, are deposited on the membrane to form a layer. Accumulation of this porous layer precipitate causes flux decline which can be described by a resistance-in-series model (Equation 2.1):

$$J = \frac{\Delta P - \Delta \pi}{\eta \cdot (R_m + R_c)} \qquad \textbf{(2. 1)}$$

where ΔP is the trans-membrane pressure (bar), $\Delta\pi$ is the osmotic pressure difference (bar), η is the permeate viscosity, R_m the membrane resistance and R_c the resistance due to cake formation.

Surface blockage can also occur due to (heterogeneous) crystallization on the membrane surface with the subsequent blockage of the membrane by lateral growth of crystals (Figure 2. 3 D). As the solute (retentate) becomes saturated, it crystallizes in the bulk solution to form nuclei, which nucleate into particles that precipitate onto the membrane surface to form a porous cake. Some of the saturated solute precipitates on the membrane surface and crystallizes. These crystals grow into an impermeable layer (cake) which subsequently blocks the membrane pores.

Hydrophobic species present in the process water tend to adsorb on hydrophobic membranes. These species form a layer on the membrane surface that cannot be removed hydrodynamically, leading to a flux reduction with time. In this case CIP can initially restore the membrane performance.

In general, fouling (and scaling) control is important as it results in increased energy consumption, decreased salt rejection and high cleaning frequency which may shorten the life time of the membrane [43, 44].

2.6 Summary and conclusion

The shortage of water in many parts of the country and the need for strategic water reuse and management, makes membrane application a necessity for supplementing current water treatment techniques. Currently however, there is a pressing need to make clean water available to the rural poor, who largely depend on the extraction of groundwater for domestic use and farming. The backlog in the usage of this water source in some areas is caused by the high pollutant content (nitrate and fluoride). This problem is intense in the Rustenburg area of the North West Province and the far regions of the Limpopo Province where the levels are unacceptably high. These pollutants can possibly be reduced to acceptable levels using the nanofiltration membrane process.

Although nanofiltration is a relatively new membrane process, it has already been widely applied specifically for water treatment in developed countries (European, Israel

and the United States of America) [45, 46, 47]. Research is ongoing in an attempt to model varying parameters involved during the membrane process (e.g. transport modeling, adsorption on surface, etc.) [48, 49, 50]. It is attempted to improve on the membrane products, efficiency and applicability of the membranes. Although there had been developments in membrane manufacturing in South Africa, there has been no commercial application and use. The potential of the nanofiltration process to reduce fluoride and nitrate results from the membrane surface charge that can repel or attract ions depending on their charge and valence. This is apart from the exclusion of the solutes based on their molecular sizes. These exclusion properties are as a result of electrostatic repulsion between the charged membrane and the solute. Retention of fluoride, nitrate and/or sulfate is dependent on the charge effects. The monovalent ions are less effectively repelled than the di- and trivalent ions of the same sign of charge. In NF, retention is also influenced by the co-ion which will be repelled by the membrane of the same charge.

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3 Dead-end NF and preliminary tests

3.1 Filtration set-up

The bench-scale unit was built (courtesy of Twente University, Henk Veldhuis) to allow the solution through the top opening or feed inlet as shown in Figure 3.1. A membrane of a required diameter (9.0cm) is cut and placed at the bottom of the unit on a porous support. After sealing the unit, it is pressurised up to 20 bar.

The solution (~1.2 litres) is then stirred with a free rotating magnetic bar propelled by the magnetic stirrer (field). The permeate through the membrane (A = 64cm^2) was collected with plastic sample beakers whilst monitoring the mass flux with the help of a weighing pan.

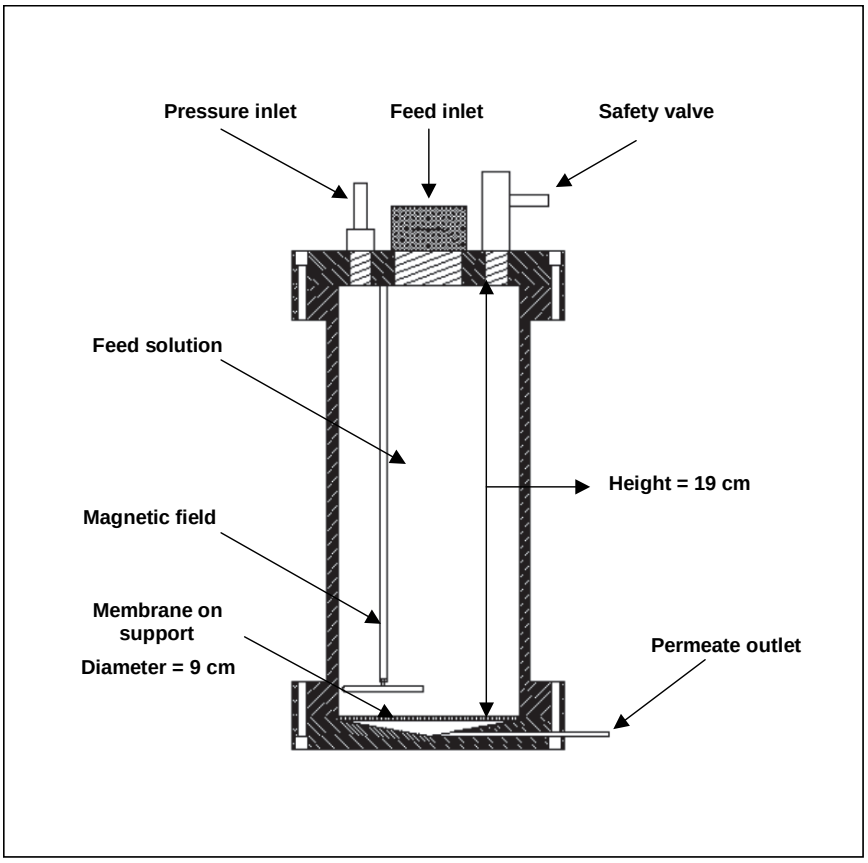


Figure 3. 1 The high-pressure dead-end module

3.2 Membranes

The NF-membranes of different specifications (Table 3. 1) used in this study were obtained from different manufacturers. These polymeric membranes were supplied as flat sheets, except for the NF70 and NF90, which were spiral-wound and thus had to be unwound and cut to flat sheets. The membranes used were:

- D11 and D12 from MembraTek-Envig South Africa*,
- NF70 and NF90 from Dow – FilmTec®,
- TFC-S, TFC-SR, and TFC-HR from Koch Membrane Systems*, and
- CTC1 (Chlorine tolerant membrane) from Hydranautics*.

Table 3. 1 Specifications of NF-membranes

	D11	D12	NF70	NF90	CTC1	TFC-S	TFC-SR	TFC-HR
MWCO (Da)	180	180	200	–	–	–	–	–
NaCl (%)	50	15	–	–	90[e]	≤85[c]	30[c]	99.5
$MgSO_4$ (%)	96[a]	96[a]	95[b]	96[b]	–	95[d]	98.5[d]	–
Design- or pressure range (bar)	5 – 28	5 – 28	17	17	41.6	4 – 7	5	15
Max. temp (^oC)	50	50	35	35	45	45	45	45
pH range	4 – 11	4 – 11	3 – 9	3 – 9	3 – 10	4 – 11	4 – 11	4 – 11
Flow ($m^3.d^{-1}$)	7.6[f]	10.6[g]	3.2[g]	2.5[g]	0.3[g]	–	–	–

a: 1000ppm solute at 6.9bar net pressure; b: <2000ppm solute, at 5bar, pH = 7 and 25^oC; c: 1000ppm solute, 6bar, pH = 7 and 25^oC; d: 2500ppm solute, 6bar, pH = 7 and 25^oC; e: 500ppm solute at 4.5bar applied pressure, pH = 6.5-7.0 and 25^oC; f: model D11 4040 element, g: 2540 elements, area = 2.6m^2.

The Envig (D11 and D12) membranes are both thin film composite membranes with the molecular weight cut-off range well within that of nanofiltration membranes. The NF70 and NF90 are composite membranes. NF70 has a negative charge at high pH values due to the dissociation state of the amine groups in the thin layer [1]. TFC-S is a thin layer composite polyamide membrane on a polysulfone base. It is usually stored

* these membranes were donated courtesy of the manufacturers

wet in a dark area and must be “cleaned” or pretreated before use. TFC-SR is a thin-film composite propriety membrane on a polysulfone base. It is supplied dry with a poly(vinyl)alcohol (PVA) coating which has to be removed by washing or water permeation before use. TFC-HR is also a thin-film polyamide membrane on a polysulfone base. It is stored dry and also has a PVA coating. CTC1 is a thin layer composite polyamide membrane.

All the membranes were pretreated by flushing the membrane with feed *in situ*, sending the permeate to drain for about 10min or until the permeate was clear.

3.3 Permeation measurements

There are various variables that have an influence on the performance of a membrane. Normally, a compromise is struck between the retention capacity and the flux of a membrane. Although a high retention and flux are desirable, the two parameters (retention and flux) are antagonistic, with high fluxes yielding low retention and vice versa. The volume fluxes are influenced by the applied pressure while the solute fluxes are proportional to the concentration gradient.

There is also the sterical hindrance of solutes that are transported through the membrane pores, which is dependent on the molecular weight and ionic charge and size of the transported solutes. This means that solutes will be discriminated based on their molecular sizes as well as on their ionic charge in case of electrolytes. Larger molecules will be rejected while the smaller ones are transported through the membrane “pores” to the permeate phase.

3.3.1 Clean water flux

Clean water (demineralized) is used as a reference in membrane characterization since charge or concentration polarisation and/or molecular weight have no effect on the flux. The water flux (J_w) is measured at various trans-membrane pressure differences (TMP) to yield the water permeability (A_W or L_p in $L.m^{-2}.s^{-1}.bar^{-1}$ or $m.s^{-1}.bar^{-1}$). This relation is best described by the Hagen-Poiseuille Equation:

$$J_w = \frac{\varepsilon \cdot r^2}{8 \cdot \eta \cdot \tau} . \frac{\Delta P}{\Delta x} \qquad \textbf{(3. 1)}$$

where J_w is the water flux (in $m.s^{-1}$ or $L.m^{-2}.hr^{-1}$), ε is the porosity, r is the pore radius (in m), τ is the tortuosity (indicative of how straight the pores are, equals one when the pores are straight), η is the viscosity of water (in Pa.s), Δx is the membrane thickness (in m) and ΔP is the applied trans-membrane pressure (in kPa).

The linear relationship between flux and pressure is indicative of a constant permeability for every membrane. The water flux can be described according to the model of Darcy [2]:

$$J_w = A_w \cdot (\Delta P - \Delta \pi) \qquad \textbf{(3. 2)}$$

Since both the feed and permeate of the membrane consist of water, the osmotic pressure difference ($\Delta \pi$) across the membrane is zero and Equation (3. 2) is reduced to:

$$J_w = A_w \cdot \Delta P \qquad \textbf{(3. 3)}$$

which is comparative to the Hagen-Poiseuille model.

Combining Equations (3. 1) and (3. 3), Equation (3. 4) is obtained:

$$A_w = \frac{\varepsilon \cdot r^2}{8 \cdot \eta \cdot \tau \cdot \Delta x} \qquad \textbf{(3. 4)}$$

where

$$\tau = \frac{\ell_P}{\Delta x} \qquad \textbf{(3. 5)}$$

τ is the tortuosity (-) with ℓ_p the real length of the pore (in m) and Δx the membrane thickness (in m). Tortuosity equals one if both Δx and ℓ_p are the same, which means that the pores are perpendicular to the membrane surface.

The permeate flow rate measured for the cross-flow module is presented in Figure 3. 2 as an example of the flux-time plot at a trans-membrane pressure of 5 bar. No major difference was observed for clean water flux between the dead-end and cross-flow units. An increase in applied pressure yields a linear increase in flow rate ($L.m^{-2}.hr^{-1}$) for all membranes tested as can be seen from Figure 3. 3.

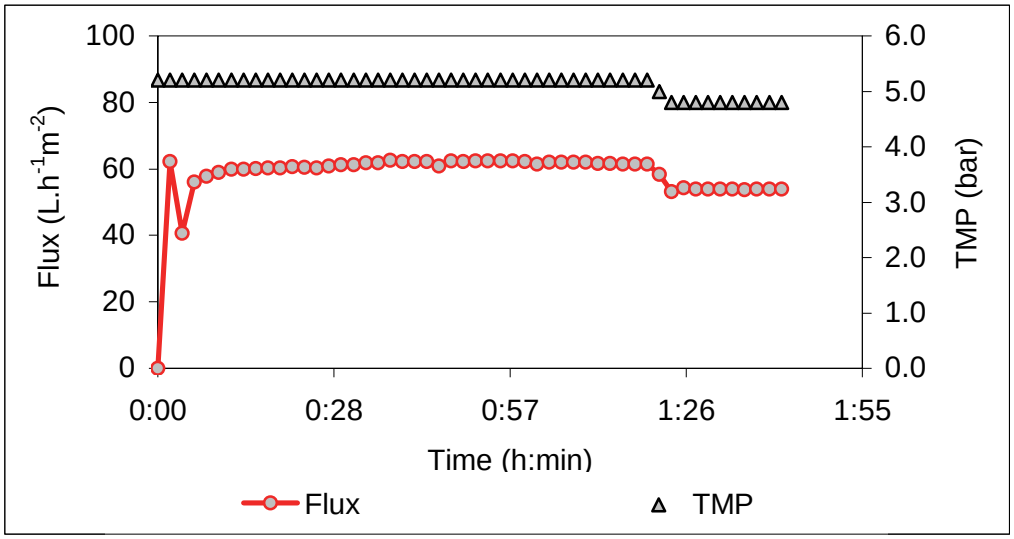


Figure 3. 2 Water flux- time plot on TFC-S nanofiltration membrane (T = 25°C, cross flow module)

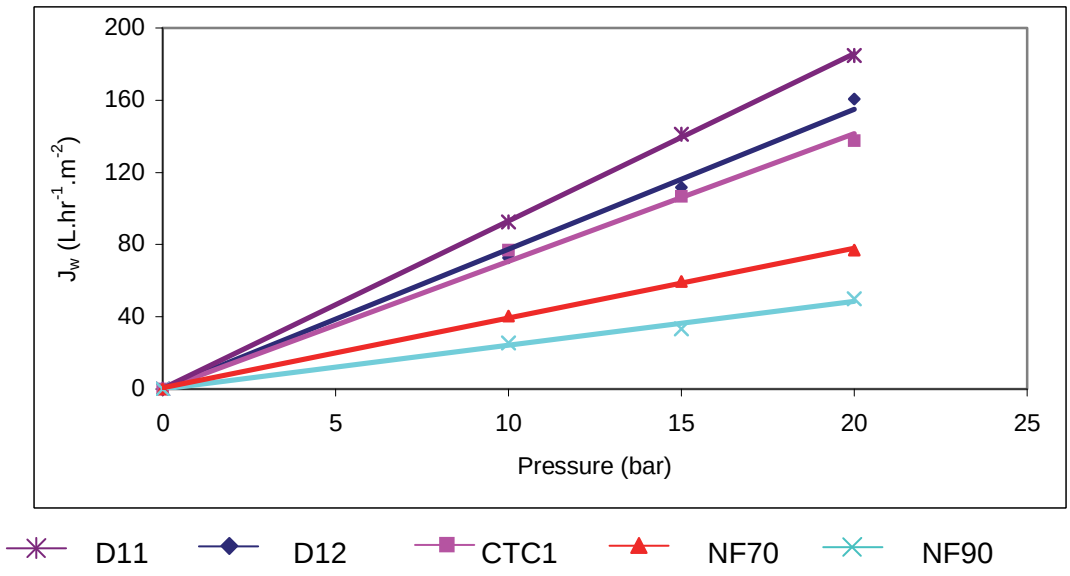


Figure 3. 3 Water flux – pressure plot for different membranes (T = 25°C, dead-end module)

When it is approximated that $\varepsilon \cong \frac{1}{\tau}$ then

$$(\varepsilon \cdot r)^2 = 8 \cdot \eta \cdot \Delta x \cdot A_w \qquad (\mathbf{3.\ 6})$$

The value of A_w is obtained experimentally from the slope of the plot of volume flux ($L.m^{-2}.hr^{-1}$) versus pressure (bar) as in Figure 3. 3. It can be assumed that the viscosity of pure water is 0.001Pa.s and Δx is 1μm. From the above approximation $\varepsilon.r$ can be calculated from the water permeability data (Table 3. 2).

Table 3. 2 Clean water permeability and porosity value of NF-membranes

Membrane type	**A_w ($L.m^{-2}.hr^{-1}.bar^{-1}$)**	**ε.r (Å)**
D11	9.21	4.52
D12	8.79	4.42
CTC1	6.08	3.68
NF70	3.66	2.85
NF90	2.48	2.35
TFC-S	2.04	2.13
TFC-SR	12.0	5.16
TFC-HR	3.45	2.77

The values of water permeability (A_w) and $\varepsilon.r$ are given in Table 3. 2 for the membranes tested. Two classifications of the membranes can be done; those that have low clean water permeability between 2 and 3 $L.m^{-2}.hr^{-1}.bar^{-1}$ (NF70, NF90, TFC-S and TFC-HR) and those that exceed 6 $L.m^{-2}.hr^{-1}.bar^{-1}$ (D11, D12, CTC1 and TFC-SR). The latter suggests that these membranes are more loosely packed while NF70, NF90, TFC-S and TFC-HR are more tightly packed. The observed water permeability are proportional to the product $(\varepsilon.r)^2$.

3.4 Nanofiltration of salts

The ability of nanofiltration membranes to reject electrolytes is owed to the Donnan exclusion effect. During the membrane surface's contact with electrolytes, co-ions (those having the same charge as the membrane) and counter-ions are distributed

between the membrane and the solution. At this stage, the electrical forces on the membrane-electrolyte interfaces (feed-membrane and permeate-membrane interfaces) play an important role in the membrane performance. In the case of salt mixtures, the diffusion coefficients and the hindrance factors also come into play resulting in the Donnan equilibrium. These added factors yield improved multivalent rejections.

In this section, the rejection capabilities of the NF-membranes that are used later for water treatment are presented. The ions (sulfate, chloride and nitrate), both as single salts and salt mixtures, were used to determine the retention behaviour of the NF70, NF90, D11, D12, CTC1, TFC-S, TFC-SR and TFC-HR membranes. The effect of pH on retention was also determined.

3.5 Theory

It was stated before that the properties of NF-membranes are between those of reverse osmosis and ultrafiltration. The separation by ultrafiltration membranes is largely influenced by steric effects whilst electric effects influence the reverse osmosis membrane processes. NF-membranes are influenced by both effects. Separation is influenced by the physical parameters such as pore radius, membrane thickness and the electrical charge density on the surface. The overall result is that the NF-membrane can reject mono- and divalent ions. As complex as the process can be, it can be explained in terms of theories such as the extended Nernst-Planck model, charge shielding, Donnan exclusion and the degree of hydration. Modeling of electrolytes has been done by a number of researchers [3, 4, 5, 6] and will not be dealt with in this section. Instead, only performance in terms of the rejection coefficient and flux will be investigated.

3.6 Tests

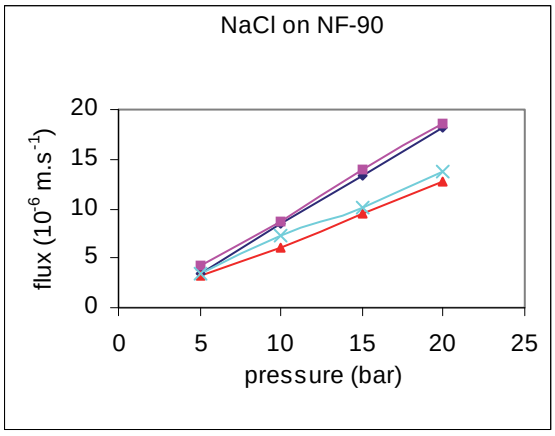
3.6.1 NF of single salts

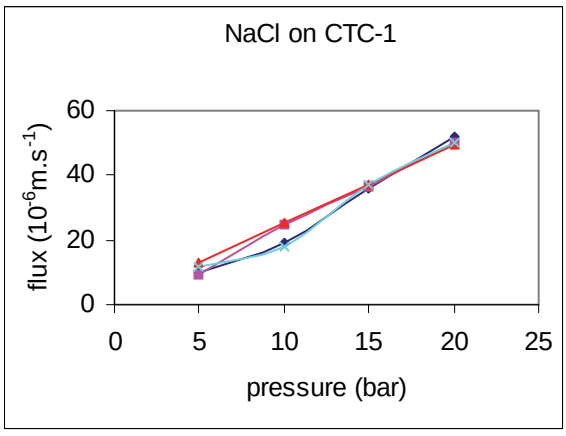
The effects of stirring (and speed), concentration and pressure (and flow mode) were investigated. All the concentrations were monitored by a colorimeter (HACH DR/890), a conductimeter (HI pH9032) and an IC (Waters Model 510). All experiments were carried out on CTC1, TFC-S, TFC-SR TFC-HR, NF70 and NF90 membranes on a dead-end unit, unless otherwise stated.

The fluxes of the membranes were first determined using solutions of sodium chloride (NaCl), sodium sulfate (Na_2SO_4), calcium chloride ($CaCl_2$), sodium nitrate ($NaNO_3$), sodium fluoride (NaF), and calcium sulfate ($CaSO_4$). The solutions were prepared at concentrations of 20, 50, 100 and 200ppm (prepared as anion concentration). The sulphuric acid concentration (H_2SO_4) ranged from 50 to 2000ppm as total sulphate concentration. The pressure applied in all experiments were 5, 10, 15 and 20bar. Additionally, some experiments at lower trans-membrane pressures (2–6bar) were carried out for $CaSO_4$, $NaNO_3$, H_2SO_4, NaCl, Na_2SO_4 and $CaCl_2$ on NF70, NF90, and CTC1 membranes.

Fluxes of single salts

Solute flux versus pressure plots for the permeation of NaCl are shown in Figure 3. 4 for the CTC1, TFC-S, TFC-HR, TFC-SR, NF70 and NF90 membranes. There is a notable but small volume flux ($m^3.m^{-2}.s^{-1}$ or $m.s^{-1}$) increase for the increasing salt concentration through the membranes. The same graphs as for NaCl shown in Figure 3. 4 were obtained for all other salts (see **Appendix A)**. According to these results the volume flux through the TFC-S membrane is very low for all salts. This is in correlation with its small pore radii and possibly also polarization (and formation of absorption layers on the surface), which can easily prevent or exclude the large ionic salts from being transported.





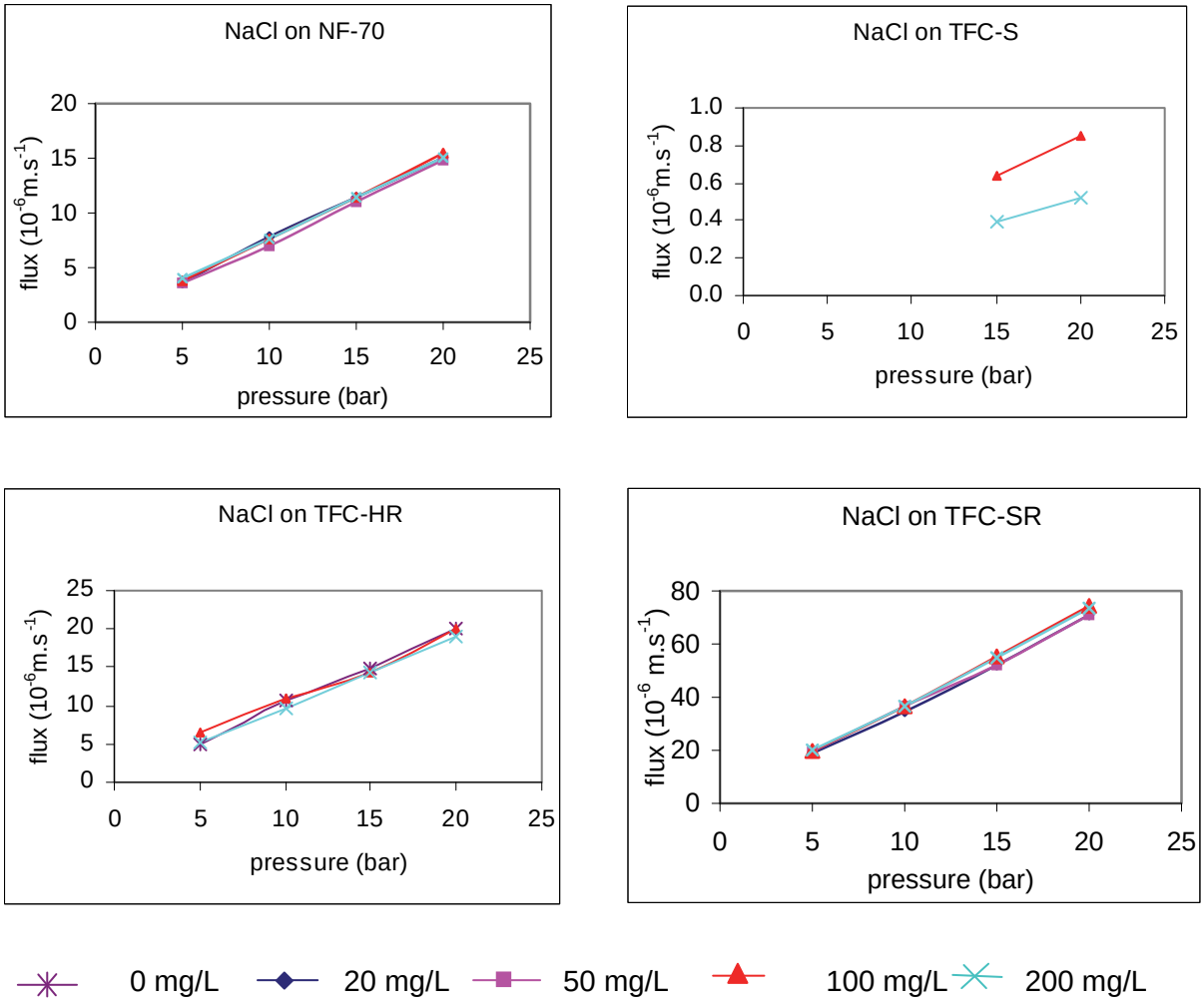


Figure 3. 4 Solute flux – pressure relations of varying NaCl concentrations through different membranes (T = 25°C, dead-end mode)

Contrary to TFC-S, TFC-SR has high fluxes in the presence of all salts. Furthermore, the permeated flux through the membrane is relatively constant for all the salts (1-1 (e.g. NaCl), 2-1 (e.g. $CaCl_2$), and 1-2 (e.g. Na_2SO_4)). The water flux (A_w in $L.m^{-2}.hr^{-1}.bar^{-1}$) shows the same trend as the solute fluxes for the TFC-SR membrane, indicating that the membrane is equally permeable even for the charged solutes. The same cannot be said for the CTC1 membrane which has higher water fluxes than solute fluxes. In general, the concentration polarization is not that severe for the membranes except for TFC-S and NF90 which show noticeable differences in fluxes, probably due to surface polarization and restricted pore radii. Solute flux decreases in the order TFC-SR > CTC1 > NF70, NF90 > TFC-S.

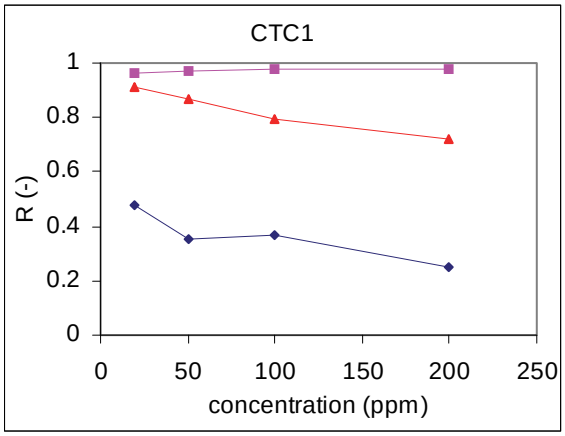
Retention of single salts

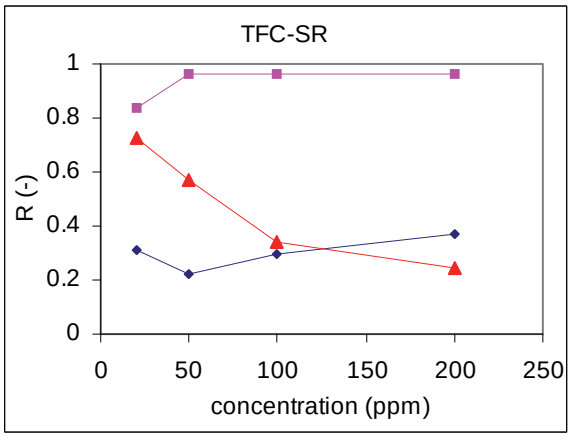
The retention of single salts measured at varying pressures is indicative of two groups of membranes:

i) those for which Donnan exclusion seemed to play an important role and
ii) those for which retention was neither completely determined by Donnan exclusion nor by size effects [7].

The first category can be further sub-divided into two membrane types. The first type is of the valence retention sequence R (1-2) salt > R (1-1) salt > R (2-1) salt and is typical of the negatively charged membrane. In general, the retention of these membranes decreases with increasing solute concentration.

An example of this membrane type is shown in Figure 3. 5 for the membranes CTC1, TFC-S, TFC-SR, NF70 and NF90 (see **Appendix B – E)** which also include TFC-HR). For all these membranes, the Na_2SO_4 solution was highly rejected and the $CaCl_2$ was poorly rejected (R (1-2) > R (2-1)).





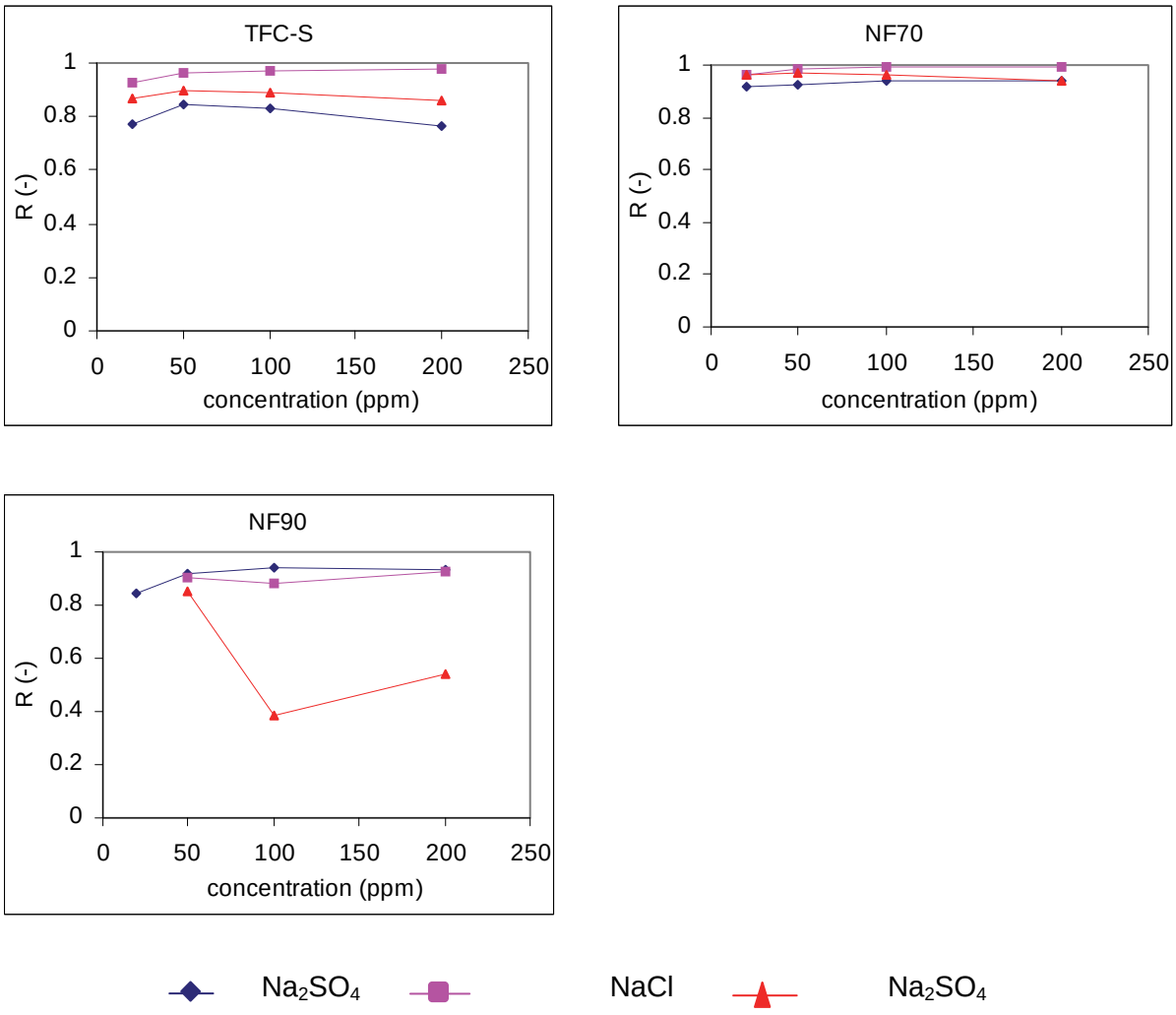


Figure 3. 5 Retention versus concentrations of (2-1), (1-1), and (1-2) salts (anions)

The second type of the first category shows the ionic valence retention sequence R (2-1) salt > R (1-1) salt > R (1-2) salt, which is a reverse of the first type. This sequence is typical of positively charged membranes. An example of this type in this category was however not found among the membranes evaluated.

In Table 3. 3 a summary of the behaviour of membranes in terms of the rejections of $CaCl_2$, NaCl, and Na_2SO_4. According to these results, all membranes tend to fall within the first category. The difference in retention for (2-1) salt and (1-1) salt by NF70, NF90, TFC-S, and TFC-SR, is statistically not significant in assigning a membrane surface charge. While NF70, TFC-S, and TFC-SR show a tendency towards negatively charged membranes, CTC1 gives the typical behaviour of a negatively charged membrane. NF70 and NF90 showed membrane characteristics that are

closer to those of reverse osmosis membranes than NF, as all salts were retained equally well by these membranes.

Table 3. 3 Single salt retentions of (2-1), (1-1), and (1-2) salts on different membranes

Single salts retention * (%)			
Membrane	$CaCl_2$ (2-1)	NaCl (1-1) salt	Na_2SO_4 (1-2) salts
NF70	92.3	96.2	99.1
NF90	93.8	91.0	92.7
CTC1	36.4	79.6	97.7
TFC-S	82.7	88.9	97.3
TFC-SR	29.3	33.8	96.2

*at concentration = 20ppm and pressure = 20bar

3.6.2 Salt mixtures

The experiments were done at pressures of 10 and 20bar using mixtures of $CaCl_2/CaSO_4$, $CaCl_2/CaF_2$, $NaCl/CaCl_2$, $CaSO_4/Na_2SO_4$, and $NaCl/Na_2SO_4$ on TFC-SR, NF70 and NF90 membranes. The ion ratios used were 1:9, 3:7, 5:5, 7:3 and 9:1. The total concentration of the common ion was set to 200ppm. A pH meter (HI pH301), colorimeter (HACH DR/890), ion chromatography (Water model 510), and atomic absorption (Varian SpectrAA 250 plus) were used for monitoring the ions. All mixtures were prepared using demineralized water.

The dead end unit was equipped with a stirrer to maintain the concentration as homogenous as possible throughout the reactor. The stirrer could be set at low or high stirring modes. To study the effect of stirring rate on concentration polarization at low concentration, clean water and a 100ppm solution of $CaSO_4$ was used on a TFC-SR membrane.

Figure 3. 6 shows the retention versus pressure relationship as a function of no stirring, slow and high stirring. As convection forces the solute towards the membrane surface, back diffusion counters this phenomenon. At higher pressure differences, convection becomes higher and renders back diffusion less effective as the “thickness” of the polarization layer increase. Concentration polarization would then occur especially at slow or no stirring which might lead to negative rejections.

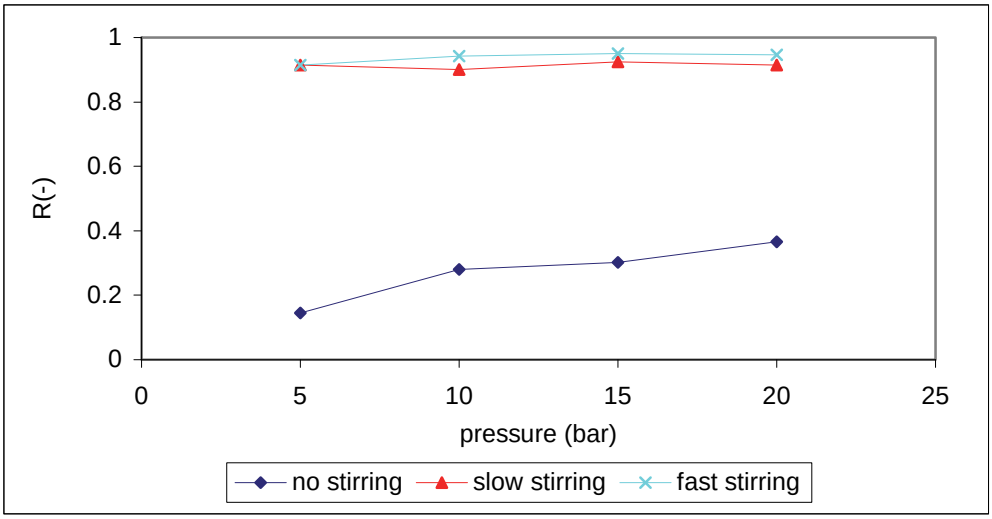


Figure 3. 6 Retention – pressure relation showing the effect of stirring on TFC-SR membrane (T = 25°C, dead-end mode)

Stirring (slow/fast) compared to no stirring leads to high rejections but does not necessarily mean it would completely remove polarisation. Since the solvent permeates through the membrane, the solute that was formerly dissolved accumulates on the membrane surfaces. The concentration of the solute then increases, especially in the boundary layer. The local concentration difference across the membrane would then increase, ultimately resulting in increased fluxes of the solute through the membrane.

The flux–pressure relationship for clean water and $CaSO_4$ solution is shown in Figure 3. 7 at varying stirring rates. The solute flux decreases with decreasing stirring rate while fast stirring improves the solute flux to such an extent that it becomes comparable to, although somewhat lower than the flux of clean water, which remained the same regardless of the stirring speed. This is because water has no charged ions that concentrate on the membrane surface. Therefore, it can be concluded that stirring is important when using a dead–end mode in order to minimize concentration polarization.

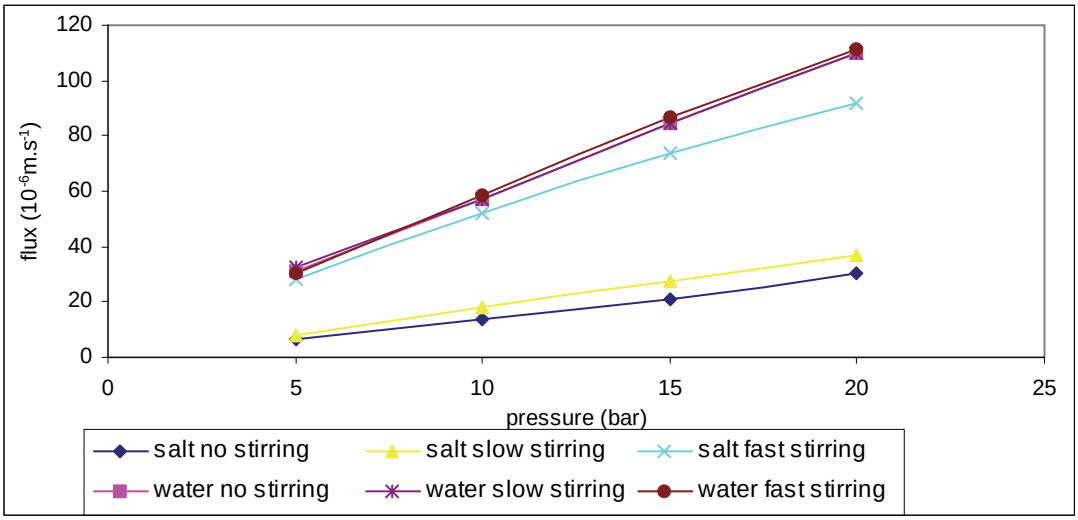


Figure 3. 7 Flux – pressure relations showing the effect of stirring on TFC-SR membrane (50ppm $CaSO_4$, T = 25°C, dead-end mode)

A set of salt mixtures were prepared and permeated through all the membranes as with the single salts.

Retention of NaCl/Na_2SO_4

These experiments were carried out on TFC-SR, NF70 and NF90. The two former membranes showed a slight negatively charged behaviour during single (NaCl and Na_2SO_4) salt studies and were classified within the first category of the membranes (Donnan exclusion important). NF90 seemed to reject both divalent anions and cations equally well, while also retaining NaCl.

Figure 3. 8 is an example of the retention-ion fraction plot of the NaCl/Na_2SO_4 mixture for the three chosen membranes. Except for TFC-SR, the chloride retention decreases as the concentration of the sulfate increases in the mixture. The implication is that increasing high valence co-ion (SO_4^{2-}) concentration will "push" more chloride into the membrane and decrease its retention while the retention of sulfate would simultaneously increase. The rejection of the sulfate is depressed by an increasing chloride concentration in the solution (except for TFC-SR). The reason for this is that the sulfate concentrations are low at this ratio and their retention is compromised by the retention of the chlorides.

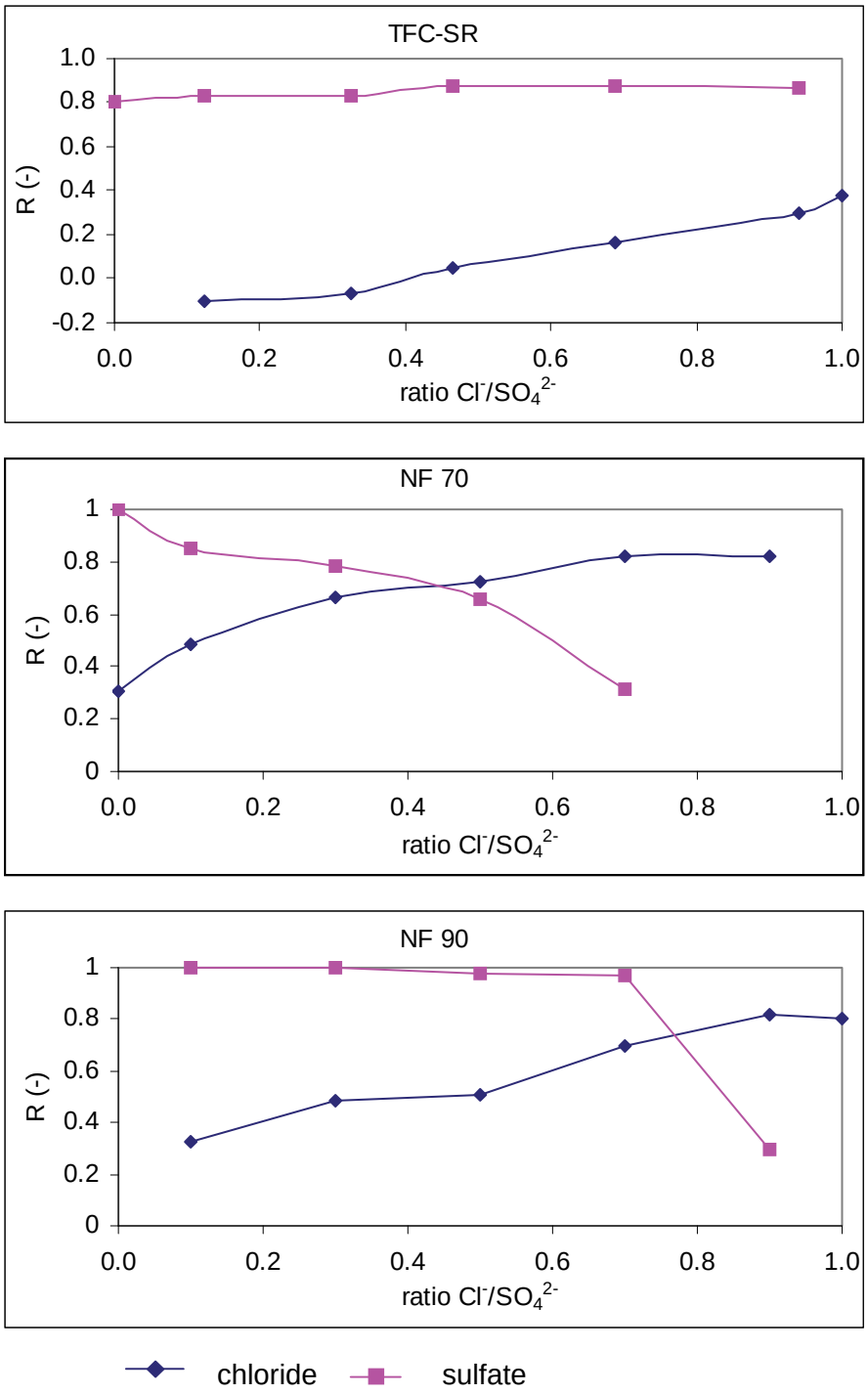


Figure 3. 8 Rejection of NaCl and Na_2SO_4 mixture on 3 different membranes (pressure = 10 bar, total Na^+ concentration = 200ppm)

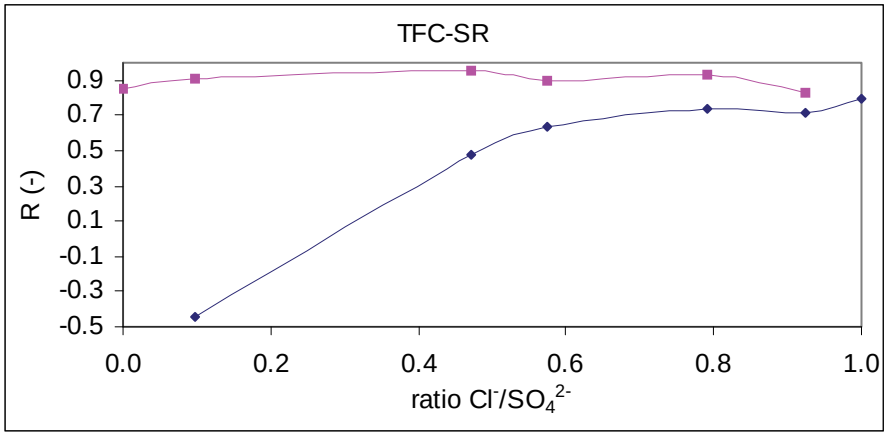
The NF90 membrane shows a similar pattern as NF70 although the retention of sulfate decreases even at low a SO_4^{2-}concentration. Retention of sulfate on TFC-SR seems constant at about 80%, while the retention of chloride is negative at high sulfate concentrations. At low sulfate concentrations, the chloride retention is still reasonable

for NF70 and NF90 (~80%), but low for TFC-SR (~30%). This shows that there is little transport of sulfate into the membrane whilst that of the monovalent co-ion is increased. In general, the retention of the monovalent co-ion was lower for the salt mixtures as compared to the single salt studies.

The volume flux ($m.s^{-1}$) of the mixtures remains constant for increasing ratios but increases with increasing pressure. For TFC-SR the volume flux was ~22 x 10^{-6} $m.s^{-1}$ at 10 bar and ~41 x 10^{-6} $m.s^{-1}$ at 20 bar.

Retention of $CaCl_2$/$CaSO_4$

The difference between this mixture and the previous one ($NaCl/Na_2SO_4$) is only that the counter ion (Ca^{2+}) is divalent and a bit larger in size than the monovalent sodium ion. The retentions follow the same trend as obtained for the $NaCl/Na_2SO_4$ mixture (Figure 3. 9). However, rejections of the sulfate ions improved drastically for the NF70 and NF90 membranes (~100%). For the TFC-SR membrane the rejection of sulfate is constant, as was the case for the $NaCl/Na_2SO_4$ mixture. Again, the negative rejection of chloride is observed for TFC-SR at high sulfate concentrations (Figure 3. 9). Furthermore, the chloride rejection is greatly improved at lower sulfate concentrations for all the membranes.



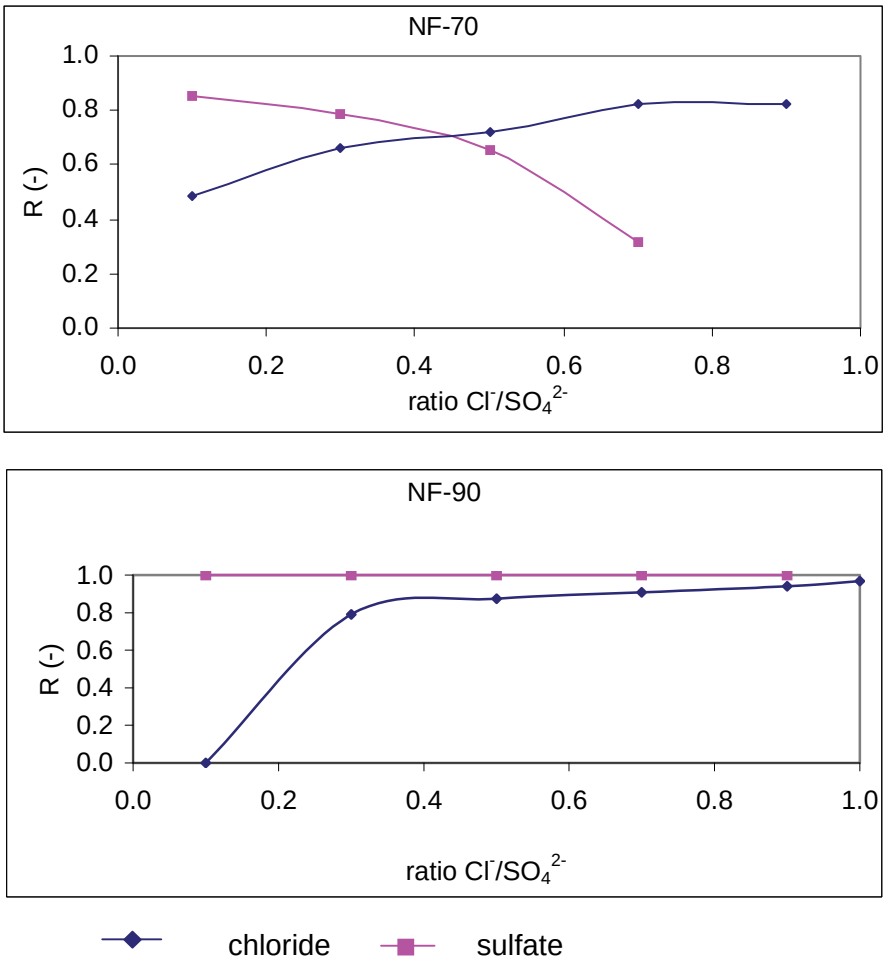


Figure 3. 9 Rejection of $CaSO_4$ and $CaCl_2$ mixture on 3 different membranes (pressure = 10 bar, total Ca^{2+} concentration = 200ppm)

This can be due to the slight impermeability of counter ions, which causes chloride ions to remain behind on the feed side. This effect 'costs' two chloride ions for every calcium that fails to be transported through the membrane. It seems, however, that this effect is countered by high sulfate concentrations.

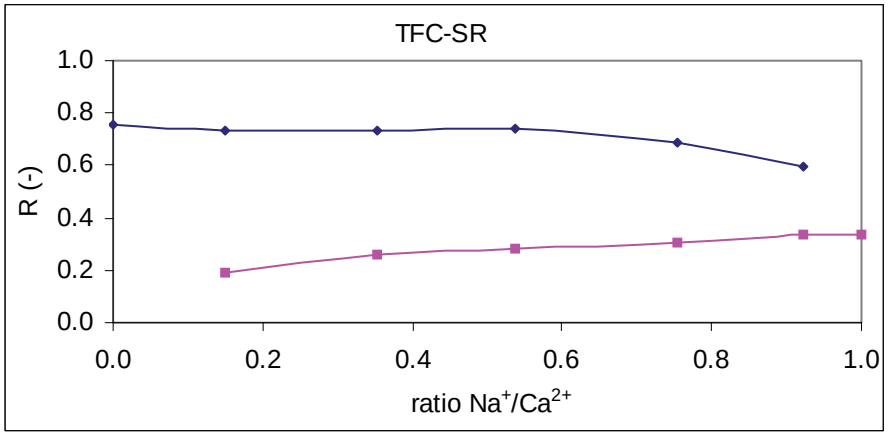
Retention of NaCl/$CaCl_2$

The NF70 and NF90 membranes show almost similar tendencies as with the anionic co-ion rejections (Cl^-/SO_4^{2-}). The calcium rejection by NF70 and NF90 is about 90% and remains nearly constant even with increasing calcium concentrations (Figure 3. 10). Contrary to the monovalent anion retention pattern, the monovalent cation retention is high even at high calcium concentrations. That is, retention does not

increase with increasing high valence concentration. This is because the transport of Na^+ is not accelerated resulting from the negative charge of the membrane.

The high retention of both cations (Na^+ and Ca^{2+}) by the NF90 membrane results in the improved rejections of the monovalent anion, which is a co-ion in this case. The retention of sodium decreases with increasing concentration at low divalent cation concentrations. This is an opposite effect to a decrease in retention in chlorides at high divalent cation concentrations. Also, there would be reduced retention of cationic divalents as compared to the anionic divalents if the $NaCl/Na_2SO_4$ or $CaCl_2/CaSO_4$ mixture were to be used. The same trend is observed for the NF70 membrane.

The rejection on the TFC-SR shows a similar pattern as in the anionic co-ion retentions except that rejections here are even lower (not more than 70% for calcium). Calcium shows a decrease in rejection at low concentrations, increasing at high calcium concentrations. Again, sodium ions have their rejections reduced at high divalent cation concentrations. No negative retention was observed though, as seemingly not much of the sodium is transported into the membrane when using this mixture, owed to the poor rejection of divalent calcium, even at high concentrations.



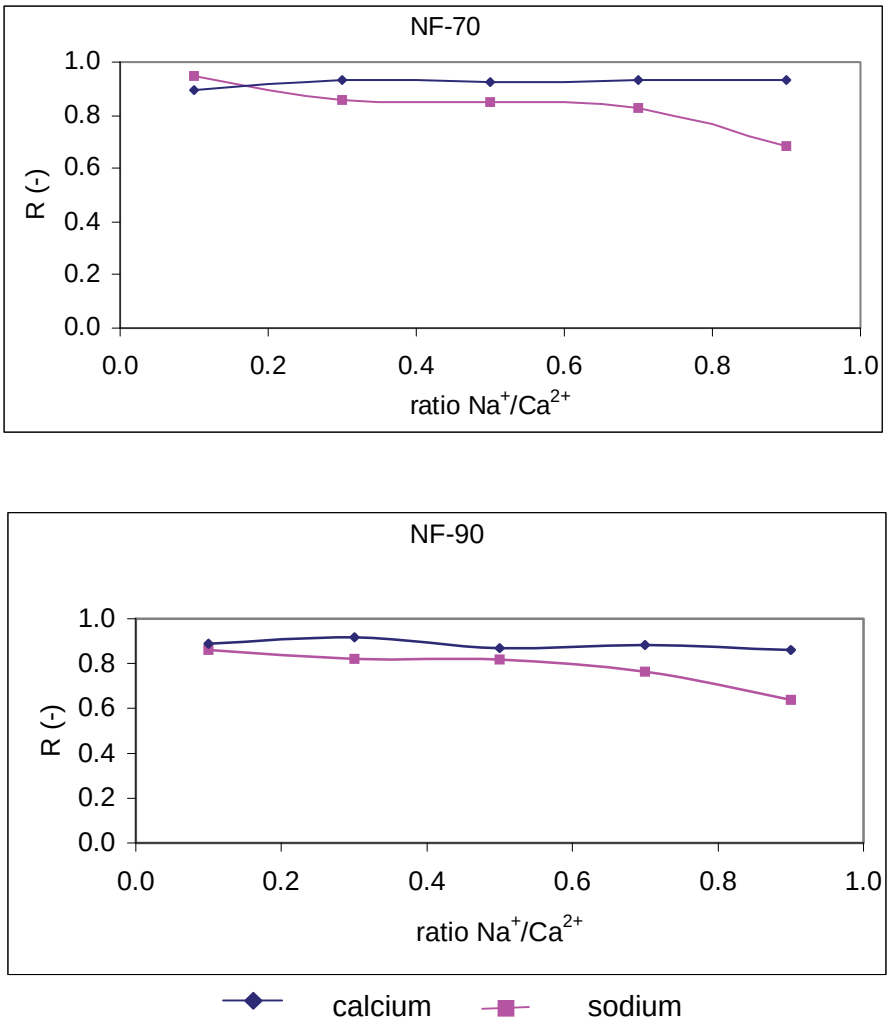


Figure 3. 10 Rejection of NaCl and $CaCl_2$ mixtures on 3 different membranes (pressure = 10 bar, total Cl^- concentration = 200ppm)

Retention of Na_2SO_4/Ca_2SO_4

Figure 3. 11 is a retention-ion fraction plot for the NF70, NF90 and TFC-SR membranes.

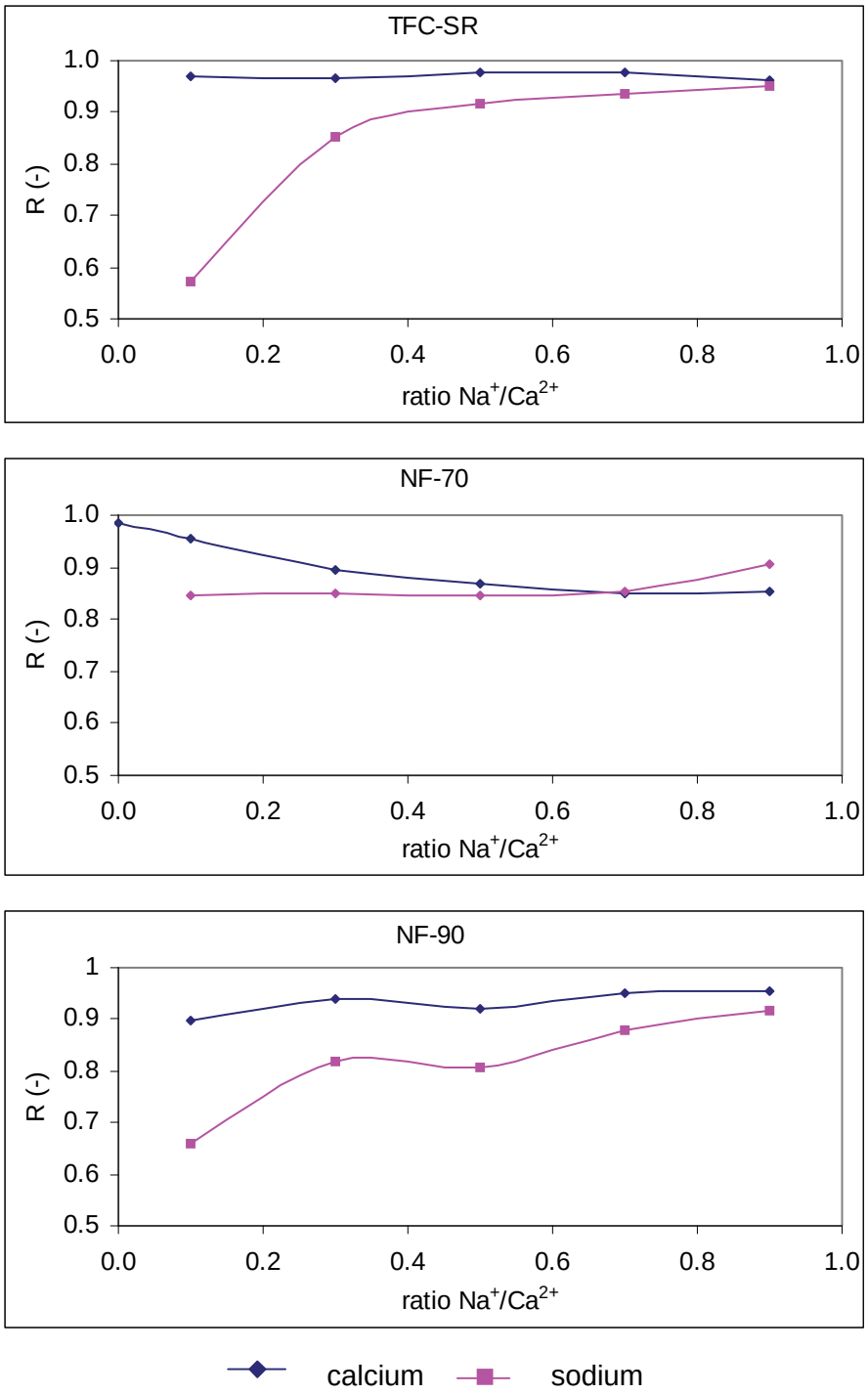


Figure 3. 11 Rejections of Na_2SO_4 and $CaSO_4$ mixtures on 3 different membranes (pressure = 10 bar, total SO_4^{2-} concentration = 200ppm)

The difference between this mixture and the one in the previous section is that the co-ion is a divalent (SO_4^{2-}). The NF70 and the NF90 show high rejection of calcium and the sulfate co-ion. The two membranes show the same behaviour as for the

$NaCl/CaCl_2$ mixtures. TFC-SR shows the same behaviour as the NF70 and NF90 also for the $NaCl/CaCl_2$ rejected ion since the ratio of the counter-ions are similar.

Retention of $CaCl_2/CaF_2$

Mixtures of $CaCl_2/CaF_2$ were prepared with a maximum concentration of 5ppm calcium fluoride and calcium chloride due to the low solubility of CaF_2, and tested on TFC-SR. The rejections of both fluoride and chloride were high (80% and 85%, respectively) irrespective of the Cl^-/F^- ratio (Figure 3. 12).

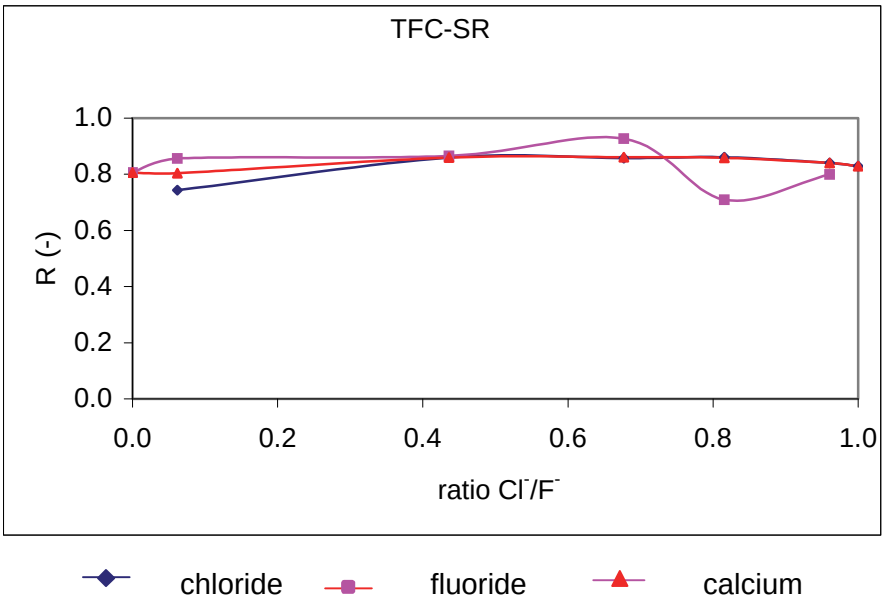


Figure 3. 12 Rejection of $CaCl_2$and CaF_2 mixtures on TFC-SR (pressure = 10 bar, F^- concentration = 5ppm)

This constant rejection may be dependent on electronegativity but not on the ion size and valence since although chloride has a larger ion radius (1.81 Å) than fluoride (1.33 Å), it is not rejected more. It could be that calcium is not transported through the membrane, but at the same time it cannot be retained without a neutralising charge. One could assume that a mixture of NaCl/NaF would probably have reduced rejections since both the counter-ions (sodium) and co-ions (fluoride and chloride) are monovalent.

3.7 Summary and conclusion

The possible occurrence of concentration polarization can be minimized by stirring at high speeds. This polarization was evident when there was no stirring or at very low stirring speeds. This results from the concentration build-up on the membrane surface. By stirring, the concentration becomes homogenous throughout the feed tank and in the membrane reactor.

All membranes in this study seem to have a negative membrane surface charge. As a result, the negatively charged co-ions, especially of high valence are easily retained by the membrane. Such retention is even more effective at high concentrations of such divalents. This has been demonstrated by single salt and salt mixture experiments. The Donnan equilibrium and exclusion plays an important role in the rejections of these ions.

All membranes, except NF90 were found to fall within the first type of the first category. For this category and type, the valence retention sequence noticed is R (1-2) > R (1-1) > R (2-1). The NF90 could not be classified in any of the categories as it rejects ions equally suggesting that the membrane is amphoteric in nature.

Studies with salt mixtures showed decreased retention for monovalent co-ions but improved retention for divalent co-ions, especially at high concentrations which will "push" more monovalents into the membrane, thereby decreasing their retention. The high valence counter-ions are generally poorly rejected but cause a better rejection of monovalent co-ions.

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4 Building and testing the cross-flow unit

The following factors were considered in designing and constructing the NF unit:

1. Capacity,
2. Operation modes and multi-functionality.

4.1 Capacity

The number of intended consumers in rural areas and the chosen water treatment process and volume product per capita needed determines the capacity. The full-site pump should be able to deliver the minimum flow pressure to counter the osmotic pressure so as to maximize performance of the commercial available spiral wound membrane module. The pump used is a B0204 monopump (from Orbit Pumps) and can deliver cross-flow of up to $0.75 m^3.hr^{-1}$ with a pump speed of $600 rev.min^{-1}$ to induce an applied pressure of 21bar over the membrane.

The valves and flow meters should be able to handle the required flow and pressure. A spring-loaded safety valve (nominal pressure 25bar, nominal diameter 40 inch) from Rolyn Instruments is used as a safety measure to prevent pressure from exceeding 25bar. When there is pressure build-up the valve will relief pressure from the line by purging the excessive feed back to the reservoir. Two 2-port electrical attenuated valves (Rolyn Instruments) are used to regulate the feed flow and induce pressure on to the membrane. The valves are placed before (flow control) and after (pressure control) the membrane. The control can be done electronically or manually and the latter option was used in this project.

The pipes and the reservoir on the other hand should be large enough to handle the pump feeding flow to the membrane without having the pump to go dry. The pressure drop in a pipe is basically a function of the Reynolds number in the pipe and the pipe roughness, expressed as the factor e/d [1]. For commercial steel the e-factor is 0.046 mm. The following equation describes pressure drop along a pipe due to friction:

$$\frac{\Delta P}{L} = \frac{4f}{d}\frac{\rho v^2}{2} \qquad \textbf{(4. 1)}$$

where *ΔP* is the pressure drop (in Pa), *L* is the length of the tube (in m), *4f* is the friction factor (equals *64/Re* for laminar flow and can be obtained from chart or from Blasius equation for turbulent flow) (-), *d* is inner tube diameter (in m), *ρ* is the density of fluid (in $kg.m^{-3}$) and *v* is the fluid velocity (in $m.s^{-1}$).

Coulson [1] suggested the friction factor *f/2* to be as a function of the Reynolds number and *e/d*. Blasius suggested a few fits, depending on the roughness of the pipe. For smooth pipes Blasius suggests:

$$\frac{f}{2} = 0.0396\,\mathrm{Re}^{-0.25} \qquad \textbf{(4. 2)}$$

for flow velocity greater than $2m.s^{-1}$, which is high. When a water stream containing small particles is fed to a NF module it will certainly plug resulting in a Reynolds number decreasing below the turbulent regime. If one wants a turbulent regime the Reynolds number should be higher than $2x10^3$ at the end of the module where the Reynolds number is defined as:

$$\mathrm{Re} = \frac{\rho v d}{\eta} \qquad \textbf{(4. 3)}$$

where *Re* is the Reynolds number (-), ρ is the feed density (in $kg.m^{-3}$), *v* is feed cross flow velocity ($m.s^{-1}$), d is the hydraulic diameter (in m), and η is viscosity ($kg.m^{-1}.s^{-1}$). If a hydraulic diameter of 0.001m and a viscosity of $0.001kg.m^{-1}.s^{-1}$ is assumed, then the cross flow velocity has to be as high as $2m.s^{-1}$. If the inner volume is occupied by the membrane and spacer, then a velocity of $2m.s^{-1}$ corresponds to a flow of $28m^3.hr^{-1}$. Even with a recovery of 0% it will be difficult to get this flow through the ½inch inlet of the module.

The difference between the calculations by Blasius and the one obtained from the chart is rather big. The table below gives the pressure drop per meter of pipe, obtained by both Blasius and Coulson [1]. Furthermore, it gives the pressure drop estimated for the entire plant, without the NF module. There are some rules of thumb given by Coulson [1], to compare for example a bend or a valve with a piece of straight pipe. In the table, 8x 90° bends and 1 valve were taken into account.

Table 4.1 Pressure drop over the system as a function of the pipe diameter used

d_o (mm)	inner surface area ($x10^{-4}$)	e/d	Re ($x10^4$)	f/2 chart	dP ($Pa.m^{-1}$)	process (bar)	f/2 Blasius	dP ($Pa.m^{-1}$)	process (bar)
12.5	1.23	0.00368	8.49	0.0023	34234	3.08	0.0032	47219	4.25
25	4.91	0.00184	4.24	0.0028	1272	0.17	0.0032	1476	0.19
40	12.6	0.00115	2.65	0.0031	136	0.02	0.0032	141	0.03

Considering the table results, one should choose 1 inch piping. Despite this fact, 1½ inch piping was chosen because the mono pump has a delivery side flanged this size. The wall thickness of the piping can be calculated. But just like there are standard sizes, there is also only standard thickness of different schedules. Schedule 25 means that the piping can withstand 25bar of pressure. The next standard is Schedule 40. Normally one would not operate the nanofiltration process above 25bar, but in case something goes wrong it is good to know, that the piping will stay intact. This is the reason why Schedule 40 piping and flanging was chosen.

4.2 Avoiding rusting of equipment

All high pressure piping, valves and fittings are of 316 steel. Fittings are flanges, which enable transportation without having to dismantle the entire installation. For the piping and flanges 316L steel was chosen because it is weld-able. The low-pressure part of the installation can be made of plastic or rubber provided that it is non-toxic. Heli-steel rubber hoses were used for this purpose.

4.3 Possibility of transporting the unit

Because the unit is to be commissioned on different kinds of borehole water, it would be the most convenient to take it on-site for pilot testing, instead of taking water to the unit site. If the entire installation could be loaded onto a bakkie or in a small truck then transportation would be possible. Furthermore, the unit has to fit through ideal entrances and exits (e.g. door), which limits the vertical size to 1.90m and the horizontal size to 0.70m. The installation can be as long as a normal transport allows. It would be possible but not necessary to put wheels on it, as the frequency of transport is limited. For the purpose of testing the unit performance, water was instead transported to the unit site.

4.4 Operation modes and parameters

4.4.1 Sand filter and microfilter

The most important reason for putting a sand filter before the nanofilter is fouling. When water feed containing small particles is fed to a NF module it will certainly foul the NF membrane. Therefore, small particles will have to be filtered out before the NF module. The reason for a microfiltration membrane pre-treatment is mainly to further deal with micro-organisms in the feed. It is intended that the microfilter permeate will feed the NF reservoir. The various operations were designed to function separately to be able to study what the single effect of one process step and all of them collectively would be. The first two pre-treatment steps were used during the rural water treatment but not when testing single salts for membrane and unit performance.

4.4.2 NF membrane operation

In commercial plants membranes are mostly placed horizontally. For compactness, it is favourable to place the membrane vertically. During operation the membrane can be placed in either ways. To make these modes possible, there has to be a flexible connection between the rigid system and the membrane module, which can handle a 25bar operating pressure. For the connection a steel-wire supported flexible hose (Bellows tubing) was used.

4.5 Process flow diagram

From the demands and operation modes described above, a PFD can be deduced. When only operation in series is required the PFD will be as illustrated in Figure 4. 1.

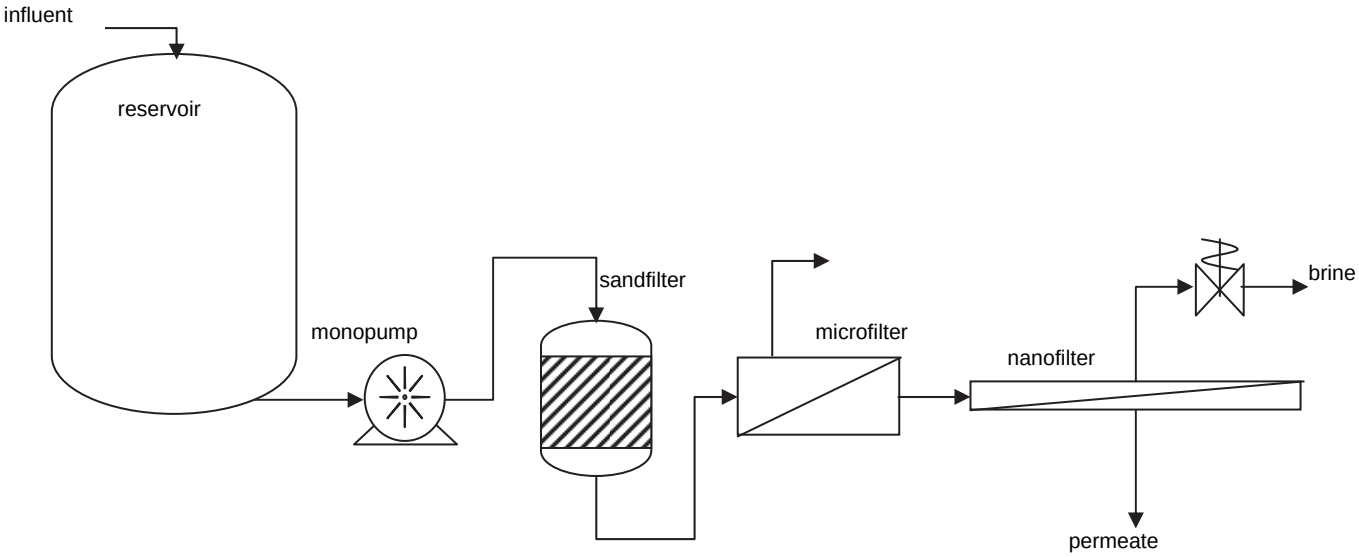


Figure 4. 1 Process flow diagram of sand filter, micro-filter and NF unit in series

However, since independent operation of the different components has to be a possible option, the PFD is in fact more complex.

4.5.1 Instrumentation and safety

The inlet pressures for the feed flow have to be measured for control purposes as well as quantification of results. Secondly the differential pressure over the membrane needs to be measured so as to protect the membrane. When this pressure rises as a result of excessive plugging, the pressure on the pump or on the membrane might cause damage to one of the two elements. Therefore the pressure gauge meter is connected to a relay switch to turn the pumps off when the differential pressure reaches a critical value.

A level control is required to ensure that the Mono pump does not run dry. Devices are available to drive a relay switch when the water level comes over or under a certain point. This relay switch stops the pumps when the reservoir is almost empty. A flow meter is required to know exactly what the feed rate is onto the membrane (cross-flow velocity). To measure the permeate flow a flow indicator was used. An alternative

measuring technique would be to use a mass balance which can be placed in line with the help of Sartorius (Sartowedge) software.

With this instrumentation a hybrid diagram of a PFD and a PID is obtained, with electronic signals shown in dotted lines (Figure 4.2).

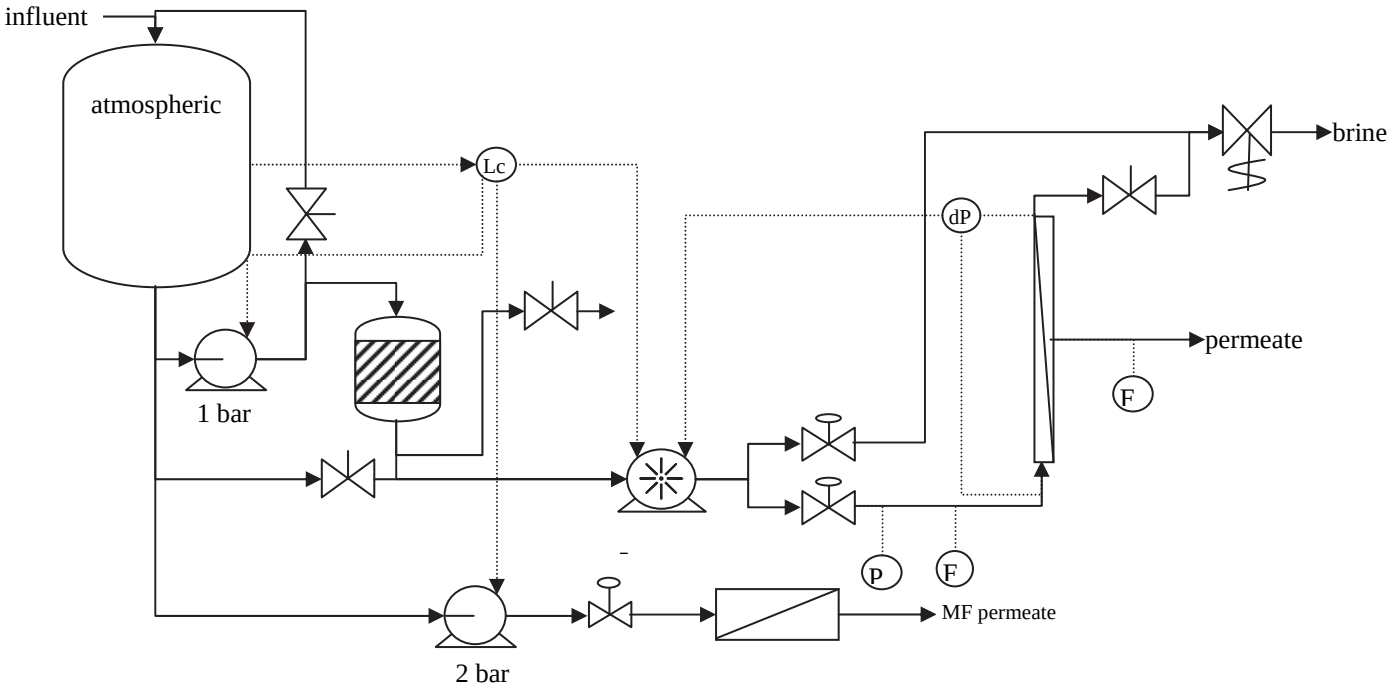


Figure 4. 2 Process flow diagram of the NF unit

4.5.2 Bypass

There are three reasons for creating a bypass from the NF module. The first is to be able to finely adjust the feed flow to the membrane. The Mono pump is indeed adjustable between several flows, but when one wants to work at a flow that is even lower than the lowest set flow, or in between two, it would be convenient if one could bypass some of the feed away from the membrane module. This has to be done making sure what the exact feed flow is. This is typically a feature that will not appear in a commercial version of this process.

The second reason for a bypass is for commissioning reasons. When starting up the plant for the first time, one can expect flow and pressure problems. If this problem occurs in the pressure-reducing valve, one can blow up the membrane. The third reason has to do with replacing a membrane. Normally one would have to shut down

and drain the entire system. Now the system can keep on running. One only has to release the pressure-reducing valve and drain the part between the two valves where the membrane is situated.

When doing duration tests, one can choose to lead both permeate and brine/bypass mixtures back to the reservoir. Then one does not waste all of the bypassed feed while ensuring constant concentrations. When using only this bypass, one has to ensure that water is not entering the NF module from the backside. Therefore a valve has to be added at the brine side of the module.

During operation, one wants to have easy access to all instrumentation and valves. It is, for example, not favourable to set a valve and have to walk back to see what the effect on the flow is. Or another example: When pressure rises too quickly, one wants to be able to switch off the process immediately. Therefore the ambition is to have all valves and instrumentation in one geometric plane. The best would be to have names on the equipment as well, so that one can see immediately what is going on.

A final diagram is as in Figure 4. 3 whilst the electrical installations for operating the pumps are given in **Appendix F**.

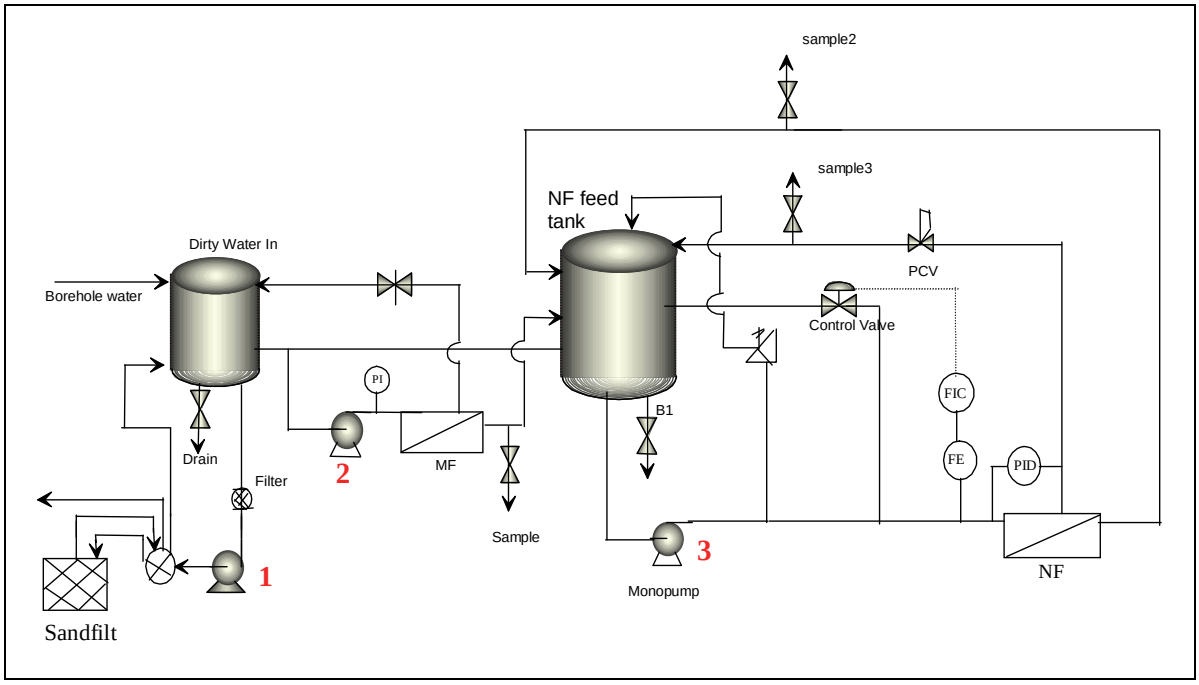


Figure 4. 3 Modified NF unit diagram

Problems experienced during operation include the danger of the pump running dry when the unit is not on auto-run. This can occur since the level controllers are not active as they are not on-line when the manual switch is used. Once dry the pump burns the rubber at its rotor, which further blocks the pipeline towards the flow controller. Such blockages cause pressure build-up between the pump and the flow meter with a risk of damage to the pump. This is to an extent relieved by the pressure relieve valve which purges excessive pressure and contents back to the reservoir (green line). Because some membranes have more water and volume flux than the others the feed flow required at a specific pressure is difficult to attain, especially at highly permeable membranes. Such membranes have high fluxes and an attempt to get to higher pressures only cause high permeates of poor quality.

4.6 Testing the unit

4.6.1 Clean water flux

The membranes were tested for clean water flux at 5 bar (Figure 4. 4).

Total volume					
Flux(solute)					
volume/(time.area)					
4.03609E-06	4.036087				
4.1548E-06	4.154796				
4.19437E-06	4.194365				
4.21415E-06	4.21415				
4.22602E-06	4.226021				
4.23393E-06	4.233935				
#DIV/0!	#DIV/0!				
4.22323E-06	4.223228				
#DIV/0!	#DIV/0!				

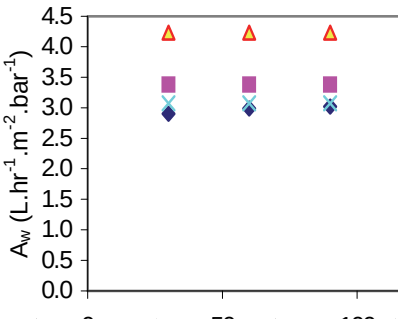


Figure 4. 4 Permeabilities of clean water on various membranes

D11 and D12 membranes yielded lower permeabilities (3.05×10^{-6} and 3.39×10^{-6} L.hr^{-1}.m^{-2}.bar^{-1} respectively) compared to the permeabilities attained in the dead-end module (see Table 3.2). In the dead-end mode, the water permeability in the D11 (9.21×10^{-6} L.hr^{-1}.m^{-2}.bar^{-1}) was slightly higher than that of D12 (8.79×10^{-6} L.hr^{-1}.m^{-2}.bar^{-1}). The two values are however, well within the range of those for NF90 and CTC1 (3.10×10^{-6} and 4.3×10^{-6} L.hr^{-1}.m^{-2}.bar^{-1}, respectively), the values are equivalent to those

when used in the dead-end mode. It is not clear why a deviation in the D11 and D12 water permeabilities for the two modes of operation were obtained.

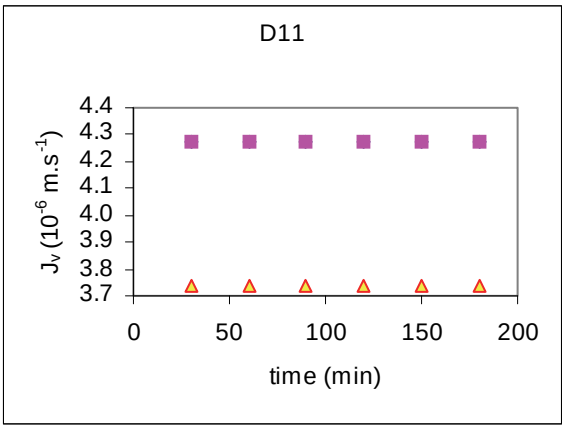
4.6.2 Single salt retention and volume flux

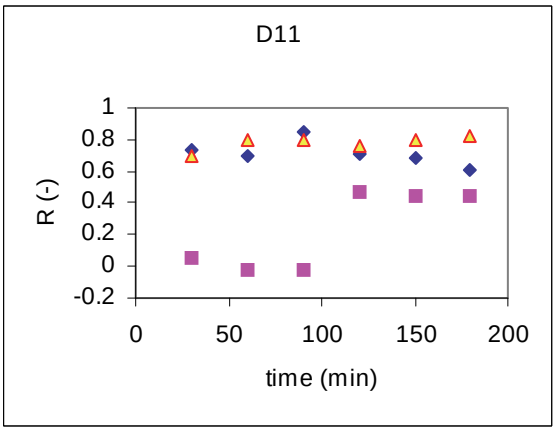
20ppm salt solutions of NaF (as F^-), $NaNO_3$ (NO_3 as N) and MgSO4 (SO_4^{2-}) were prepared and investigated for rejection on D11, D12, NF90 and CTC1 2540 membrane elements. The cross-flow unit was run for 3 hours for every salt and membrane, and samples were taken every 30 minutes for ion analysis (Figure 4.5).

The volume flux of $NaNO_3$ is about $5.0x10^{-6}$ $m.s^{-1}$ for the D11, D12 and NF90 membranes and ~$8.0x10^{-6}$ $m.s^{-1}$ for CTC1 membrane. This flux is comparable to those of studies on dead-end mode. The rejections of nitrate ranged between 30 and 50% (for all membranes). The lowest rejection on CTC1 are contrary to its performance during dead-end studies. No negative rejections were observed.

The volume flux (J_v in $m^3.m^{-2}.s^{-1}$) of NaF is $4–6x10^{-6}$ $m.s^{-1}$ on all membranes, and is comparable to the volume fluxes obtained during dead-end studies. The rejection on the membranes varies considerably and is higher for D11 (60%) with D12 the second highest (~45%). NF90 and CTC1 have the lowest fluoride retention (24 and 31%, respectively).

Sulfate volume flux was in the same order as fluoride and nitrate for all membranes. The rejection is however higher than the two mentioned salts (70–80%). This high rejection of sulfate confirms the findings obtained from the dead-end studies.





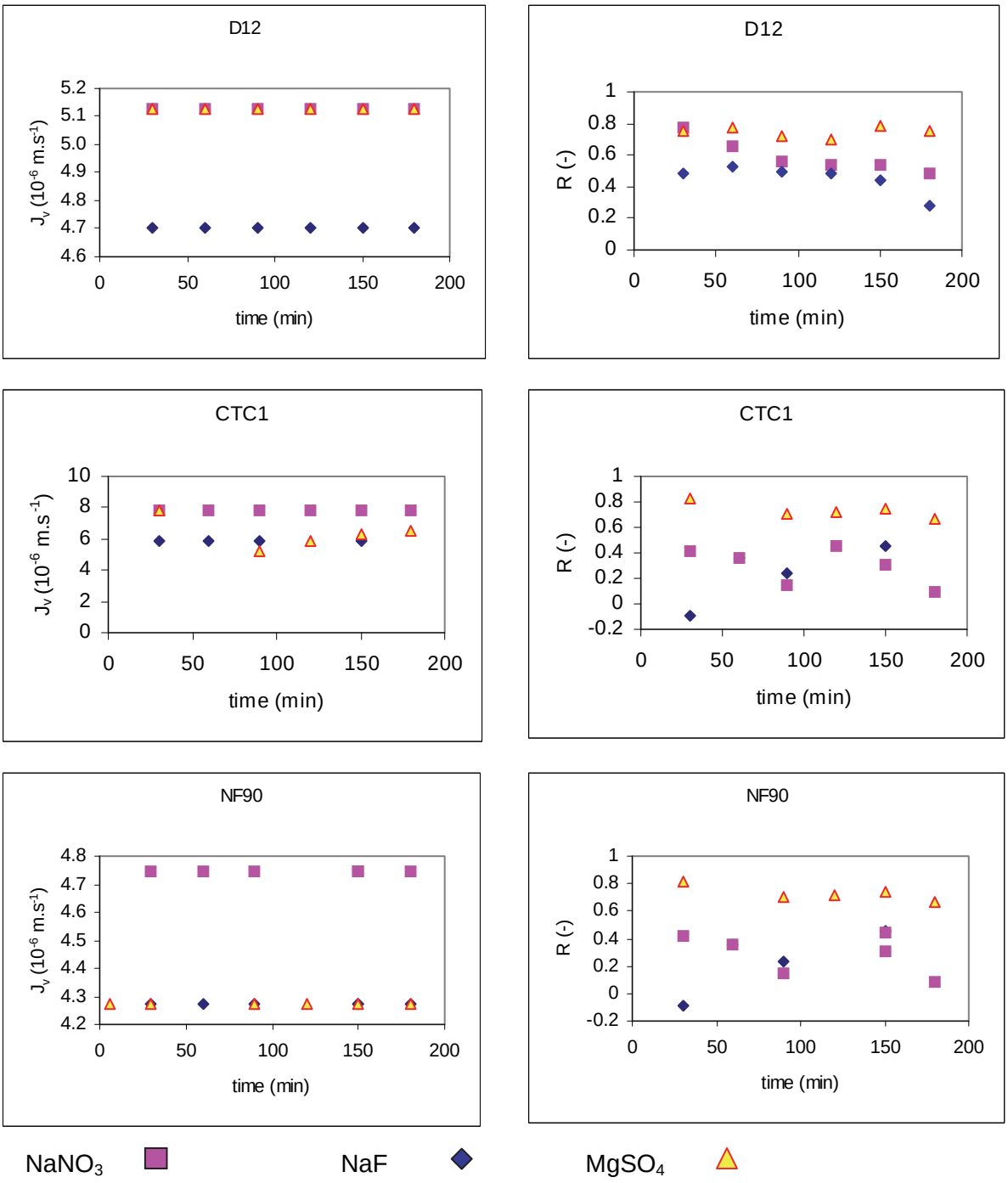


Figure 4. 5 Volume flux and retention coefficient of various salts on various membranes

To summarize, the selected membranes show good rejections for divalent sulfate and poor (up to 50%) for monovalent fluoride and nitrate. This trend is typical of NF membrane processes in which monovalents are not completely rejected as opposed to multivalents, which are highly rejected.

1. Coulson and Richardson's Chemical Engineering, volume 6, second edition, R.K. Sinnott; 1993, Butterworth-Heinemann, Oxford

5 Treatment of rural water

The levels of nitrate and fluoride are high in the rural water of some parts of the North West Province. This water is however ideally suited for this study and was used in an attempt to remove the nitrate and fluoride concentrations to acceptable or recommended levels by nanofiltration membrane processes. Other chemical components including sulfate, chloride, copper, total hardness (TH), and total dissolved solids (TDS) were also monitored. The sampled water was also classified in terms of its quality for domestic use with the help of colour coding.

5.1 Pollution and its effect

The management of water use and reuse is made critical by the extensive agricultural practices (e.g. livestock and crop farming), industrial activities (e.g. gold and platinum mining), lack of proper sanitation and geohydrochemical influences. The poor quality of the water available for rural domestic use is of concern. Sadly, however, this pollution goes unchecked, or is minimally monitored in many towns.

Nitrate, which has harmful biological effects when converted to nitrite, has its many sources of pollution from human waste (especially due to the use of pit latrines in South African rural areas), animal waste (due to heavy cattle farming), industrial waste (e.g. pesticides, food processing, munitions and some polyresin facilities), spills of nitrogenous compounds, and septic tanks. The most harmful effect of nitrate pollution is *methemoglobinaemia* (“blue baby syndrome”) in infants and ruminants. Also, in the nitrogenous environment and under favourable conditions, algae may grow rapidly if uncontrolled, with subsequent clogging of valves, pipelines, sprinklers and filtering equipment, resulting in high maintenance costs.

High fluoride levels are found around Pilanesberg of the North West Province and around some parts of the Limpopo Province as fluor-deposit in soil and rocks [1, 2]. Fluoride from minerals and in geochemical deposits is released into the subsoil water sources (aquifers) by the slow natural degradation of fluorine contained in the rocks [3]. Its presence in the groundwater is pH dependent as it only leaches under acidic conditions. Its harmful effects include skeletal and dental fluorosis characterized by hardening of skeletal joints and/or mottling (staining) of the teeth.

5.2 Experimental

Sampling was done over a two-year period during two different (wet and dry) seasons (equivalent to a total of 4 sampling opportunities) at numerous locations within the North West Province (Table 5. 1). Samples were collected in the beginning and middle of both the dry and wet seasons. The dry season is characterized by high temperature with very little or no rain, normally at the beginning of spring (from September to October). As such, not much seepage of pollutants to the groundwater is expected during this season. Chemical compositions during this season are therefore expected to be mostly influenced by the rock composition of the aquifers (geohydrochemical factors). Furthermore, the surface water as well as most of the streams have run dry or have low water content. As a result, chemical components might concentrate, as the solute water decreases.

The wet season is characterized by heavy rains (from December to April). During this period, aquifers are recharged and a lot of chemical seepage can be expected with subsequent increase in, or dilution (leaching) of, the already present chemical components. For surface water however, dilution of chemical components is expected. The areas or locations mentioned in Table 5. 1 were sampled and monitored for nitrate (NO_3-N), fluoride (F^-), sulfate (SO_4^{2-}), chloride (Cl^-), total hardness (Ca^{2+} and Mg^{2+} as $CaCO_3$), copper (Cu^{2+}), total dissolved solids (TDS) and pH.

Sampling steps were adapted from the protocols as outlined in the Hach DR/890 manual which adheres to the sampling, storage and analysis specifications according to the US Environmental Protection Agency. Water quality classification is done in line with the SA Bureau of Standards (SABS) "*Specifications for water for domestic supplies*" (SABS 241, 1998) [4] and the Department of Water Affairs and Forestry's "*Quality of domestic water supplies* "[5].

Table 5. 1 List of locations where water samples were collected

Sample name and location		Sample number	Source type	Locality description
Klerksdorp region	Mooi River	1	River	River flowing through the sporting fields of the University, from Potch dam.
	Potch University	2	Groundwater	Borehole within the University terrain, used for irrigation.
	Boitshoko School	2a	Groundwater	Borehole in the Ikageng semi-rural area.
	Sarafina	2b	Groundwater	Borehole in the Ikageng rural area, new settlement.
	Haaskraal	3	Groundwater	Cattle and maize farm with about 10 family units.
	Taaiboschspruit	4	Spring	Holiday resort. Dominated by different species of birds.
	Vaal River	6	River	Sampled downstream of the gold mines. Also tourist destination.
Koster region	Kaallaagte1	8a	Groundwater	Domestic use by about 30 family units.
	Kaallaagte2	8b	Groundwater	Domestic use by about 30 family units.
	Rhenosterfontein	9	Groundwater	Livestock (cattle) and domestic use by about 6 scattered family units.
	Tlholego 1	10a	Groundwater	Domestic use by about 5 family units.
	Tlholego 2	10b	Groundwater	Domestic use by about 5 family units.
	Tlholego 3	10c	Groundwater	Domestic use by about 5 family units.
	Tlholego 4	10d	Groundwater	Domestic use by about 5 family units.
	Roodewal	11	Groundwater	Livestock (cattle) and domestic use by about 5 scattered family units.
Rustenburg region	Rietvlei	12	Groundwater	Around an industrial area.
	Greenside	13	Groundwater	Private borehole, near platinum mines.
	Mogwase stream	14	Stream	Stream normally with drinking cattle on site.
	Beestekraal	15	Stream	Sampled downstream the dam but closer to the communities.
	Bakgatla	20	Groundwater	Public tap.
	Lerome 1	13a	Groundwater	Public handpump for use by about 100 family units.
	Lerome 2	21	Groundwater	Private borehole.
	Lerome 3	25	Groundwater	Private borehole.
	Ledig 1	23	Groundwater	Public tap.
	Ledig 2	22	Groundwater	Public tap.
	Lefaragatlhe	24	Groundwater	Private tap.
Mafikeng	Lichtenburg	5	Groundwater	Irrigation water. Lime plant in the vicinity.
	Mmabatho	16	Groundwater	Private borehole.
	Letlamoreng 1	17	Groundwater	Tourist and holiday resort. Cattle and holiday makers around the dam.
	Letlamoreng 2	18	Spring	Tourist and holiday resort. Cattle and holiday makers around the dam.

The sampling and storage procedure was as follows:

- Clean, acid washed plastic (PTFE) sample holders were used for every sample (100ml–5000ml);
- Before sampling, the stopper and holder were rinsed a number of times with sample water;
- For surface water, the holder was dipped, cautiously not to disturb the bottom sediments, in the water before it was capped;

- ❖ For boreholes (mechanical and hand pumps), the pump was operated for some time with subsequent bottle rinsing before sampling;
- ❖ Samples from running streams were taken as close as possible to the middle of the stream (crocodiles were friendly!);
- ❖ Electrical conductivity and pH were measured on site.

A wide distribution of sampling was necessary to elucidate the water quality status in the Province. Both the south-east and the north-west of the Province were not sampled due to travelling constraints. The sample points were grouped into four regions (Klerksdorp, Rustenburg, Koster and Mafikeng Regions). Groundwater was the main sampling target although streams, rivers and catchments (or springs) were also sampled.

The following instruments were used for the sample analysis:

- ❖ An ion chromatograph (IC) with Waters column IC-Pak anion HC, Model 430 conductivity detector and Model510 pump for the analysis of NO_3^-, Cl^- and SO_4^{2-};
- ❖ An atomic absorption analyser (AA Varian 250+) was used for the analysis of Ca^{2+} and Mg^{2+};
- ❖ A colorimeter of Hach DR/890 was used for the analysis of NO_3-N, F^-, Cl^-, SO_4^{2-} and total hardness (as $CaCO_3$);
- ❖ A pH301 from Hanna Instruments was used for pH detection and
- ❖ A Hanna Instruments' HI 9032 conductimeter was used for the conductometric (and TDS) determination.

The complete sampling data is shown in **Appendix G**, including tables of average and maximum chemical components (**Appendices H** and **I**). A combined graphical presentation is shown in **Appendix J**.

5.3 Water classification methodology

The sampled water was classified specifically for domestic use in terms of drinking (health and aesthetic), food preparation, bathing and laundry for every concentration of pollutant analysed. In Table 5. 2 the structure of the classification system with description of the effects of different classes of water on various domestic uses is shown. Such an approach gives an idea of how suitable water is for these various domestic uses.

Table 5. 2 Colour code classification and effects of components in water intended for domestic use [5]

Class	Colour	Water quality	Effects
0	Blue (B)	Ideal	**Drinking health**: no effects, suitable for many generations. **Drinking Aesthetic**: water is pleasing. **Food preparation**: no effects. **Bathing**: no effect. **Laundry**: no effects
1	Green (G)	Good	**Drinking health**: suitable for lifetime use. Rare instances of sub-clinical effects. **Drinking Aesthetic**: some aesthetic effects may be apparent. **Food preparation**: suitable for lifetime use. **Bathing**: minor effects on bathing or on bath fixtures. **Laundry**: minor effects on laundry or on fixtures.
2	Yellow (Y)	Marginal	**Drinking health**: may be used by the majority of individuals of all ages but may cause effects in some individuals in sensitive groups. Some effects possible after lifetime use. **Drinking Aesthetic**: possible taste and appearance are noticeable. **Food preparation**: may be used without health or aesthetic effects by the majority of individuals. **Bathing**: slight effects on bathing or on bath fixtures. **Laundry**: slight effects on laundry or on fixtures.
3	Red (R)	Poor	**Drinking health**: poses a risk of chronic health effects, especially in babies, children and the elderly. **Drinking Aesthetic**: bad taste and appearance may lead to rejection of the water. **Food preparation**: poses a risk chronic health effects, especially in the children and the elderly. **Bathing**: significant effect on bathing or on bath fixtures. **Laundry**: significant effect on laundry or on fixtures.
4	Purple (P)	Unacceptable	**Drinking health**: severe acute health effects, even with short-term use. **Drinking preparation**: taste and appearance will lead to rejection of water. **Food preparation**: severe acute health effects, even with short-term use. **Bathing**: serious effects on bathing or on fixture. **Laundry**: serious effects on laundry or on fixtures.

In Table 5. 3 [5] selected concentration ranges used for colour classification are given.

In the long run, this classification helps decision-making regarding water quality management. Quality of water does not suddenly change from good to bad or worse when a specific or given chemical concentration is exceeded, implying that it will still

be usable for some time before it will have unbearable effects. Classification is done by use of a colour coding range from ideal to totally unacceptable water quality.

Table 5. 3 Concentration ranges of various chemical components used in water colour classification

Range →		<450	450–1000	1000–2400	2400–3400	> 3400	-
Total dissolved solids ($mg.L^{-1}$)	Drinking (H)	B	G	Y	R	P	-
	Drinking (A)	B	G	Y	R	P	-
	Food preparation	B	G	Y	R	P	-
	Bathing	B	B	B	G	Y	-
	Laundry	B	B	G	Y	R	-
Range →		< 0.7	0.7 – 1.0	1.0 – 1.5	1.5 – 3.5	> 3.5	
Fluoride ($mg.L^{-1}$)	Drinking (H)	B	G	Y	R	P	-
	Drinking (A)	B	B	B	B	B	-
	Food preparation	B	G	Y	R	P	-
	Bathing	B	B	B	B	B	-
	Laundry	B	B	B	B	B	-
Range →		< 6	6 – 10	10 – 20	20 – 40	> 40	-
Nitrate ($mg.L^{-1}$ as nitrogen)	Drinking (H)	B	G	B	R	P	-
	Drinking (A)	B	B	B	B	B	-
	Food preparation	B	G	B	R	P	-
	Bathing	B	B	G	Y	R	-
	Laundry	B	B	B	B	B	-
Range →		<100	100 – 200	200 – 400	400 – 600	600 – 1000	> 1000
Sulfate ($mg.L^{-1}$)	Drinking (H)	B	B	G	Y	R	P
	Drinking (A)	B	B	G	Y	R	P
	Food preparation	B	B	G	Y	R	P
	Bathing	B	B	B	G	Y	R
	Laundry	B	B	G	Y	R	P
Range →		< 100	100 – 200	200 – 600	600 - 1200	> 1200	-
Chloride ($mg.L^{-1}$)	Drinking (H)	B	G	Y	R	P	-
	Drinking (A)	B	G	Y	R	P	-
	Food preparation	B	G	Y	R	P	-
	Bathing	B	B	B	B	B	-
	Laundry	B	G	Y	R	P	-

H = health, A = aesthetic. B = blue (ideal), G = green (good), Y = yellow (marginal), R = red (poor), P = purple (completely unacceptable)

5.4 Water sampling and monitoring

Samples were collected during the beginning and middle of the dry and wet seasons to cover the full range of possible conditions. The samples collected during the wet season (middle rainy season (MRS) and beginning rainy season (BRS)) indicate that the chemical components (pollutants) were well below their recommended limits (Figure 5. 1). This means that both the groundwater and surface water components are diluted by continued water recharge resulting in improved ground water quality.

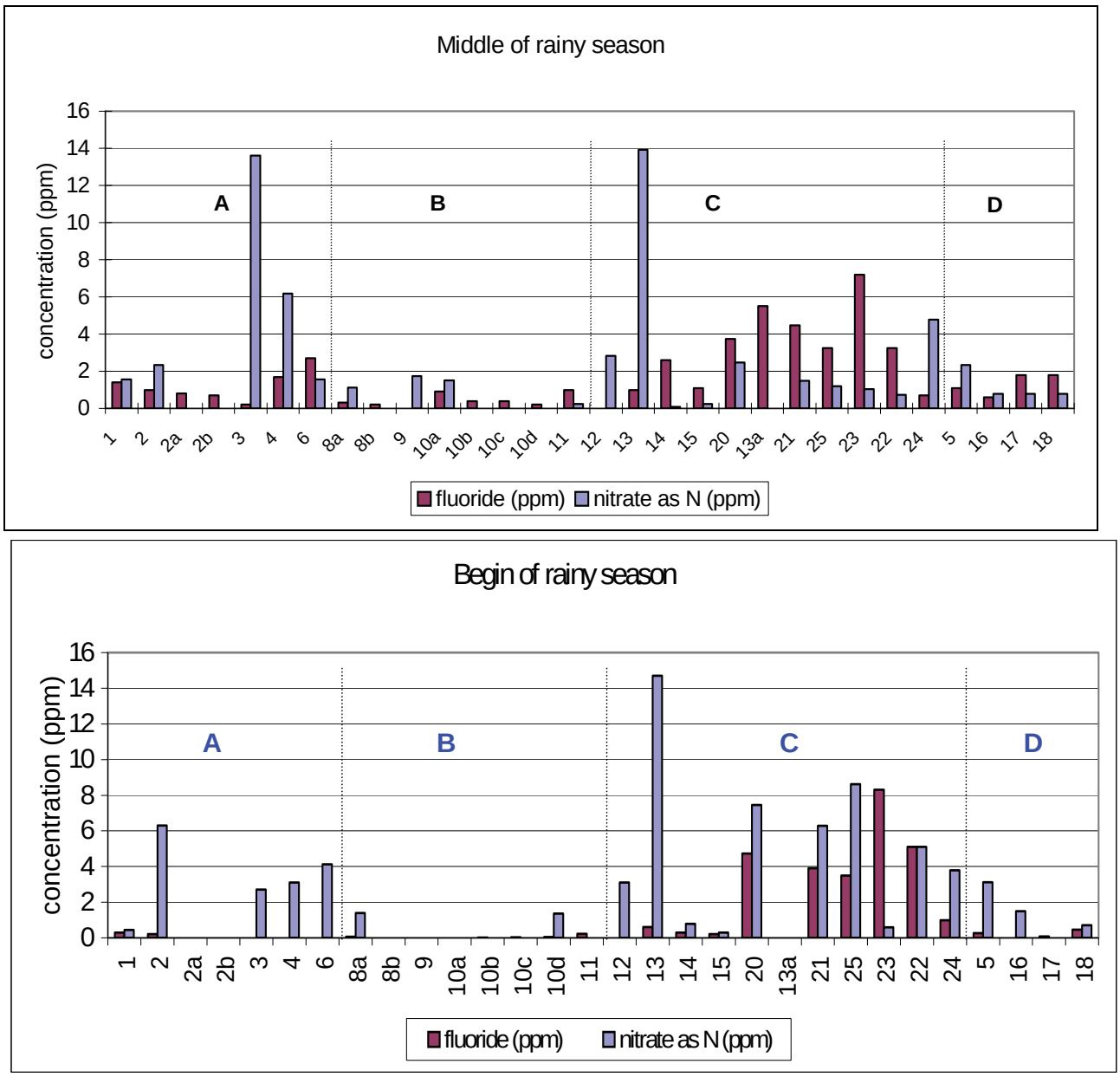
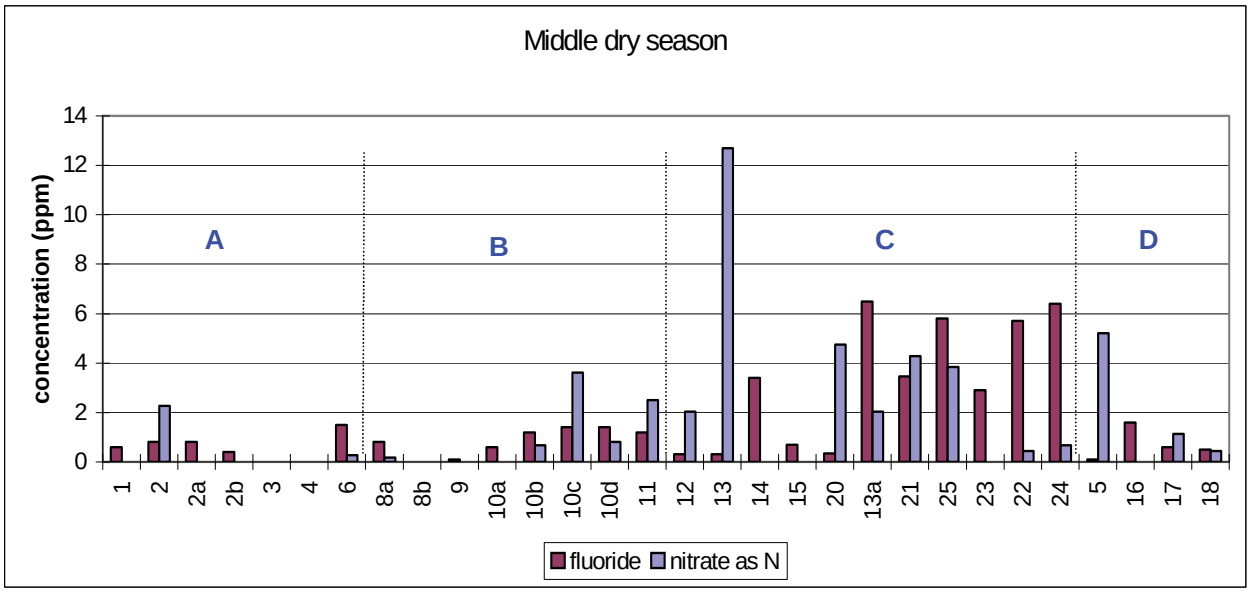


Figure 5. 1 Selected chemical component concentrations recorded for various sampling sites during the wet season (A = Klerksdorp, B = Koster, C = Rustenburg, and D = Mafikeng Regions. x-axis = sampling points)

When sampled immediately after the first rainfall (BRS), increased concentrations of chemical components are observed although not as high as those observed during the dry seasons (beginning dry season (BDS) and middle dry season (MDS)) as presented in Figure 5. 2.



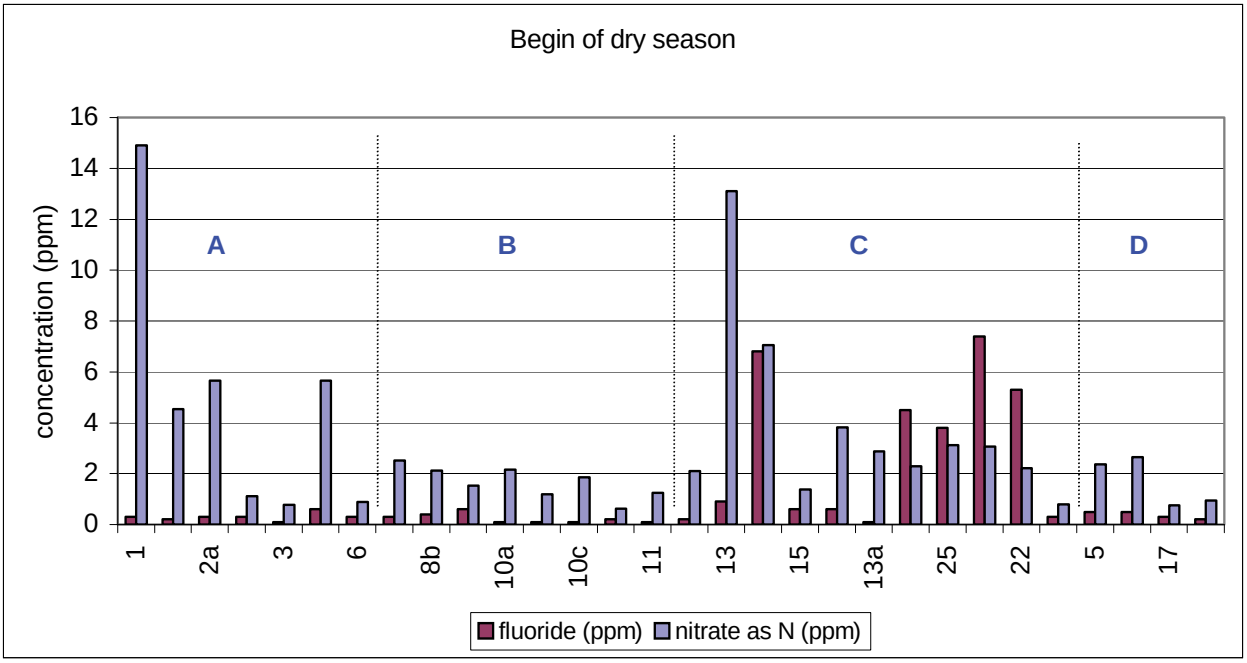


Figure 5. 2 Selected chemical component concentrations recorded for various sampling sites during dry seasons (A = Klerksdorp, B = Koster, C = Rustenburg, and D = Mafikeng Regions. x-axis = sampling points)

The nitrate concentration is low in groundwater (sample points 2, 5, 9–13, 16, 18–25) during the dry season but increases immediately after the first rains. This is probably due to seepage/leaching of nitrate that was adsorbed by the soil. Also, during dry seasons, farming activities are low and any nitrate pollutants (and other ions) are held in the soil. These nitrates will enter the aquifers during the first rain, leading to an increase in concentrations (Figure 5. 2).

Sulfate concentrations (see **Appendix G – J**) seemed to be low during wet seasons but slightly higher during dry seasons, increasing further immediately after the first rainfalls as it is leached from the soil into the aquifers. Fluoride is within acceptable limits within all regions except the Rustenburg region (marked C) where it is at unacceptable levels throughout the year.

Figure 5. 3 shows the graphical presentation of the average concentration of chemical components (for four sampling opportunities) in surface (sample points 1, 3, 4, 6, 14, 15 and 17) and groundwater (2, 5, 9–13, 16, 18–25).

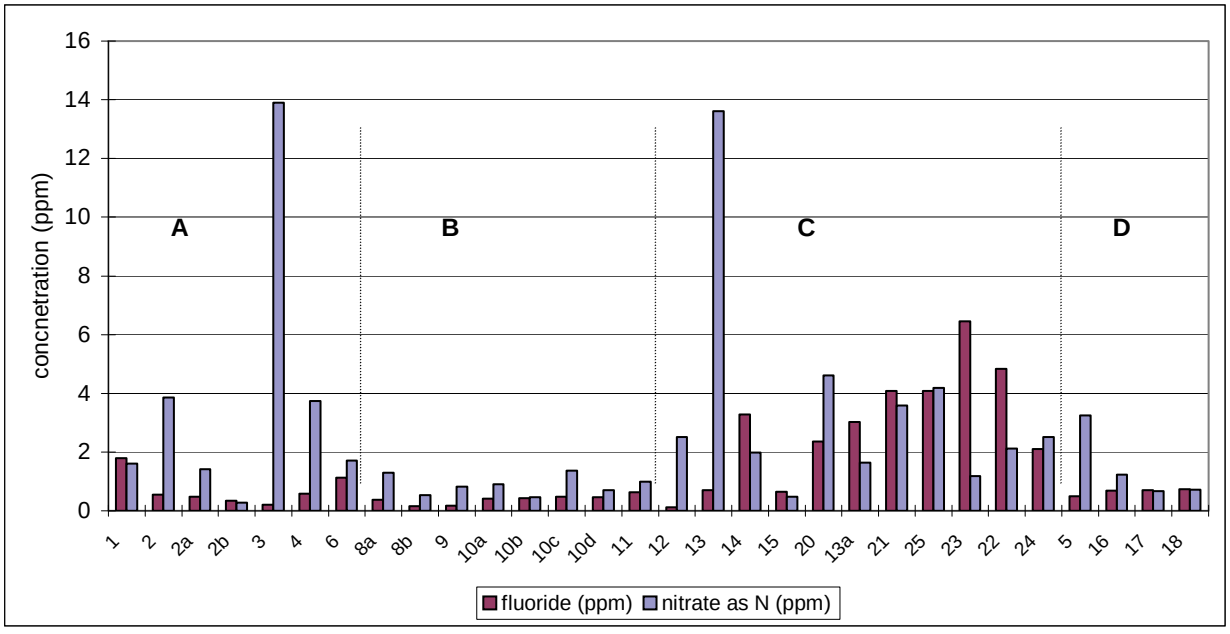


Figure 5. 3 Average chemical component concentrations recorded for various sampling sites over one year (A = Klerksdorp, B = Koster sub-, C = Rustenburg, and D = Mafikeng Regions. x-axis = sampling points)

Due to the nitrate (as nitrogen) concentration found in the private borehole (sample 13) within the Rustenburg region, the water is of marginal quality (Figure 5. 3), which gives

an adequate reason for discouraging its use (drinking, food preparation and bathing). The average total dissolved salts (TDS) within the Rustenburg region (sample 14 and 15) are also unacceptably high and making domestic uses (drinking, food preparation, bathing and laundry) risky. This necessitates a strong education campaign regarding water quality and safety in these rural areas, as well as low-cost purification systems on-site that are effective and easy to operate.

The Klerksdorp (marked A), Koster (marked B) and Mafikeng (marked D) regions generally have ideal water quality. In these regions the chemical components are within acceptable limits throughout the year (all seasons).

5.5 Water classification results

The water classification is done for each component at maximum and average concentrations, as presented for the Rustenburg region in Table 5. 4 and Table 5. 5, respectively. This section focuses on the Rustenburg region since it had the highest fluoride pollutant level.

Table 5. 4 The Rustenburg region water classification for maximum concentration values observed

		Sampling point										
		12	13	14	15	20	13a	21	25	23	22	24
Fluoride	Drinking (Health)	B	G	P	Y	P	P	P	P	P	P	P
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	G	P	Y	P	P	P	P	P	P	P
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Nitrate	Drinking Health	B	Y	G	B	G	B	G	G	B	B	B
	Drinking Aesthetic	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	Y	G	B	G	B	G	G	B	B	B
	Bathing	B	G	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Sulfate	Drinking Health	B	B	Y	G	G	B	B	B	B	B	B
	Drinking Aesthetic	B	B	Y	G	G	B	B	B	B	B	B
	Food preparation	B	B	Y	G	G	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	Y	G	G	B	B	B	B	B	B

B = ideal, G = good, Y = marginal, R = poor, and P = unacceptable. TDS = total dissolved solids.

As previously demonstrated (Table 5. 2), blue (B) represents ideal water quality, green (G) good water quality, yellow (Y) marginal water quality, red (R) poor water quality and purple (P) unacceptable water quality. As can be seen from the classification by maximum concentration, fluoride levels for many sample points in this region are at an unacceptable level and are a health risk when this water is used for drinking and food preparation. All nitrate and sulphate levels were at an acceptable level.

Table 5. 5 The Rustenburg region water classification for average concentration values observed

		Sampling point										
		12	13	14	15	20	13a	21	25	23	22	24
Fluoride	Drinking (Health)	B	G	R	B	R	R	P	P	P	P	R
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	G	R	B	R	R	P	P	P	P	R
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Nitrate	Drinking (Health)	B	Y	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	Y	B	B	B	B	B	B	B	B	B
	Bathing	B	G	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Sulfate	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B

B = Blue, G = Green, Y = Yellow, R = Red, and P = Purple. TDS = total dissolved solids.

Most of the highly affected sample points are from the Lerome and Ledig rural communities. It is not surprising that many people from these regions have mottling teeth. It should be noted that at sample points 14 (Mogwase) and 15 (Beestekraal), water was taken from the streams flowing through these rural areas. There was no evidence that residents were extracting water directly from these streams (points 14 and 15) for domestic use. As a result, the recorded nitrate and sulfate levels may not be of threat to the residents.

The remaining water quality classifications from all the other areas are presented in **Appendix K** (maximum) and **Appendix L** (average) for the Klerksdorp, Mafikeng and Koster regions. In **Appendix M** the classification of the Mafikeng region's water is presented.

Four sites (sampling points 14, 20, 13a and 24) have poor levels of fluoride for drinking (health) and food preparation whilst another four sites (21, 25, 23 and 22) show unacceptable levels for the same practices. There seems to be no immediate threat at other sites (including from streams). Although this is the case, care should be exercised, as the water quality is often less than ideal. The high fluoride concentration within the Mafikeng region, which was recorded at the Letlamoreng dam (sample 17 and 18) and a private borehole (sample 16) is of concern since the region was never associated with fluoride pollution before. The total dissolved solids (TDS) also have the potential to be at unacceptable levels at the Letlamoreng dam (sample 18). The Klerksdorp regions in general have good water quality although, in some cases, not ideal. The only concern is the two streams/river at Orkney (Vaal River, sample 6) and Taaiboschspruit (sample 5), which had high fluoride concentrations. The Orkney Vaal, (Vaal River, sampled downstream of the gold mines), is average, showing acceptable TDS and sulfate levels, although higher than elsewhere in the region.

5.6 Water treatment

Nanofiltration

In the previous section, a number of membranes were tested to evaluate their ability to reject single salts. This section investigates the possible behaviour of NF membranes during rural water treatment. The samples for nanofiltration studies were collected at Lerome, Ledig (both of greater Rustenburg region), Haaskraal and Vaal River (both of Klerksdorp-region). The sampled water consists of numerous salts with sometimes complex ionic combinations which makes these samples more complex than the single or binary salt mixtures used in the laboratory during the characterization work [6].

5.7 Dead-end studies

The water samples were nanofiltered through the NF membranes at a trans-membrane pressure difference of 20bar without any pre-treatment. The concentration of each component (pollutant) in every sample was monitored for feed, permeate and brine chemical composition with subsequent calculation of the retention coefficient using Equation 5.1:

$$R = \left(1 - \frac{C_p}{C_f}\right) 100\% \qquad \textbf{(5. 1)}$$

where C_p and C_f are the permeate and feed concentrations (in ppm), respectively.
The unit was stirred at the maximum possible speed to minimize concentration polarization and to hinder possible fouling. The pH of the samples was not adjusted and the experiments were carried out at ambient temperatures. Ion chromatography, atomic adsorption, conductimeter and a colorimeter were used for concentration monitoring.

Selected rural groundwater sites (sample 13a, 22, 3) and the stream water of the Vaal River (sample site 6) were chosen for treatment by nanofiltration. Site 3 was chosen because it is in a farming area (cattle and maize farm), is in the proximity of the Potchefstroom University and showed high nitrate levels. Sites 22 and 13a were chosen because they are in the rural Rustenburg area and have higher levels of fluoride and nitrate than any other sampled area. Site 6 was chosen because the sampling point in the Vaal River is downstream from the gold mines, and has low nitrate and fluoride levels but high sulfate levels.

In the following sections, results of the treatments of the various water samples are presented.

5.7.1 Lerome (sample 13a)

According to Figure 5. 4, improvement of the Lerome rural water was achieved with all the tested membranes (D11, D12, NF90, NF70, TFC-S, TFC-SR, TFC-ULP and CTC1). Sulfate was retained (up to 100%) by the membranes (Figure 5. 4) confirming

that the membranes are negatively charged as characterized [6]. Total hardness (TH) is poorly rejected by D11 and CTC1 (about 20%) and well rejected by all other membranes. Total dissolved solids (TDS) is moderately rejected by all membranes (30–60%).

Monovalents (fluoride and nitrate) showed negative rejection on some membranes. These monovalent co-ions are transported through the membrane in the presence of high valence co-ions. Such negative rejections are due to increased transport induced by the high valence co-ions, causing the permeate concentration to be higher than the feed concentration. For the Lerome rural water (containing high levels of fluoride) negative fluoride rejection is, in particular, observed for the TFC-SR and D12 membranes whilst D11, NF90 and CTC-1 show poor rejections (5–20%). Good fluoride retentions are recorded only for the membranes TFC-S (~70%), and NF70 (~75%).

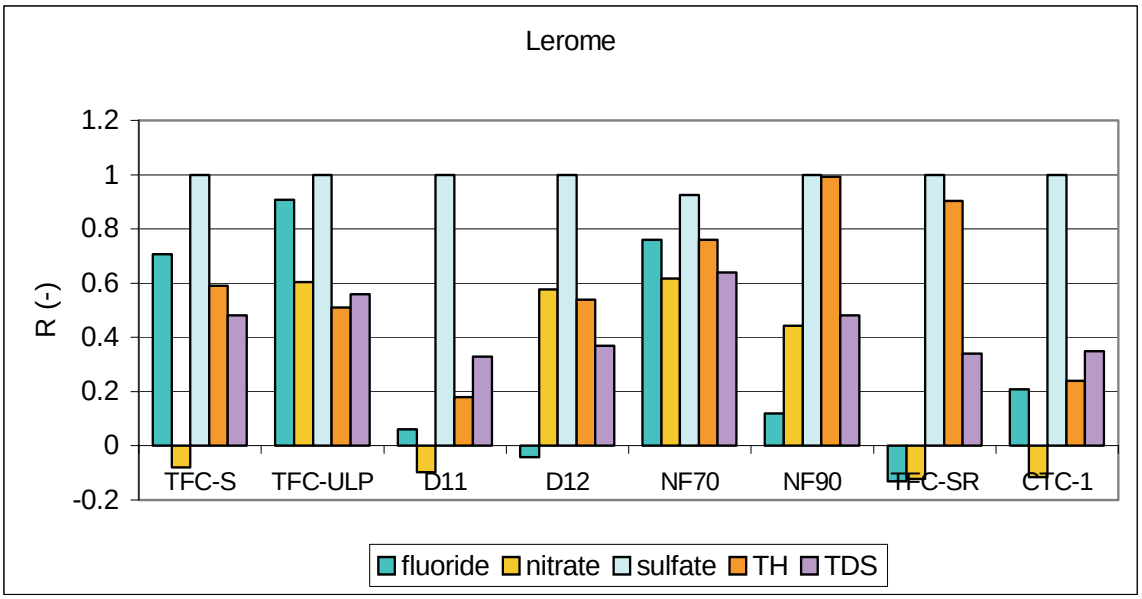


Figure 5. 4 Retention coefficient of various NF membranes on the treatment of the Lerome groundwater (Pressure = 20 bar, temperature = 20°C. x-axis = membrane types)

Nitrate is negatively rejected by TFC-SR and D12 and poorly rejected by D11, NF90 and CTC1 (1–20%). Good nitrate rejection is again observed on TFC-S (~70%), NF70 (~75%) and also TFC-ULP (~90%). Figure 5. 5 summarizes rejections for different ions and membranes used in the Lerome water treatment.

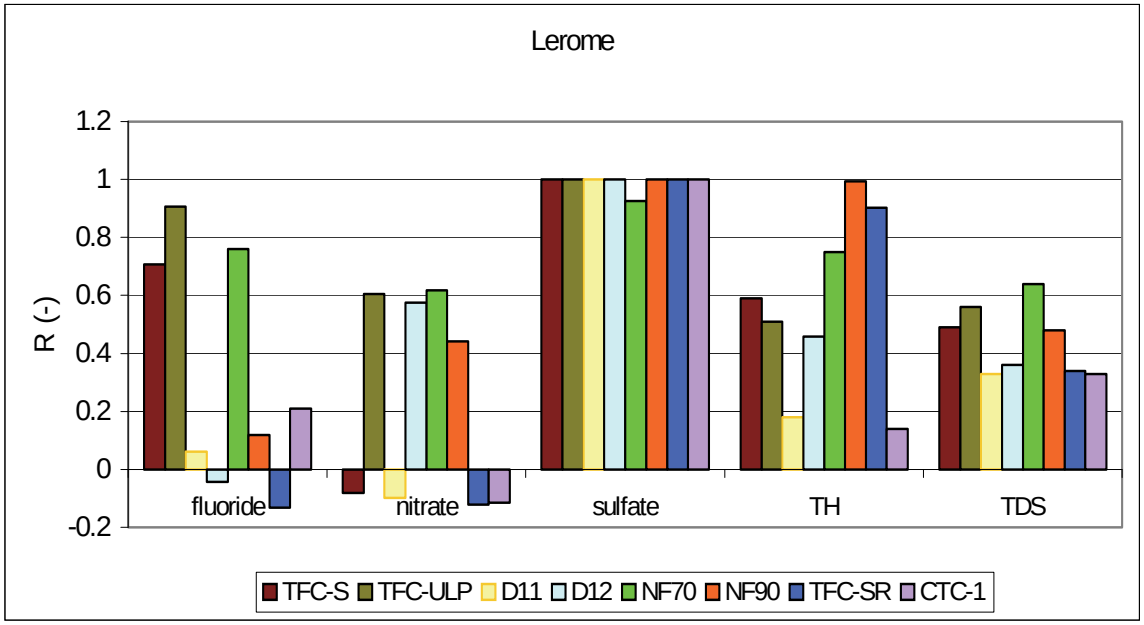


Figure 5. 5 Presentation of membrane performance for Lerome groundwater (Pressure = 20 bar, temperature = ambient)

5.7.2 Ledig (sample 23)

The efficiency of the removal of ions from the Ledig (a rural area in Rustenburg) water sample differed for varying membranes (Figure 5. 6). Sulfate rejection is excellent (>95%) whilst TH is well reduced by all membranes (60–80%) except for TFC-S and TFC-ULP. TDS is moderately rejected by all membranes (30–60%). This is comparable to the performance of these membranes for the Lerome water.

Good rejection of nitrate is attained for the Ledig rural water on TFC-S (~58%), NF90 (~70%) and NF70 (~80%) (Figure 5. 6). TFC-ULP also performed poorly, even though it showed better rejections of this anion on the Lerome rural water owing to the effect of different other ions (e.g. chloride, copper, sulfate, magnesium, etc.) in the different water sources. Fluoride levels detected in the Ledig water are as high as in the Lerome water. The rejection is negative for the NF90 and D11 (was positive for the Lerome water treatment on both membranes). Moderate fluoride rejection is attained by all other membranes (10–30%). TFC-S retains fluoride in the Ledig poorly (~15%) compared to 70% fluoride rejection observed for the Lerome water.

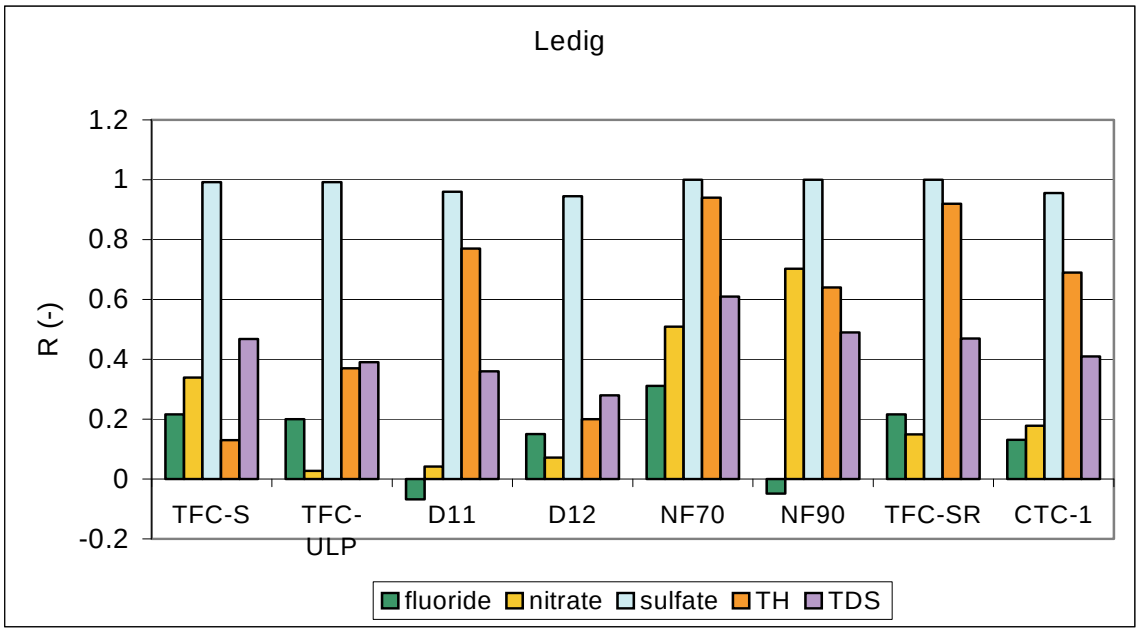


Figure 5. 6 Retention coefficient of various NF membranes on the treatment of the Ledig rural water (Pressure = 20 bar, temperature = 20^{o}C. x-axis = membrane types)

Figure 5. 7 shows the performance of different membranes in the removal of selected ionic components in the Ledig rural water.

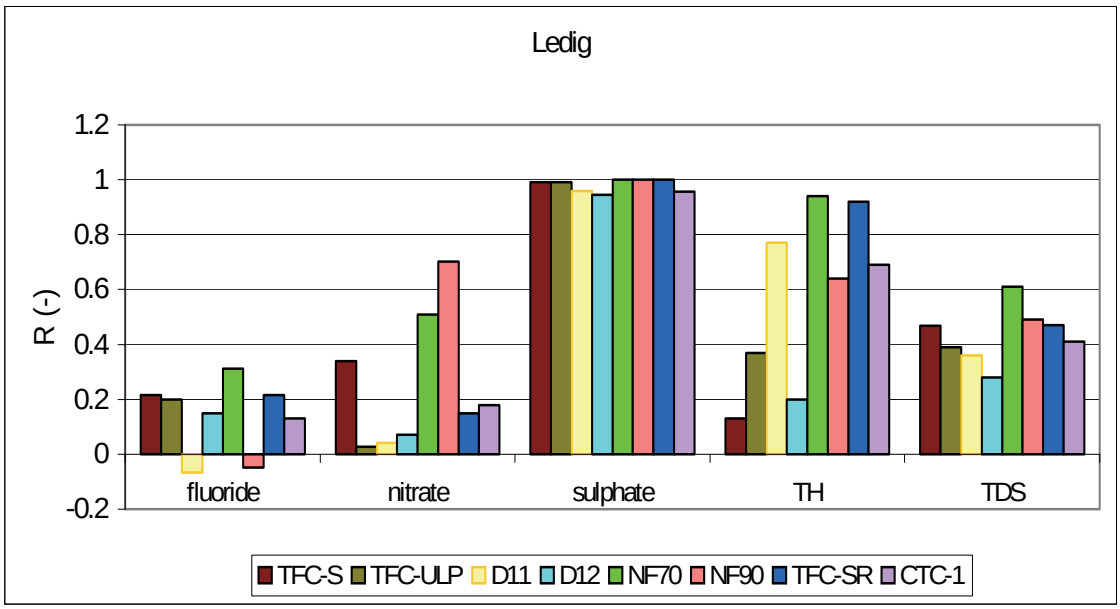


Figure 5. 7 Presentation of membrane performance on Ledig rural water (Pressure = 20 bar, temperature = ambient)

5.7.3 Haaskraal (sample 3)

Similarly, sulfate removal was excellent in the Haaskraal (cattle and maize farm) water sample (Figure 5. 8). This rejection, although not as high as in the Lerome and Ledig rural water, ranged from 90–100%. The sulfate content in this water was higher than that of Lerome and Ledig. It is not clear what causes this slight decreased rejection of sulfate. Again, the rejection of TH is high for the TFC-SR (~90%), NF70 (~85%), NF90 (~70%) and D11 (~78%) membranes. Moderate TH rejection were shown by TFC-ULP (~38%) whilst TFC-S (~9%) and D12 (~30%) showed poor rejections. TDS, like in Lerome and Ledig, is moderately rejected by all membranes.

Only TFC-ULP showed negative rejection for nitrate whilst, contrary to Lerome and Ledig, TFC-S showed improved nitrate rejection (~55%). D11, D12, TFC-SR and CTC1 all show poor to moderate nitrate rejection (1–30%). Good nitrate rejection is recorded for the NF70 and NF90 membranes (70–80%). Negative fluoride rejections are noticed for CTC-1 and NF90 membranes. TFC-S, D12, NF70 and TFC-SR rejected fluoride poorly (10–30%). Good fluoride rejection is observed for the TFC-ULP and D11 (60–70%) membranes.

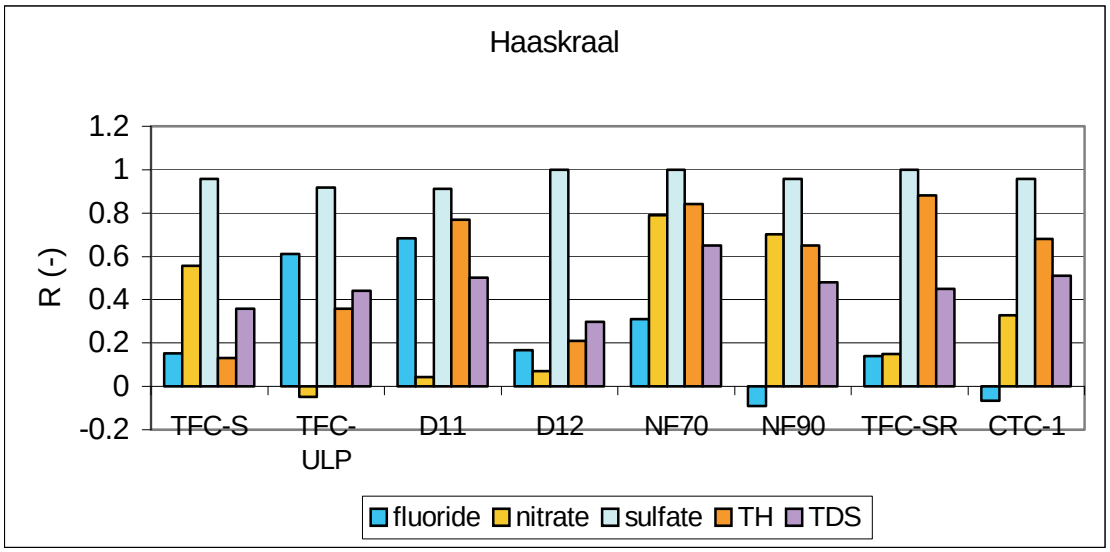


Figure 5. 8 Retention coefficient of various NF membranes on the treatment of the Haaskraal water components (Pressure = 20 bar, temperature = 20^{o}C. x-axis = membrane type)

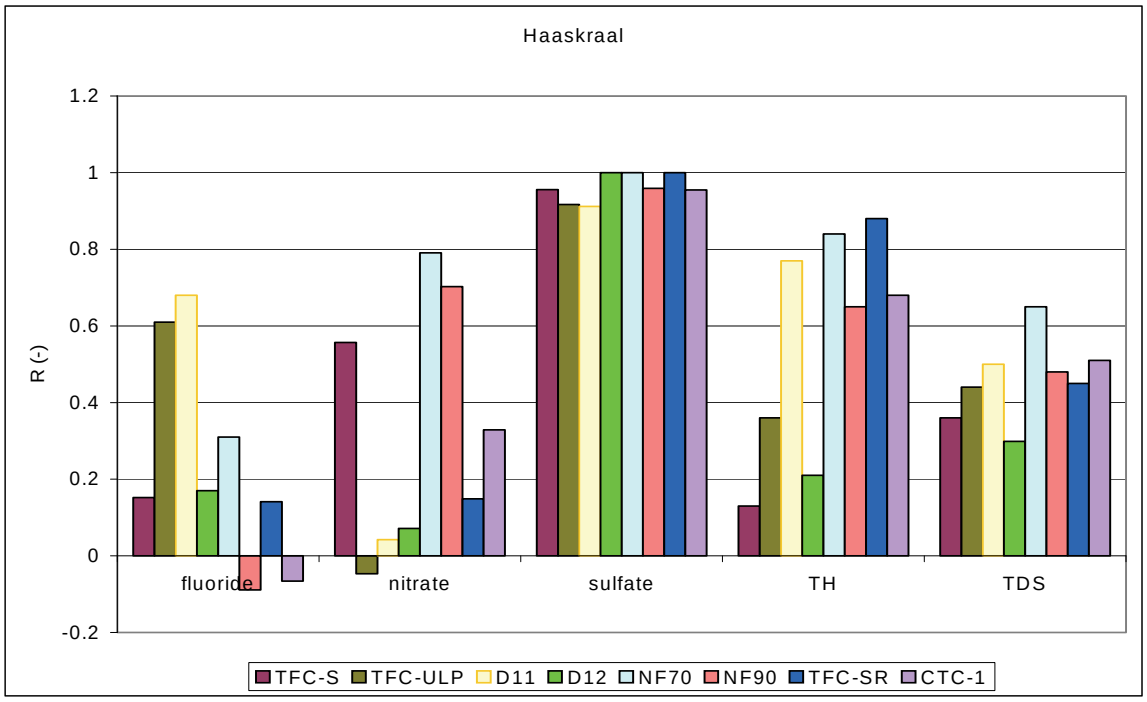


Figure 5. 9 Presentation of membrane performance on Haaskraal rural water (Pressure = 20 bar, temperature = ambient)

The remaining membranes showed poor fluoride rejection. Figure 5. 9 illustrates performance of these membranes for the treatment of the Haaskraal rural water.

5.7.4 Vaal River (sample 6)

The Vaal River sample showed high sulfate rejections for all membranes (70–100%) (Figure 5.10 and Figure 5. 11). TH rejection is high for the NF70, NF90, TFC-S and TFC-SR (70–95%) membranes, moderate rejection by TFC-ULP (50%) and poor rejection by D11, D12 and CTC-1 membranes. TDS is well rejected by TFC-S, TFC-SR, TFC-ULP membranes (45–75%) whilst moderately rejected by D11 and CTC-1 (35–40%).

Nitrate rejection is also improved for the river water and was moderate for all the membranes (40–60%). Negative fluoride rejections are found for the CTC-1 and TFC-S membranes and are otherwise poorly rejected by all other membranes (up to 25%). Such a rejection is not detrimental as fluoride composition is generally low in this sampling site.

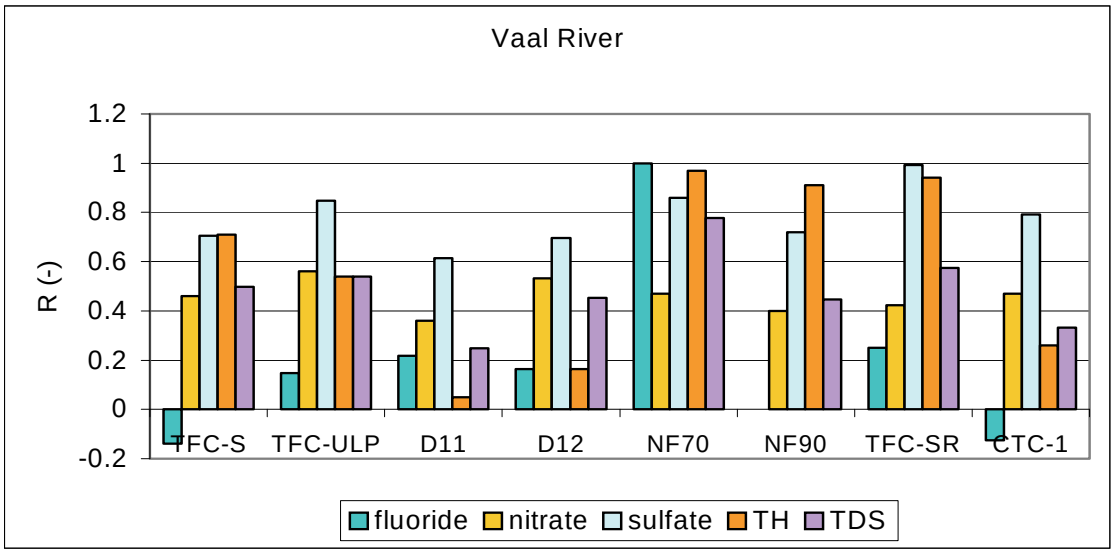


Figure 5. 10 Retention coefficient of various NF membranes on the treatment of Vaal River water (Pressure = 20 bar, temperature = 20°C. x-axis = membrane type)

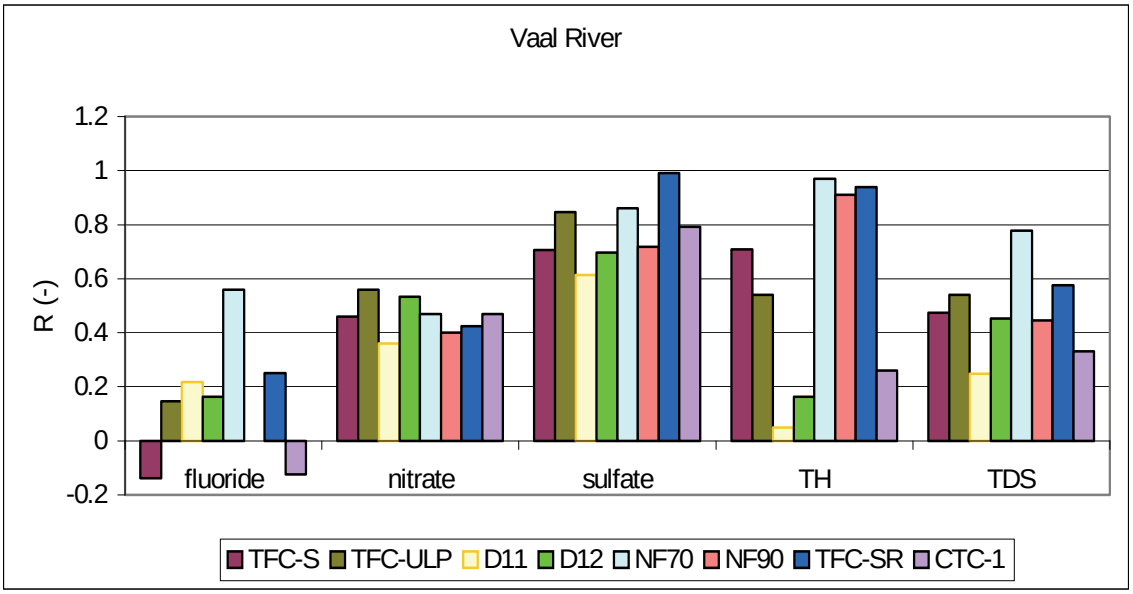


Figure 5. 11 Presentation of the membrane performance on Vaal River water (Pressure = 20 bar, temperature = ambient)

5.7.5 Fluoride rejection

Fluoride levels are a cause for concern due to high levels in the North West Province. Successfully removing or reducing it to acceptable levels from the affected water will bring hope of improving water quality in the rural areas. This section compares performance of various membranes (TFC-S, TFC-ULP, D11, D12, NF70, NF90, TFC-SR and CTC1) in reducing fluoride from water samples (Lerome, Ledig, Haaskraal, and Vaal River) of different initial fluoride levels. Furthermore, the overall performance of these membranes in improving water fluoride content are compared to each other.

5.7.6 Effect of initial fluoride concentration

The effect of initial fluoride concentration of sampled water on rejection is shown in Table 5. 6. TFC-S, TFC-ULP and NF70 membranes had high rejections for high fluoride levels (Lerome). NF90, TFC-SR and CTC1 membranes had poor rejections. Poor rejections for both high and low levels of fluoride were observed at all sampling sites when TFC-SR, CTC1, NF90 and D12 membranes are used. D11 had poor rejection for all the sampled water except for the Haaskraal water (70%) which is already low in fluoride.

In general, high rejections are observed for higher fluoride concentrations. The rejections at Vaal River are influenced by a high sulfate content leading to zero or negative rejections (by “pushing” the monovalents through the membrane). This is consistent with the observed trend when divalent co-ion levels are high [6]. The NF70 membrane rejects the fluoride even in the presence of high sulfate level, suggesting that the membrane has more reverse osmosis properties than other nanofiltration membranes. This RO property of NF70 confirms earlier observations made in our laboratory[6].

Table 5. 6 Initial concentration (feed), permeate and brine of sampled and treated water by NF membranes on a dead-end mode unit.

Fluoride retention								
	Lerome $[F^-]_o^*$ **= 5.50ppm**		**Ledig** $[F^-]_o$ **= 1.15ppm**		**Haaskraal** $[F^-]_o$ **= 0.41ppm**		**Vaal River** $[F^-]_o$ **= 1.13ppm**	
Membrane	Permeate (ppm)	Brine (ppm)	Permeate (ppm)	Brine (ppm)	Permeate (ppm)	Brine (ppm)	Permeate (ppm)	Brine (ppm)
TFC-S	1.06 ± 0.03	4.22 ± 0.01	0.00 ± 0.01	1.66 ± 0.03	0.52 ± 0.04	0.41 ± 0.07	1.25 ± 0.03	1.07 ± 0.04
TFC-SR	3.96 ± 0.03	3.97 ± 0.04	0.51 ± 0.05	1.20 ± 0.03	0.33 ± 0.09	0.45 ± 0.06	0.78 ± 0.06	0.95 ± 0.02
TFC-ULP**	0.36 ± 0.02	4.75 ± 0.30	1.05 ± 0.03	1.05 ± 0.01	0.30 ± 0.02	0.41 ± 0.05	0.90 ± 0.02	0.98 ± 0.05
NF70	0.91 ± 0.01	4.59 ± 0.08	1.00 ± 0.05	1.20 ± 0.02	0.31 ± 0.06	0.41 ± 0.01	0.00 ± 0.01	1.39 ± 0.03
NF90	3.41 ± 0.01	4.73 ± 0.04	1.06 ± 0.03	1.73 ± 0.05	0.45 ± 0.07	0.56 ± 0.08	0.97 ± 0.01	0.80 ± 0.01
CTC1	3.17 ± 0.35	4.99 ± 0.03	0.56 ± 0.03	1.06 ± 0.05	0.41 ± 0.05	0.40 ± 0.05	1.13 ± 0.03	0.88 ± 0.06
D11	3.31 ± 0.05	4.02 ± 0.05	0.80 ± 0.04	1.30 ± 0.01	0.36 ± 0.04	0.42 ± 0.04	1.03 ± 0.03	1.50 ± 0.02
D12	3.71 ± 0.04	4.09 ± 0.01	1.03 ± 0.07	1.20 ± 0.03	0.43 ± 0.03	0.49 ± 0.09	1.10 ± 0.02	1.50 ± 0.01

* $[F^-]_o$ = initial ion concentration

** membrane used for the first time after receiving it. TFC-HR was not used due to poor performance.

5.8 Cross-flow studies

5.8.1 Sampled water characteristics

The chemical composition of the sampled water for the cross-flow studies presented in Table 5. 7 correlates with the composition found previously (see Figure 5. 1 to Figure 5. 3). The samples were nanofiltered on various membranes (D11, D12, CTC1 and NF90) at 5bar for about 30 hours using the cross-flow unit discussed in the previous section. The choice of the membranes was based on their availability and performance on dead-end modules when using single salts. The reasons for choosing the selected sites remain the same as discussed for the dead-end mode studies.

Table 5. 7 Sampled water chemical composition and characteristics

	NO_3-N	Na^+	F^-	TH	Cl^-	SO_4^{2-}	Cu^{2+}	TDS	pH
Lerome	1.2	80	5.8	51	36	50	0.01	900	7.0
Ledig	1.8	113	6.9	19	40	22	0.13	832	6.6
Haaskraal	13.9	60	0.2	32	29	70	0.04	1000	7.3
Vaal River	1.6	210	2.7	18	41	112	0.02	1108	6.8

5.8.2 Lerome (sample 13a)

The sulfate and TDS levels are well rejected by all membranes tested (Figure 5. 12 – see also **Appendix O**). Water is softened well by all the membranes except CTC1. This poor performance of CTC1 is consistent with earlier investigations on dead-end mode. The monovalent ions (nitrate and fluoride) are not well rejected. Nitrate is poorly rejected by all membranes (8-20%) except for NF90, which rejected fluoride in the Lerome water by up to 70%. This rejection behaviour is not in line with the observations made during dead-end studies in which nitrate was rejected by all membranes. Fluoride is poorly rejected by all membranes. No negative rejections were observed for all membranes as observed in earlier studies.

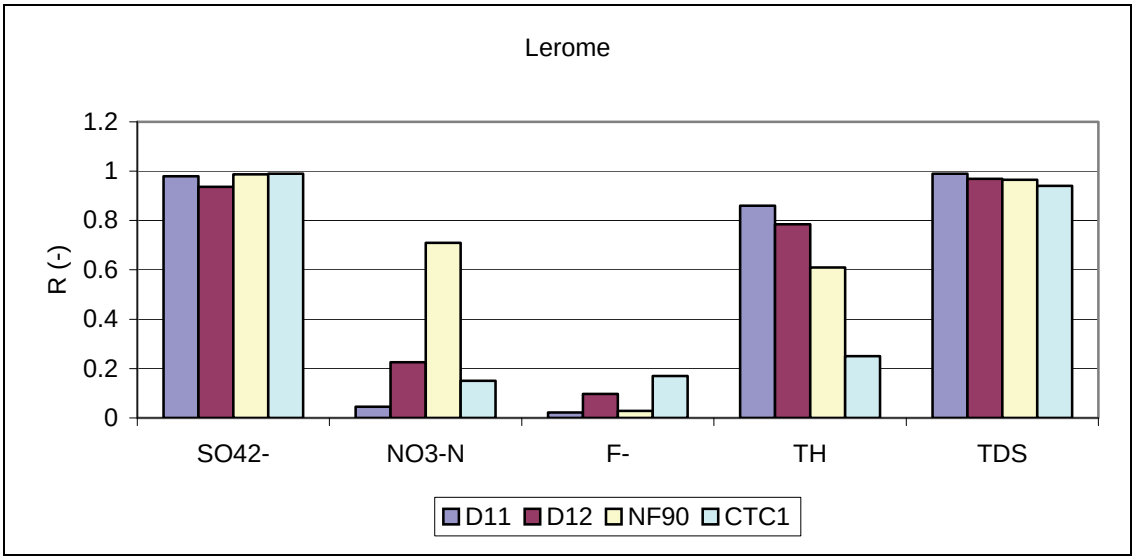


Figure 5. 12 Presentation of the membrane performance on Lerome water (Pressure = 5bar, temperature = ambient, cross-flow)

5.8.3 Ledig (sample 23)

The performance of membranes for the treatment of Ledig water is slightly better than in the case of Lerome water treatment, especially for the rejection of fluoride (30-40%) and nitrate (up to 50%) see (Figure 5. 13 – see also **Appendix P**). These improved rejections are not in line with the observations during dead-end studies in which negative fluoride rejections for D11 and D12 were displayed. Also in that study, nitrate rejections were lower than observed in cross-flow studies. The rejection of nitrate on NF90 decreased to 50% (from 70% during dead-end studies). Softening of the water and removal of TDS improved however, to about 90% compared to about 20% during dead-end studies.

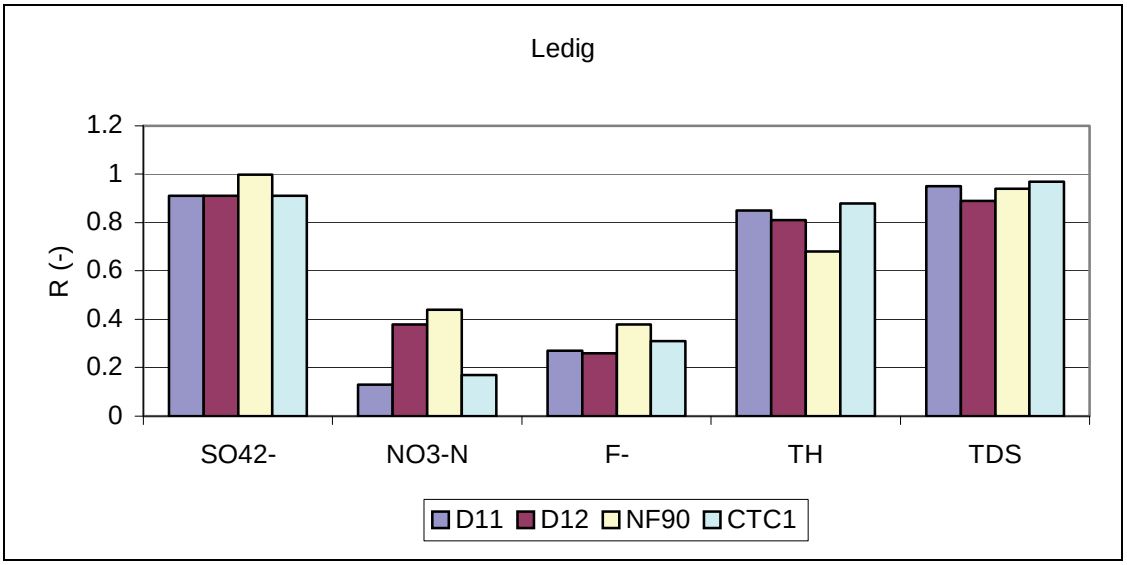


Figure 5. 13 Presentation of the membrane performance on Ledig water (Pressure = 5bar, temperature = ambient, cross-flow)

5.8.4 Haaskraal (sample 3)

Treatment of the Haaskraal water sample was even better than the former two sampled sites (Lerome and Ledig). The nitrate, sulfate and TDS levels are higher than in the Lerome and Ledig water samples (see Table 5. 7 see also **Appendix Q**). The rejection of sulfate and TDS is almost 100% (Figure 5. 14).

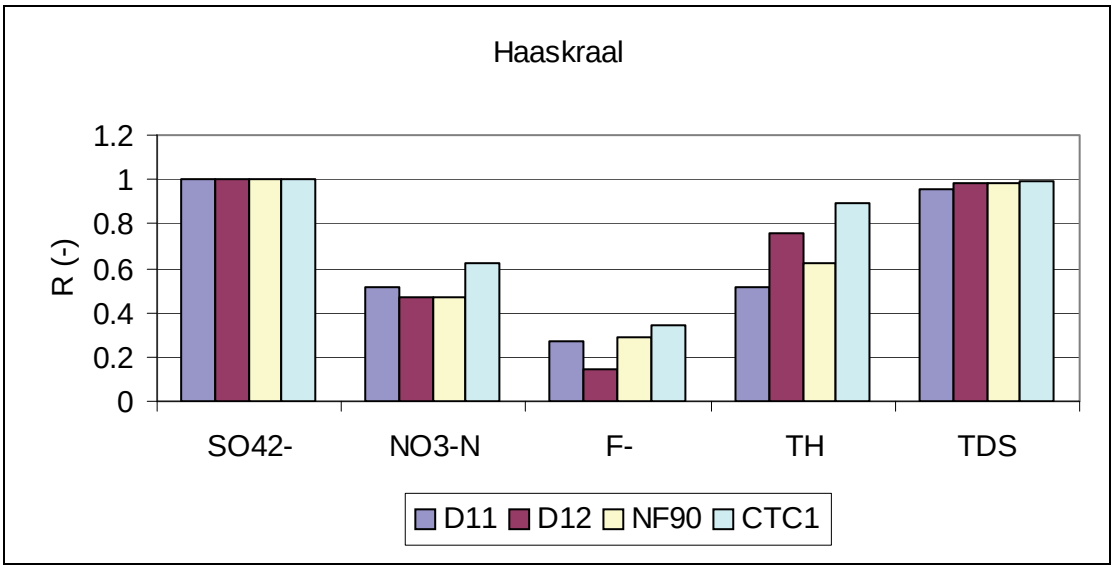


Figure 5. 14 Presentation of the membrane performance on Haaskraal water (Pressure = 5bar, temperature = ambient, cross-flow)

The TDS rejection was between 30 and 50% for all membranes tested during dead-end studies. The rejection of TH is consistent with the performance during the dead-end studies. This is except for the D12 membrane which had a rejection of about 20% during dead-end studies while improving to about 80% during the cross-flow studies. There is also an improvement in the removal of nitrate which increased up to 50% for all membranes. No negative rejection was observed for fluoride.

5.8.5 Vaal River (sample 6)

Sulfate and TDS are well removed by all membranes (Figure 5. 15 - see also **Appendix R**). This is an improvement from the dead-end studies done in which the rejections were about 80 and 40%, respectively (Figure 5.10). Good softening of water is attained by D12 (~100%) and CTC1 (~80%), which is contrary to earlier observations made during dead-end studies from which the rejections were ~20 and ~25%, respectively. Fluoride rejection from this sample water is improved and is between 30 and 40% for all membranes, including the NF90 and CTC1 which had no or negative fluoride rejections during dead-end studies. The nitrate rejection is however slightly lower than the observed membrane performance during dead-end studies. Nitrate rejection by D11, D12 and CTC1 is moderate (30-40%) but poor (~6%) for the NF90 membrane.

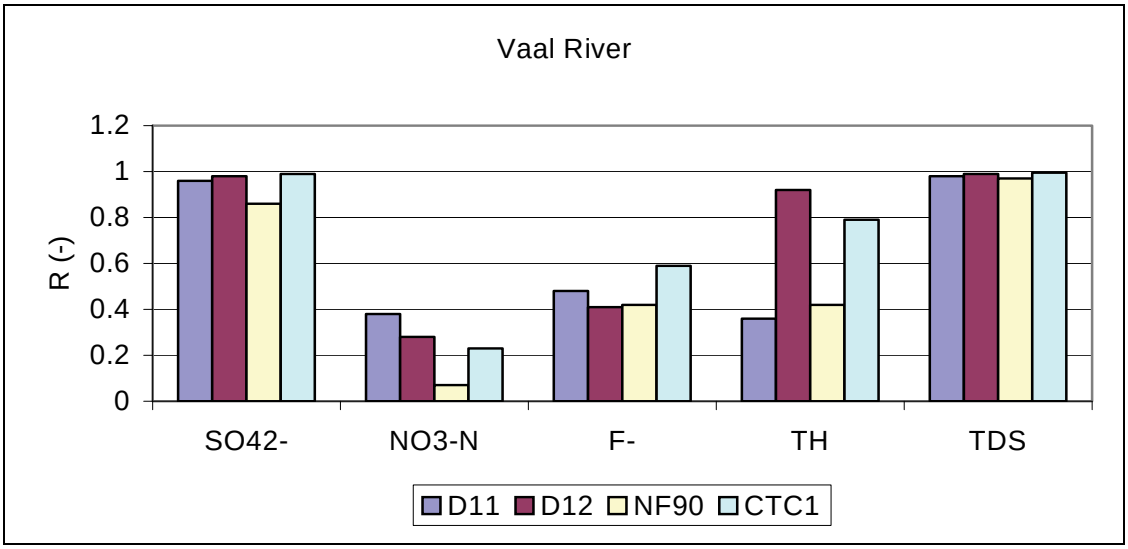


Figure 5. 15 Presentation of the membrane performance on Vaal River water (Pressure = 5bar, temperature = ambient, cross-flow)

5.9 Summary and Conclusion

The aim of this investigation was to evaluate a cross-flow nanofiltration membrane unit and process for the removal of the divalents/multivalents (sulfate, total hardness, total dissolved solids) and the monovalents (nitrate and fluoride). The separation principle of such a process is based on molecular size exclusion and ionic (charge) exclusion. Compared to reverse osmosis membranes, which indiscriminately exclude almost all dissolved solids, regardless of their charge, nanofiltration membranes remove the high valence ions (co-ions) mostly whilst selectively/partly retaining the monovalents. In the treatment of rural water, the membranes were successful in removing sulfate and in some cases effectively softened the sample waters. The monovalent fluoride and nitrate were, however, retained average to poor depending on the different compositions of the rural water.

During dead-end mode studies, NF70, TFC-S, D11 and TFC-SR membranes showed good fluoride retentions for varying water samples. NF70 could reduce fluoride in the Lerome rural water from about 4ppm to less than 1ppm (~76%) whilst permeation with TFC-ULP was even less than 0.5ppm fluoride (91%). Although it yielded negative fluoride rejection and even poor fluoride rejection for Haaskraal, Ledig and Vaal River sample water, TFC-S showed satisfactory fluoride rejection for the Lerome sample water.

Nitrate contents in all the sampled water were already within acceptable levels, except at Haaskraal and Greenside. Still, when nanofiltered, only NF70 could show satisfactory nitrate retention. Most other membranes showed little or negative rejections. **Appendix N** and **Appendix S** shows detailed membrane performance for each ionic component and sample water. The NF70 membrane can be recommended for further investigation and use in rural water treatment due to its overall retention capacity, even though (as also shown in previous work [7]) it shows reverse osmosis tendencies by rejecting almost all components. The TFC-S and TFC-SR membranes also have potential for selected cases of rural water treatment.

The high sulfate rejection by all membranes confirms that the membranes have a negative surface charge. To improve the removal of other pollutants, a combination of these membranes with the available positive NF and/or inorganic membranes can be used.

Characterization by single or even binary salt mixtures cannot be used to predict "real" performance of the membrane since it will be affected by the composite water it is in contact with. Furthermore, it cannot be assumed that if a membrane improves water quality of one contaminated site that it will do the same for other sites. As soon as ion composition and composition of sampled water changes during treatment, selectivity is drastically influenced. Each membrane has to be tested (screened) and optimized for use for each site.

Generally, the nanofiltration membranes performed better in removing divalents (especially anions) than monovalents for all sample water compositions. However, some divalents, especially cations, were not so well retained, depending on the nature of the membrane and the composition of the sample feed.

The unacceptable water quality (intended for drinking and food preparation) of Lerome (purple) was not improved by any of the membranes. The same can be said for the Ledig water. The Haaskraal water was in any case ideal so there was no difference brought about by the membranes (Table 5. 8). The moderate fluoride level at Vaal River is slightly improved to marginal quality.

Table 5. 8 Water classification (fluoride) before and after treatment by various nanofiltration membranes

Fluoride									
		Lerome		Ledig		Haaskraal		Vaal River	
		$[F]_o$ = 5.8		$[F]_o$ = 7.2		$[F]_o$ = 0.2		$[F]_o$ = 2.7	
		Brine	Product	Brine	Product	Brine	Product	Brine	Product
D11	Drinking (H)	P	P	P	P	B	B	R	Y
	Drinking (A)	B	B	B	B	B	B	B	B
	Food preparation	P	P	P	P	B	B	R	Y
	Bathing	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B
D12	Drinking (H)	P	P	P	P	B	B	R	Y
	Drinking (A)	B	B	B	B	B	B	B	B
	Food preparation	P	P	P	P	B	B	R	Y
	Bathing	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B
NF90	Drinking (H)	P	P	P	P	B	B	R	Y
	Drinking (A)	B	B	B	B	B	B	B	B
	Food preparation	P	P	P	P	B	B	R	Y
	Bathing	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B
CTC1	Drinking (H)	P	P	P	P	B	B	R	Y
	Drinking (A)	B	B	B	B	B	B	B	B
	Food preparation	P	P	P	P	B	B	R	Y
	Bathing	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B

H = Health, A = Aesthetic, B = Blue, G = Green, Y = Yellow, R = Red, and P = Purple.

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6 Evaluation and recommendations

The main findings of the characterization of the membranes, and their performance on the rejection of selected electrolytes and rural water samples are given. Finally, some recommendations for further research is presented.

6.1 Evaluation

The global importance of clean water cannot be over-emphasized. Everywhere institutions and organisations have begun reviewing provisions of safe and clean water. The South African response has been the enactment of the National Water Act 36 of 1998, which guarantees safe water by guarding against pollution with the intention to protect and conserve water. If implemented properly, many rural areas will benefit by getting clean water that is free from hazardous organic or inorganic components.

In view of the aforementioned, the high levels of fluoride (around the Pilanesberg) and nitrate (around Moretele and Kudumane districts) within the North West region cannot be left unattended. The high levels of fluoride result is mottling of the teeth and skeletal fluorosis, which is clearly noticeable within the Pilanesberg region.

Sampling in the selected regions of the North West Province was done to gain an understanding of the extent of pollution, especially in rural areas. Fluoride levels were found to be high in the greater Pilanesberg area and in some parts of the Mafikeng region. Other chemical components, including nitrates, were found to be within the acceptable limits. Sulfate concentration was high only at the Vaal River, downstream from the gold mines.

During characterization, D11, D12 and TFC-SR showed high water fluxes and permeabilities. TFC-SR membrane had higher solute fluxes than TFC-S. The lowest solute fluxes were observed for NF70, NF90 and TFC-HR. NF70, NF90 and TFC-S displayed more properties of reverse osmosis (RO) than nanofiltration (NF) characteristics with low permeability.

Various nanofiltration membranes were tested for their ability to remove the chemical components from the sampled water of Lerome, Ledig, Haaskraal and the Vaal River. Sulfate was efficiently removed by all membranes (confirming previous findings on the

removal of sulfate ions from acid mine water [1]). However, not all membranes could satisfactorily remove total hardness. Fluoride was also not retained well by all membranes. Nitrate was retained well by the NF70 membrane only. The other membranes showed poor, and in some cases even negative retention. In general, the FilmTec® NF70, and the Koch Membrane Systems' TFC-S and TFC-SR showed relative good removal of both mono- and divalent chemical components. The model solution (single and mixture salts) studies, however, cannot be used to predict the membrane behaviour in rural water treatment. One cannot even deduce that the membrane will perform the same way for different water sources.

6.2 Highlights

- Fluoride in the Rustenburg area is at an unacceptable level especially around the Pilanesberg region. Some boreholes around the Mafikeng area have fluoride levels just above 1ppm which can be a cause of concern as this area is not usually associated with these pollutants;

- Nitrate levels in the sampled areas was not a health threat except in one private borehole of Rustenburg's Greenside area (sample 13);

- Of all the sampled points, sulfate levels were high at the Vaal river, downstream of some gold mines;

- Sulfate removal by NF-membranes was excellent (as also observed in mine water treatment [1]);

- NF-membranes behave differently for different rural water compositions;

- Characterization of nanofiltration membranes does not necessarily predict how they will perform with polluted water as removal of pollutants depend largely on the composition of the water; i.e. the presence and concentration of other ions;

- NF70 can be recommended as it could remove most salts from both prepared solutions and polluted water;

- ❖ D11, D12 and CTC-1 can be recommended with restrictions (due to its limited nitrate and fluoride removal);

6.3 General discussions

The NF-membrane process offers a technique that can be used for rural water treatment. If the correct membrane is chosen for a specific locality, then sulfate, fluoride, and nitrate levels can be reduced. However, screening tests have to be done initially to select the proper membrane. The dead-end NF set-up built in this study is ideal for such membrane screening.

The scattered homes in the rural areas make it difficult for the treatment of water by NF-membranes. The difficulty is enhanced by the fact that most boreholes in the affected areas are private and in backyards and it will be difficult to closely monitor all of them. Hence, the membrane process can only be effective if the water is treated by the local (central) water authority and then distributed to the consumers. In so doing, the unit could benefit more residents than when it was placed at only a specific borehole. Such a unit might, however, be necessary in affected areas, forming a part of an integrated rural development. The other possible hindrance of a membrane application in the rural areas is the cost of technology transfer, maintenance and the availability of skilled labour. It should be noted that even though the unit might be moved to another community, it will be the owner's responsibility to make sure that it does not become a white elephant.

Water treated by NF-membranes, has value added to it. Such an addition of value would necessitate that the communities pay for the product. Such an approach might be difficult in the poverty stricken rural areas. Besides, rural communities have most of the water sources right in the yards, and as long as they can remember they never had to pay for water. Part of the solution to this addition of value will therefore require direct involvement of the communities so that they can take ownership of the activities, including the pricing of the water. It would be a futile exercise to do any of this membrane water treatment tests without the involvement of the local community.

The brine, as one of the membrane process products, needs to be disposed of or reused. It will therefore be important to study the area for possible wastewater reuse. The options that can be considered in such areas are irrigation, livestock watering, development of mini-parks, etc.

6.4 Recommendations and further research

- Private boreholes in the backyards of the rural areas need constant quality assessment, especially by the water-supply authorities. Not all boreholes need to be monitored, but they can be selected in such a way that they are representative of all other boreholes. To do this, a strategic assessment and monitoring plan might be necessary over a limited number of years.

- There is a need for further monitoring of nitrate and fluoride levels; including or extending the current sampling regions. This necessitates collaboration with the Health Department on issues like the effects of high levels on the consumers.

- Membrane characterization methods would need to be quantified and systematized as a protocol so that there is uniformity and comparability when characterizing membranes. Also, much more and better understanding of the mechanism of separation as well as the influence of other ions is required before any prediction of membrane performance is possible.

- Parameters that might hinder optimum water treatment by nanofiltration membranes (e.g. fouling) need intense investigation.

- The use of nanofiltration membranes have a backlog of poor monovalent rejections. This however, is not a limitation to optimally use the built cross-flow unit for intense nanofiltration studies.

- Campaigns on the importance and scarcity of water need to be run to educate all South Africans. In the many areas visited; leaking taps, unattended running water and overflowing water from tanks were found. In many cases the residents themselves did not know what to do with such problems (even where to report them). Water reuse (for washing cars, gardening, sanitation, etc.) has to be encouraged.

References

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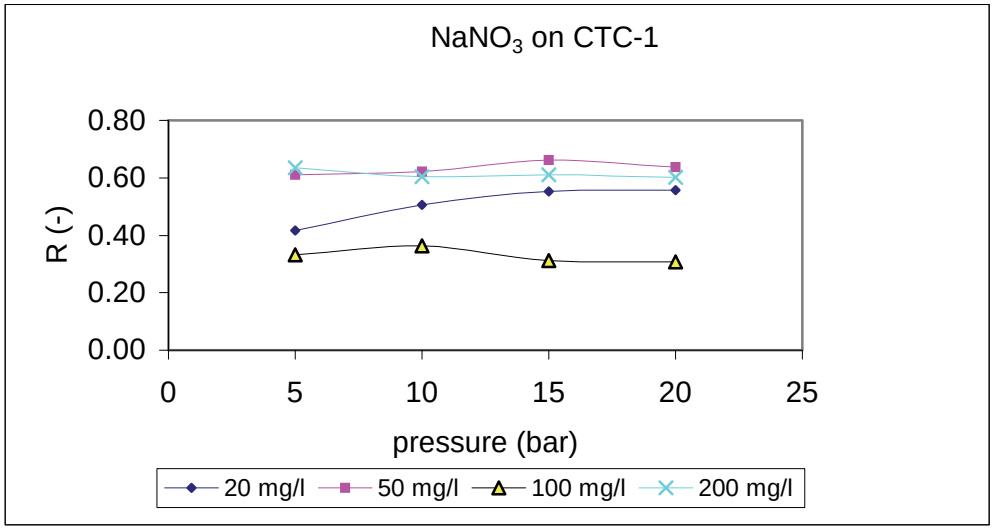
Appendix A Solute flux of various model solutions at different trans-membrane pressures

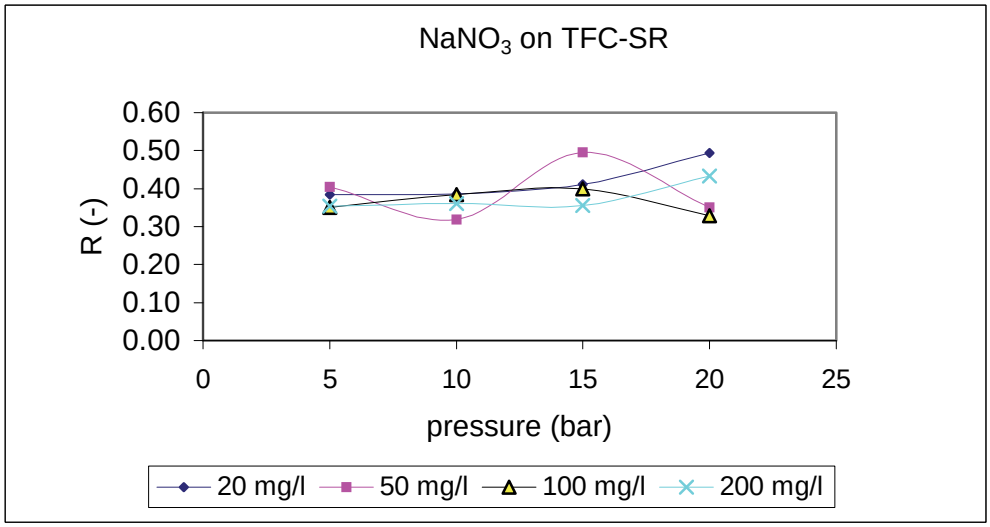
Solute flux (10^{-6} m.s^{-1})									
Membrane	Concentration (ppm)	NaCl				H_2SO_4			
		5	10	15	20	5	10	15	20
TFC-S	20	X	X	X	X	X	X	X	X
	50	X	X	X	X	X	X	X	X
	100	X	X	0.47	0.63	X	X	2.30	3.33
	200	X	X	0.27	0.39	X	X	2.89	3.71
TFC-SR	20	18.9	34.5	52.1	71.0	19.4	34.9	52.5	70.2
	50	19.5	36.5	52.1	71.0	20.3	37.2	55.8	77.2
	100	19.7	36.5	55.3	74.4	21.3	38.1	54.8	74.4
	200	20.0	36.5	54.8	73.5	20.4	38.6	56.8	72.7
TFC-HR	20	X	X	X	X	X	X	X	X
	50	X	X	X	X	X	X	X	X
	100	4.84	7.97	10.6	13.7	3.91	7.66	11.9	15.3
	200	3.75	7.18	10.6	14.1	3.59	7.18	11.1	14.7
CTC1	20	9.89	19.1	26.9	38.8	8.12	16.1	23.9	30.0
	50	9.39	24.5	36.3	50.0	7.74	15.3	23.0	32.3
	100	12.8	25.6	37.0	37.5	7.88	15.7	22.6	35.0
	200	12.0	X	37.0	50.4	8.00	15.6	23.6	33.5
NF70	20	3.60	7.84	11.4	15.1	2.66	5.31	8.13	10.8
	50	3.60	7.00	11.0	14.8	2.81	5.31	8.28	12.3
	100	3.82	7.63	11.4	15.5	2.81	5.47	8.59	11.4
	200	4.03	7.63	11.4	15.1	2.34	4.84	7.03	10.0
NF90	20	3.39	8.48	13.4	18.2	2.43	5.18	9.19	13.6
	50	4.24	8.69	14.0	18.7	2.43	5.23	8.98	13.8
	100	3.18	6.15	9.54	12.7	2.41	5.17	9.10	13.7
	200	3.39	7.21	10.2	13.8	2.43	5.31	9.06	13.3

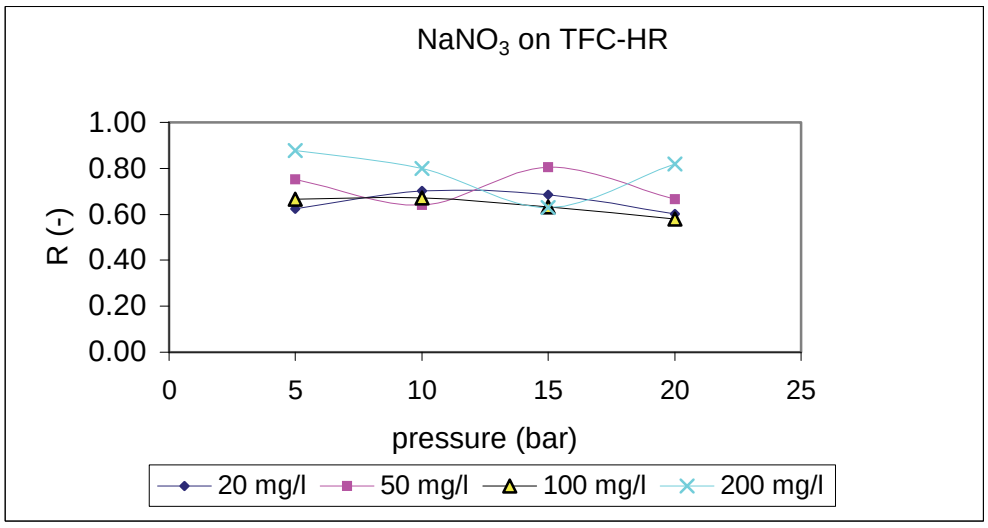
Appendix A (continued…)

Volume flux (10^{-6} m.s^{-1})									
Membrane	**Concentration (ppm)**	**$CaSO_4$**				**Na_2SO_4**			
		5	10	15	20	5	10	15	20
TFC-S	20	X	X	X	X	X	X	X	X
	50	X	X	X	X	X	X	X	X
	100	X	X	0.25	0.58	X	X	0.38	0.66
	200	X	X	0.41	0.48	X	X	0.47	0.53
TFC-SR	20	X	X	X	53.0	21.5	39.8	56.3	73.5
	50	X	39.3	55.8	71.0	21.6	38.6	54.8	69.4
	100	20.7	38.6	54.6	67.6	19.2	35.3	50.0	61.3
	200	20.3	36.2	50.0	59.0	18.9	35.1	48.8	61.3
TFC-HR	20	3.59	7.34	11.4	14.7	3.52	7.27	10.3	14.2
	50	3.59	7.34	10.6	13.9	3.56	7.26	10.3	14.6
	100	3.75	7.19	11.6	15.8	3.54	7.26	10.2	13.8
	200	3.44	6.88	10.5	14.4	3.86	7.19	10.3	13.7
CTC1	20	8.04	15.8	23.3	31.5	7.74	15.4	22.9	30.9
	50	7.76	15.7	22.3	31.0	8.23	14.8	23.5	31.2
	100	8.88	16.0	23.6	31.3	7.68	15.7	23.0	30.7
	200	7.32	14.9	22.4	32.3	7.69	15.9	23.4	31.1
NF70	20	2.66	5.63	8.75	11.9	2.74	6.01	9.13	12.1
	50	2.97	5.94	9.22	12.2	2.40	6.09	9.15	12.6
	100	2.97	5.63	8.91	12.5	2.42	6.12	9.13	11.9
	200	2.81	5.63	8.75	11.3	2.41	6.03	9.13	12.4
NF90	20	2.43	5.51	7.58	9.62	2.82	5.60	8.32	11.2
	50	2.42	5.43	7.54	9.60	2.85	5.66	8.45	11.2
	100	2.43	5.49	7.53	9.58	2.81	5.91	8.38	11.7
	200	2.43	5.47	7.53	9.61	2.84	5.73	8.36	10.8

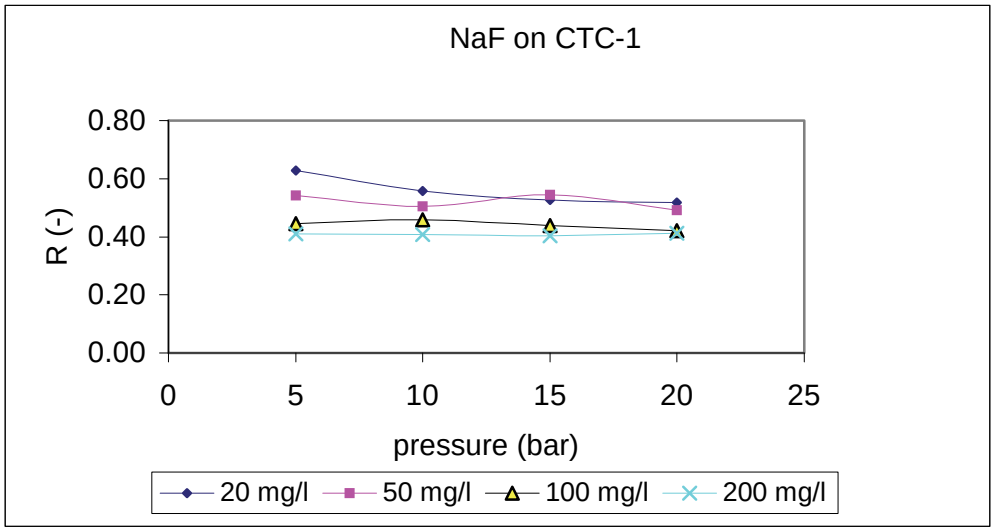
Appendix B Retention of $NaNO_3$ solutions on different membranes

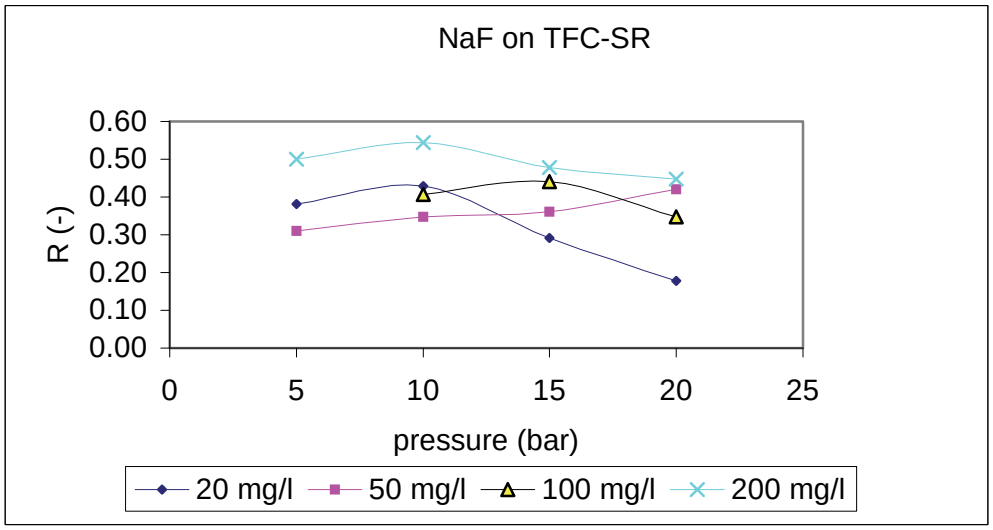


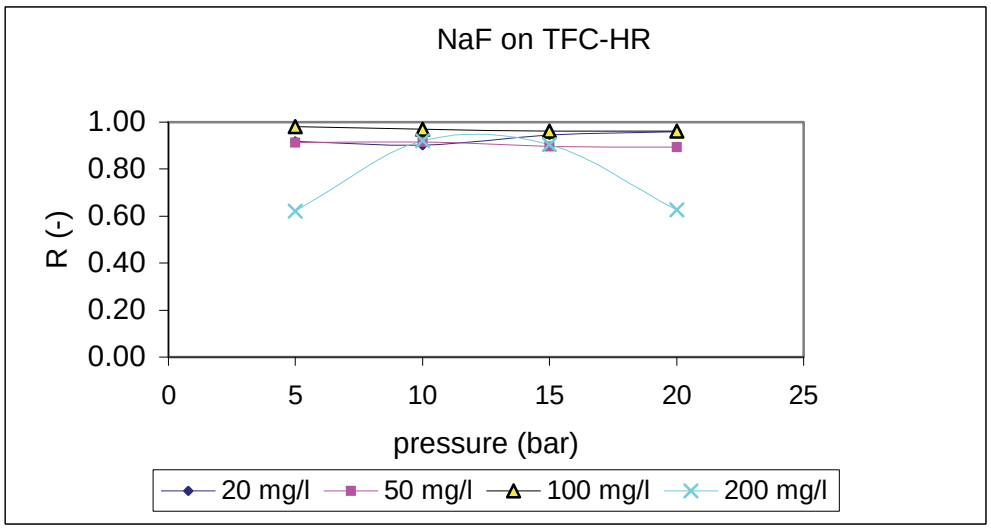




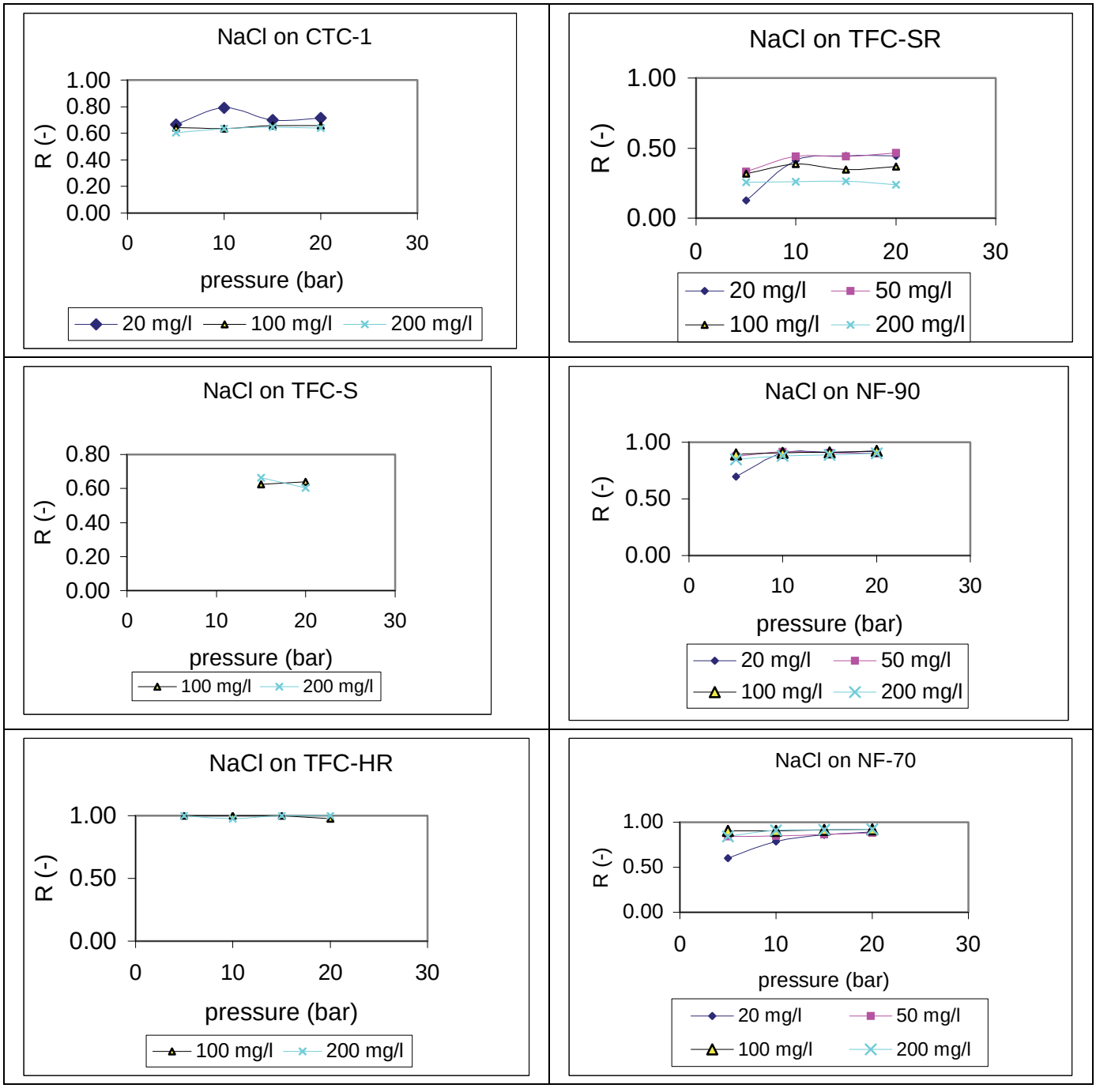
Appendix C Retention of NaF solutions on different membranes



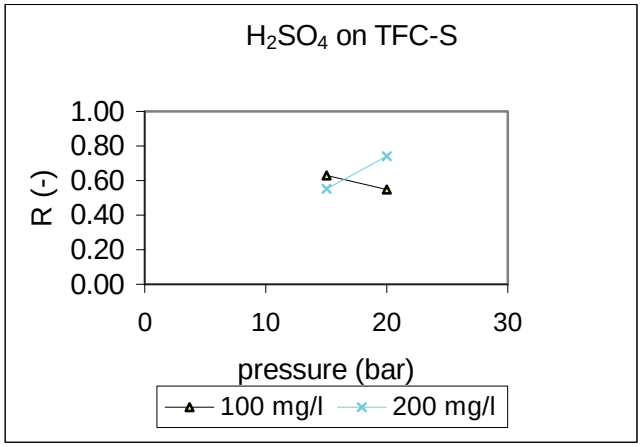


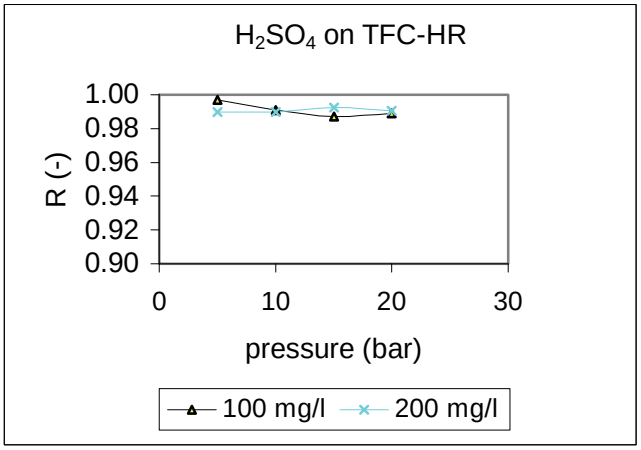


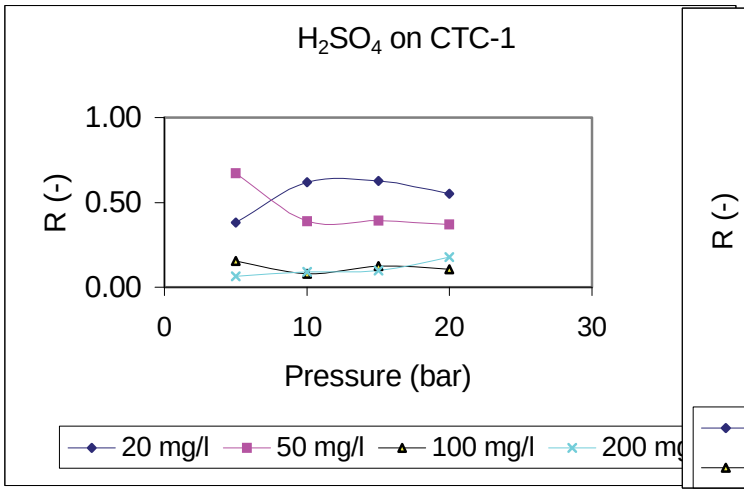
Appendix D Retention of NaCl solutions on different membranes

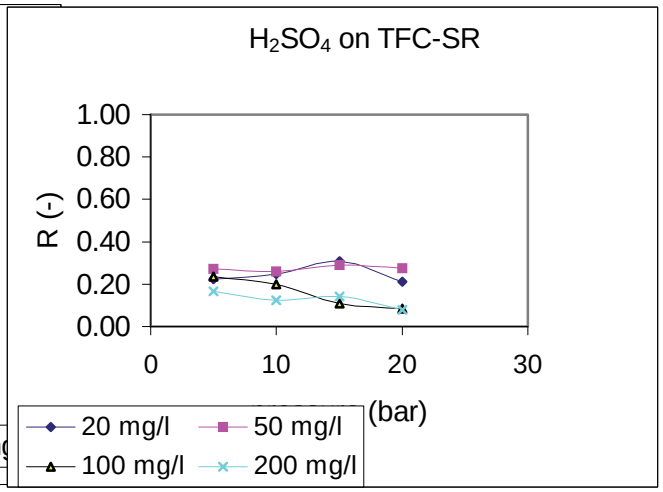


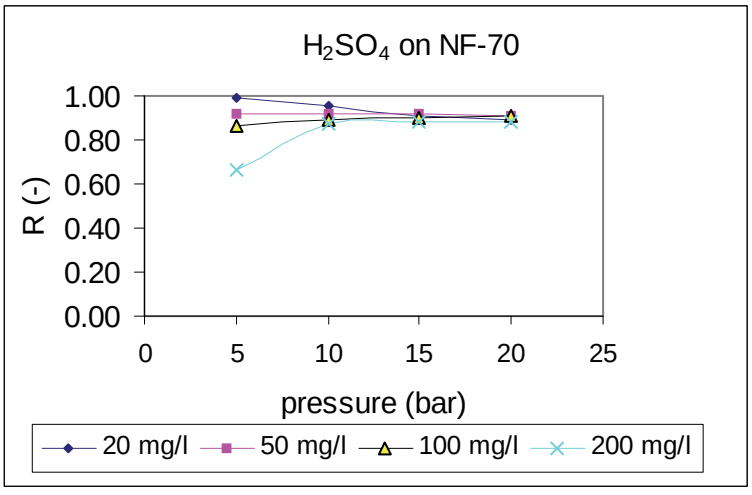
Appendix E Retention of H_2SO_4 solutions on different membranes





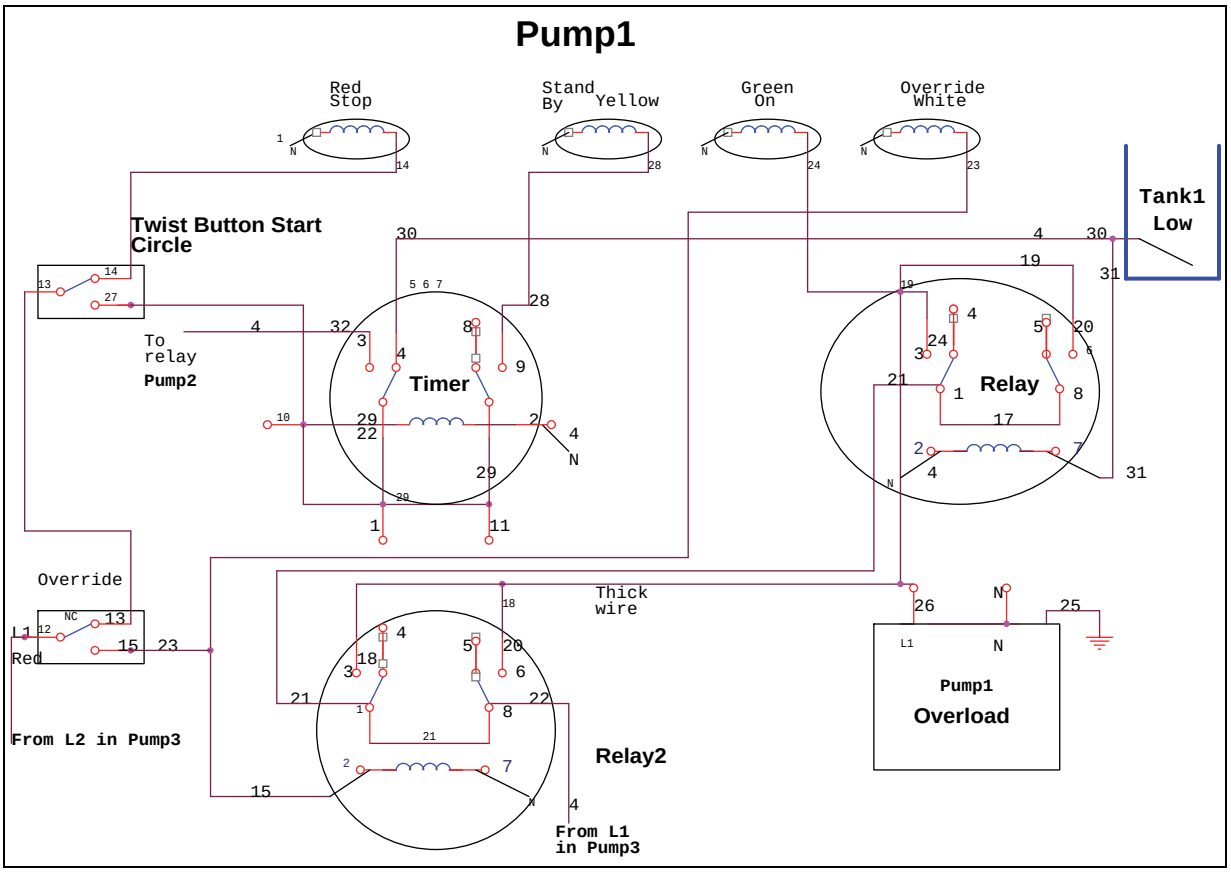






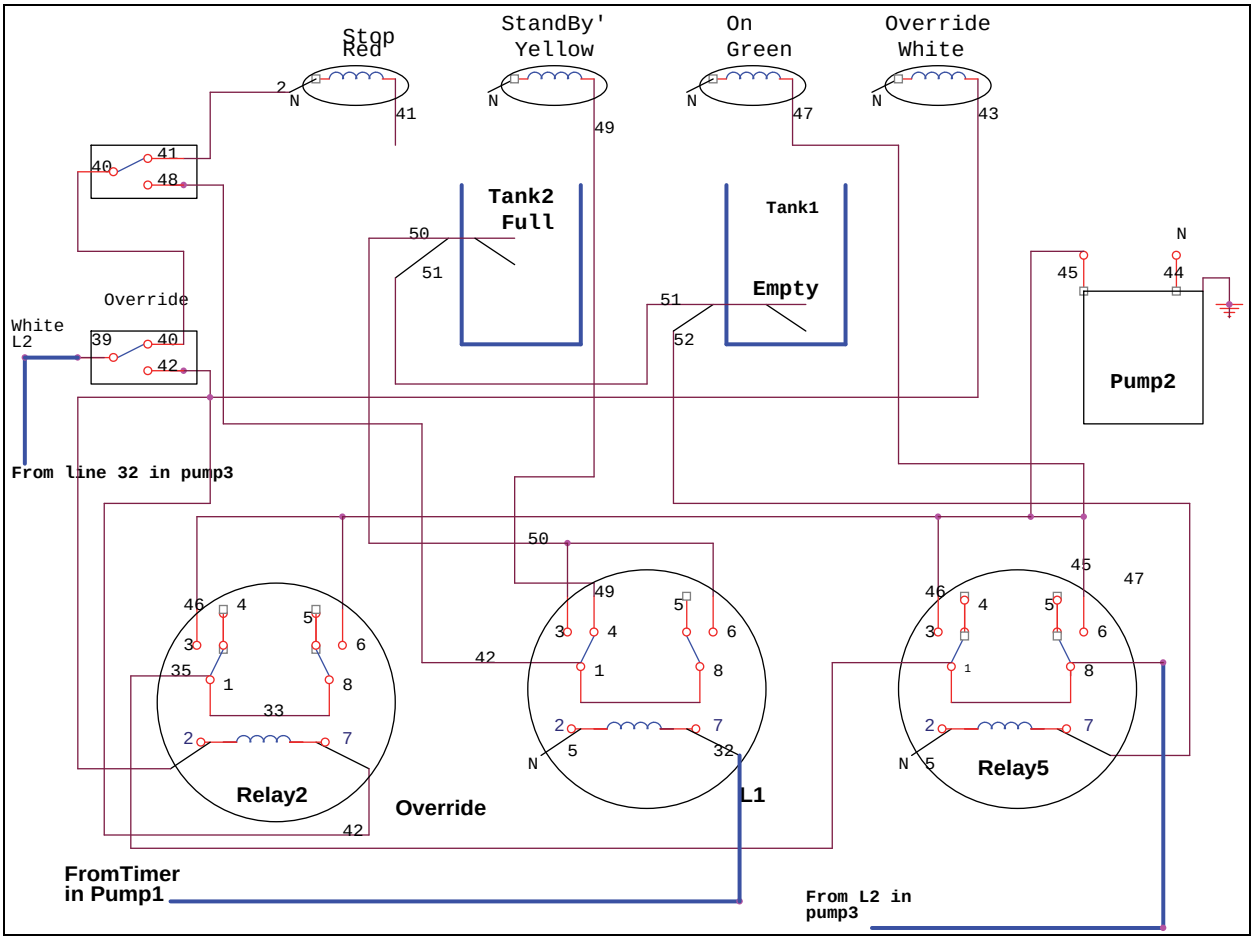
Appendix F Electrical connections to pump

1. Electrical connections to pump 1 (sandfilter pump, operating pressure = ~1 bar)



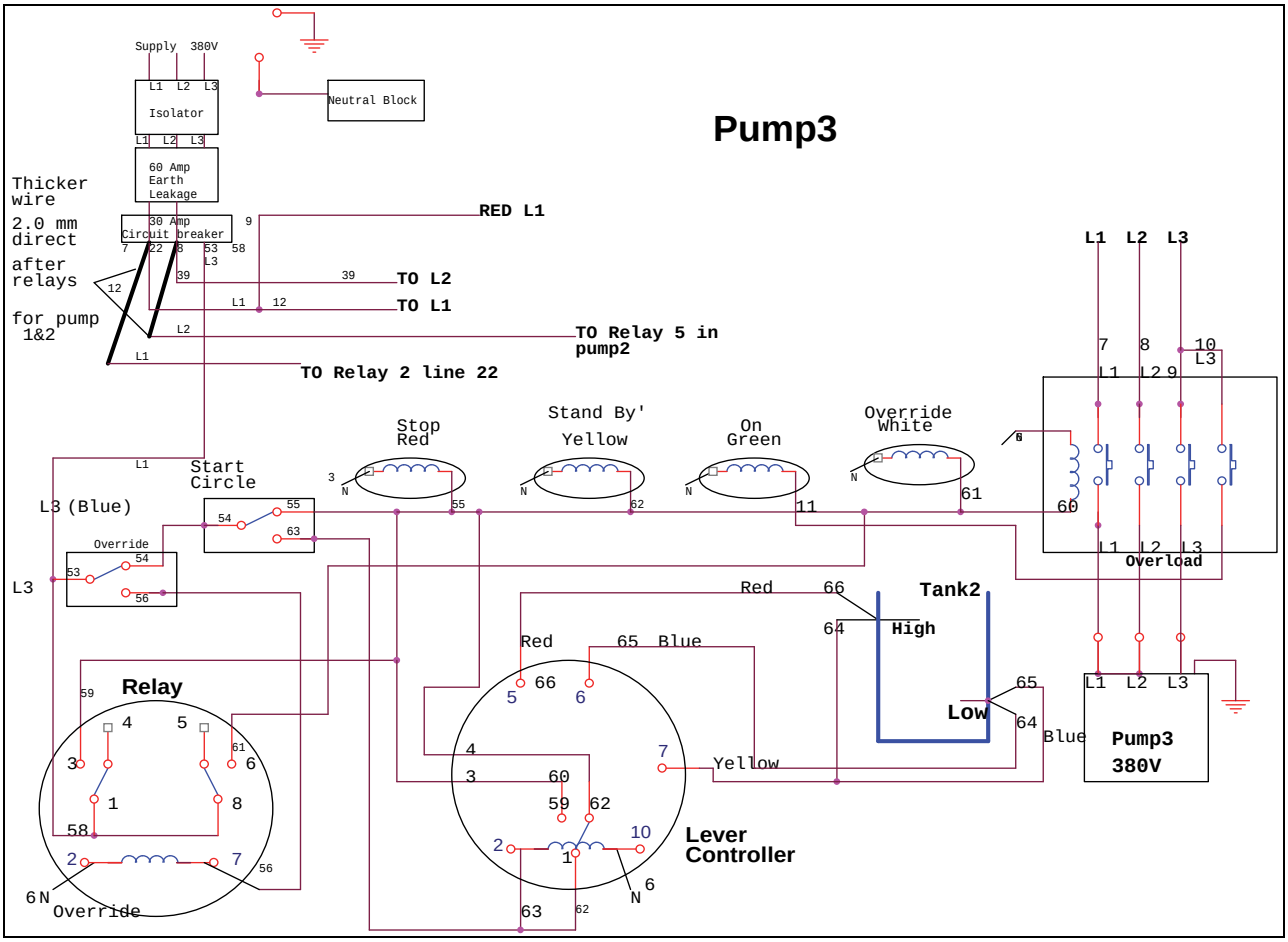
Appendix F (continued…)

2. Electrical connections to pump 2 (microfiltration pump, operating pressure = 2bar)



Appendix F (continued…)

3. Electrical connections to pump 3 (monopump, maximum operating pressure = 25 bar)



Appendix G Water quality from various sampling sites within the North West Province on four different occasions

Sampling 1: Beginning of rainy season (BRS)

			F^- ($mg.l^{-1}$)	NO_3-N ($mg.l^{-1}$)	SO_4^{2-} ($mg.l^{-1}$)	Cl^- ($mg.l^{-1}$)	Na^+ ($mg.l^{-1}$)	TH ($mg.l^{-1}$)	Cu^{2+} ($mg.l^{-1}$)	TDS ($mg.l^{-1}$)	pH
Klerksdorp region	Mooi River	1	1.4	1.6	23	18	131	67	0.08	1201	6.6
	Potch Univ.	2	1.0	2.3	19	24	42	83	0.06	198	6.6
	Boitshoko School	2a	0.8	0.0	8	21	32	38	0.03	1341	7.3
	Sarafina	2b	0.7	0.0	9	19	56	38	0.01	1800	7.8
	Rietspruit	3	0.2	5.4	21	11	90	23	0.04	305	7.1
	Taaiboschspruit	4	1.7	6.2	72	12	140	42	0.03	315	6.9
	Orkney Vaal	6	2.7	1.6	112	41	210	18	0.02	1108	7.3
Koster region	Kaallagte 1	8a	0.3	1.1	0	6	71	57	0.03	299	7.0
	Kaallagte 2	8b	0.2	0.0	0	0	39	17	0.03	600	6.5
	Rhenosterfontein	9	0.0	1.7	64	5	83	15	1.41	330	6.3
	Tlholego 1	10a	0.9	1.5	63	7	86	17	1.40	1036	6.4
	Tlholego 2	10b	0.4	0.0	60	0	79	47	0.19	1131	7.4
	Tlholego 3	10c	0.4	0.0	61	0	68	60	0.93	1203	7.1
	Tlholego 4	10d	0.2	0.0	63	0	91	76	0.81	1347	7.1
	Roodewal	11	1.0	0.2	9	5	23	83	0.04	1263	6.8
Rustenburg region	Rietvlei	12	0.0	2.8	5	5	36	57	0.08	1098	6.9
	Greenside	13	1.0	14	0	26	117	58	0.10	1018	6.4
	Mogwase	14	2.6	0.1	138	10	339	72	0.15	5280	6.3
	Beestekraal	15	1.1	0.2	60	69	143	41	0.08	2936	6.3
	Bakgatla	20	3.8	2.5	61	96	31	47	0.21	591	6.9
	Lerome 1	13a	5.5	0.0	0	16	29	35	0.14	2300	7.3
	Lerome 2	21	4.5	1.5	59	70	19	59	0.23	893	7.0
	Lerome 3	25	3.3	1.2	50	36	86	51	0.01	899	7.6
	Ledig 1	23	7.2	1.0	20	40	113	18	0.13	831	7.5
	Ledig 2	22	3.3	0.7	50	24	30	38	0.14	1200	6.8
	Lefaragatlhe	24	0.2	4.8	29	42	67	21	0.06	583	6.3
Mafikeng	Lichtenburg	5	1.1	2.3	0	28	178	21	0.03	851	6.6
	Mmabatho	16	0.6	0.8	15	63	73	56	0.09	649	6.3
	Letlamoreng 1	17	1.8	0.8	62	52	138	119	0.09	1093	6.4
	Letlamoreng 2	18	1.8	0.8	30	71	93	137	0.10	2999	7.1

TH = Total hardness as $CaCO_3$, TDS = Total dissolved solids

Appendix G (continued…)

Sampling 2: Middle of rainy season (MRS)

			F^- ($mg.l^{-1}$)	NO_3-N ($mg.l^{-1}$)	SO_4^{2-} ($mg.l^{-1}$)	Cl^- ($mg.l^{-1}$)	Na^+ ($mg.l^{-1}$)	TH ($mg.l^{-1}$)	Cu^{2+} ($mg.l^{-1}$)	TDS ($mg.l^{-1}$)	pH
Klerksdorp region	Mooi River	1	0.30	0.45	34	0.3	67	35	0.05	1300	6.1
	Potch Univ.	2	0.21	6.30	79	0.1	83	13	0.05	531	7.2
	Boitshoko School	2a	0.00	0.00	42	0.1	81	18	0.06	900	6.4
	Sarafina	2b	0.00	0.00	19	0.1	62	16	0.07	1356	6.3
	Rietspruit	3	0.00	2.71	21	0.1	78	21	0.06	831	6.5
	Taaiboschspruit	4	0.00	3.08	64	2.3	131	31	0.06	631	6.3
	Orkney Vaal	6	0.00	4.11	163	3.9	190	44	0.03	631	6.5
Koster region	Kaallagte 1	8a	0.07	1.40	35	0.6	82	28	0.06	636	6.8
	Kaallagte 2	8b	0.00	0.00	29	0.5	98	33	0.03	1039	6.1
	Rhenosterfontein	9	0.00	0.00	24	0.7	72	57	0.05	843	7.8
	Tlholego 1	10a	0.00	0.00	56	0.3	168	58	0.05	869	6.3
	Tlholego 2	10b	0.01	0.00	52	0.0	156	54	0.05	999	5.9
	Tlholego 3	10c	0.03	0.00	51	0.0	170	60	0.05	831	6.4
	Tlholego 4	10d	0.05	1.36	48	0.0	166	51	0.03	1103	6.3
	Roodewal	11	0.23	0.00	30	0.1	62	44	0.06	898	6.8
Rustenburg region	Rietvlei	12	0.00	3.08	8	0.6	63	37	0.06	1090	6.5
	Greenside	13	0.60	14.7	10	1.3	215	52	0.09	1534	6.6
	Mogwase	14	0.30	0.79	108	0.8	336	39	0.14	3606	6.6
	Beestekraal	15	0.21	0.29	43	0.8	123	43	0.03	5311	6.9
	Bakgatla	20	4.72	7.45	111	1.9	286	93	0.01	906	6.4
	Lerome 1*	13a	-	-	-	-	-	-	-	-	-
	Lerome 2	21	3.91	6.28	41	1.3	135	46	0.08	1100	6.3
	Lerome 3	25	3.50	8.61	31	0.6	86	19	0.01	837	7.6
	Ledig 1	23	8.30	0.59	68	0.7	138	35	0.03	600	7.2
	Ledig 2	22	5.10	5.11	58	0.1	142	26	0.03	1109	6.3
	Lefaragatlhe	24	0.99	3.79	70	0.5	168	73	0.03	543	6.3
Mafikeng	Lichtenburg	5	0.26	3.11	59	1.4	122	8	0.05	942	7.3
	Mmabatho	16	0.00	1.49	53	0.1	128	33	0.06	743	6.5
	Letlamoreng 1	17	0.08	0.00	27	0.0	139	50	0.01	1099	6.6
	Letlamoreng 2	18	0.46	0.70	31	0.1	193	30	0.01	2046	6.5

TH = Total hardness as $CaCO_3$, TDS = Total dissolved solids

* not sampled as no water could be pumped out.

Appendix G (continued…)

Sampling 3: Beginning of dry season (BDS)

			F^- ($mg.l^{-1}$)	NO_3-N ($mg.l^{-1}$)	SO_4^{2-} ($mg.l^{-1}$)	Cl^- ($mg.l^{-1}$)	Na^+ ($mg.l^{-1}$)	TH ($mg.l^{-1}$)	Cu^{2+} ($mg.l^{-1}$)	TDS ($mg.l^{-1}$)	pH
Klerksdorp region	Mooi River	1	0.3	14.9	51	21	128	51	0	1138	6.0
	Potch Univ.	2	0.2	4.54	83	24	53	80	0	195	7.1
	Boitshoko School	2a	0.3	5.65	39	23	28	0	0	1256	6.8
	Sarafina	2b	0.3	1.11	48	19	51	0	0.01	3042	6.4
	Rietspruit	3	0.1	0.77	28	30	88	40	0	415	6.3
	Taaiboschspruit	4	0.6	5.65	83	18	133	23	0	467	6.3
	Orkney Vaal	6	0.3	0.88	246	48	198	63	0	1280	6.8
Koster region	Kaallagte 1	8a	0.3	2.51	56	13	61	18	0	357	6.3
	Kaallagte 2	8b	0.4	2.12	55	9	43	10	0.12	817	7.5
	Rhenosterfontein	9	0.6	1.54	60	21	91	15	0	344	6.9
	Tlholego 1	10a	0.1	2.15	73	16	84	31	1.46	1882	6.8
	Tlholego 2	10b	0.1	1.19	69	22	71	0	1.41	1642	7.1
	Tlholego 3	10c	0.1	1.85	83	6	79	0	0.81	1839	6.3
	Tlholego 4	10d	0.2	0.63	71	23	93	0	0	1798	6.4
	Roodewal	11	0.1	1.24	56	71	19	53	0	1149	6.4
Rustenburg region	Rietvlei	12	0.2	2.10	63	16	29	55	0.93	1121	7.3
	Greenside	13	0.9	13.1	81	17	114	78	0.96	1753	6.3
	Mogwase	14	6.8	7.05	59	29	300	39	0.09	6468	6.3
	Beestekraal	15	0.6	1.38	183	83	123	43	0.05	3835	6.3
	Bakgatla	20	0.6	3.82	28	27	33	21	0	642	6.9
	Lerome 1	13a	0.1	2.87	47	42	31	0	0.01	2367	6.5
	Lerome 2	21	4.5	2.28	51	68	21	17	0.06	983	6.4
	Lerome 3	25	3.8	3.12	55	61	84	11	0	839	6.3
	Ledig 1	23	7.4	3.07	63	55	116	23	0	685	6.3
	Ledig 2	22	5.3	2.21	57	93	25	46	0	1035	6.2
	Lefaragatlhe	24	0.3	0.79	24	96	66	31	0	781	6.1
Mafikeng	Lichtenburg	5	0.5	2.37	58	28	102	60	0	964	7.6
	Mmabatho	16	0.5	2.64	69	197	86	113	0.03	748	6.7
	Letlamoreng 1	17	0.3	0.75	53	402	125	81	0.04	1396	6.4
	Letlamoreng 2	18	0.2	0.95	21	451	92	128	0	3373	7.2

TH = Total hardness as $CaCO_3$, TDS = Total dissolved solids

Appendix G (continued…)

Sampling 4: Middle of dry season

			F^- ($mg.l^{-1}$)	NO_3-N ($mg.l^{-1}$)	SO_4^{2-} ($mg.l^{-1}$)	Cl^- ($mg.l^{-1}$)	Na^+ ($mg.l^{-1}$)	TH* ($mg.l^{-1}$)	Cu^{2+} ($mg.l^{-1}$)	TDS ($mg.l^{-1}$)	pH
Klerksdorp region	Mooi River	1	0.6	0	120	51	22	54	0.07	1031	7.4
	Potch Univ.	2	0.8	2.3	110	11	35	54	0.04	289	6.3
	Boitshoko School	2a	0.8	0	106	0	22	35	0.12	831	6.5
	Sarafina	2b	0.4	0	114	40	21	35	0.09	1010	6.3
	Rietspruit	3	0	0	4	80	13	26	0.03	600	7.2
	Taaiboschspruit	4	0	0	6	74	20	9	0.04	559	7.6
	Orkney Vaal	6	1.5	0.3	142	50	50	26	0.03	781	6.4
Koster region	Kaallagte 1	8a	0.8	0.2	0	17	3	9	0.05	508	7.7
	Kaallagte 2	8b	0	0	0	19	3	10	0.04	810	6.3
	Rhenosterfontein	9	0.1	0	0	35	9	14	0.3	593	6.6
	Tlholego 1	10a	0.6	0	12	46	21	49	0.1	1036	7.1
	Tlholego 2	10b	1.2	0.7	93	35	59	79	0.25	1131	7.0
	Tlholego 3	10c	1.4	3.6	108	27	60	79	0.37	1340	7.1
	Tlholego 4	10d	1.4	0.9	72	12	57	91	0.58	1201	7.1
	Roodewal	11	1.2	2.5	104	17	59	78	0.22	931	6.9
Rustenburg region	Rietvlei	12	0.3	2.0	7	175	5	64	0.08	1135	6.8
	Greenside	13	0.3	13	12	81	23	78	0.05	1631	6.3
	Mogwase	14	3.4	0	272	80	99	121	0.06	4500	6.6
	Beestekraal	15	0.7	0	88	39	50	83	0.04	4103	6.3
	Bakgatla	20	0.4	4.7	95	96	26	36	0.01	939	6.5
	Lerome 1	13a	6.5	2.0	0	12	45	39	1.52	1892	6.5
	Lerome 2	21	3.5	4.3	27	70	21	47	0.14	1300	6.4
	Lerome 3	25	5.8	3.8	9	36	93	14	0.08	832	6.5
	Ledig 1	23	2.9	0	28	40	91	45	0.03	591	7.5
	Ledig 2	22	5.7	0.5	23	24	42	93	0.69	1121	7.6
	Lefaragatlhe	24	6.4	0.7	30	42	23	61	0.06	462	6.9
Mafikeng	Lichtenburg	5	0.1	5.2	1	78	7	41	0.03	800	7.1
	Mmabatho	16	1.6	0	56	47	51	4	0.07	847	6.8
	Letlamoreng 1	17	0.6	1.1	33	47	47	31	0.04	997	6.4
	Letlamoreng 2	18	0.5	0.5	69	34	106	130	1.52	2143	6.6

TH = Total hardness as $CaCO_3$, TDS = Total dissolved solids

Appendix H Average sampling values recorded over four sampling opportunities

			F^- ($mg.l^{-1}$)	NO_3-N ($mg.l^{-1}$)	SO_4^{2-} ($mg.l^{-1}$)	Cl^- ($mg.l^{-1}$)	Na^+ ($mg.l^{-1}$)	TH ($mg.l^{-1}$)	Cu^{2+} ($mg.l^{-1}$)	TDS ($mg.l^{-1}$)	pH*
Klerksdorp region	Mooi River	1	0.7	4.2	57	23	87	52	0.05	1168	6.0
	Potch Univ.	2	0.6	3.9	73	15	53	58	0.04	303	6.3
	Boitshoko School	2a	0.5	1.4	49	11	41	23	0.05	1082	6.4
	Sarafina	2b	0.4	0.3	48	19	48	19	0.05	1802	6.3
	Rietspruit	3	0.1	2.2	18	30	67	32	0.03	538	6.3
	Taaiboschspruit	4	0.6	3.7	56	27	106	20	0.03	493	6.3
	Orkney Vaal	6	1.1	1.7	166	36	162	48	0.02	950	6.4
Koster region	Kaallagte 1	8a	0.4	1.3	23	9	54	18	0.04	450	6.3
	Kaallagte 2	8b	0.2	0.5	21	7	46	17	0.06	817	6.1
	Rhenosterfontein	9	0.2	0.8	29	15	64	26	0.4	528	6.3
	Tlholego 1	10a	0.4	0.9	43	17	90	46	0.8	1206	6.3
	Tlholego 2	10b	0.4	0.5	59	14	91	48	0.5	1226	5.9
	Tlholego 3	10c	0.5	1.4	68	8	94	54	0.5	1303	6.3
	Tlholego 4	10d	0.5	0.7	56	9	102	56	0.4	1362	6.3
	Roodewal	11	0.6	1.0	50	23	41	58	0.08	1060	6.4
Rustenburg region	Rietvlei	12	0.1	2.5	21	49	33	54	0.3	1111	6.5
	Greenside	13	0.7	13.6	26	31	117	70	0.3	1484	6.3
	Mogwase	14	3.3	2.0	144	41	269	60	0.1	4939	6.3
	Beestekraal	15	0.7	0.5	94	48	110	54	0.05	4046	6.3
	Bakgatla	20	2.4	4.6	74	55	94	46	0.06	770	6.4
	Lerome 1	13a	3.0	1.6	16	23	35	33	0.6	2186	6.5
	Lerome 2	21	4.1	3.6	45	53	49	40	0.1	1069	6.3
	Lerome 3	25	4.1	4.2	36	33	87	16	0.03	852	6.3
	Ledig 1	23	6.5	1.2	45	34	115	35	0.05	677	6.3
	Ledig 2	22	4.8	2.1	47	35	60	47	0.2	1116	6.2
	Lefaragatlhe	24	2.1	2.5	38	45	81	47	0.04	592	6.1
Mafikeng	Lichtenburg	5	0.5	3.3	30	34	102	41	0.03	889	6.6
	Mmabatho	16	0.7	1.2	48	77	85	67	0.06	747	6.3
	Letlamoreng 1	17	0.7	0.7	44	125	112	61	0.05	1146	6.4
	Letlamoreng 2	18	0.7	0.7	38	139	121	106	0.4	2640	6.5

*minimum values, TH = Total hardness as $CaCO_3$, TDS = Total dissolved solids

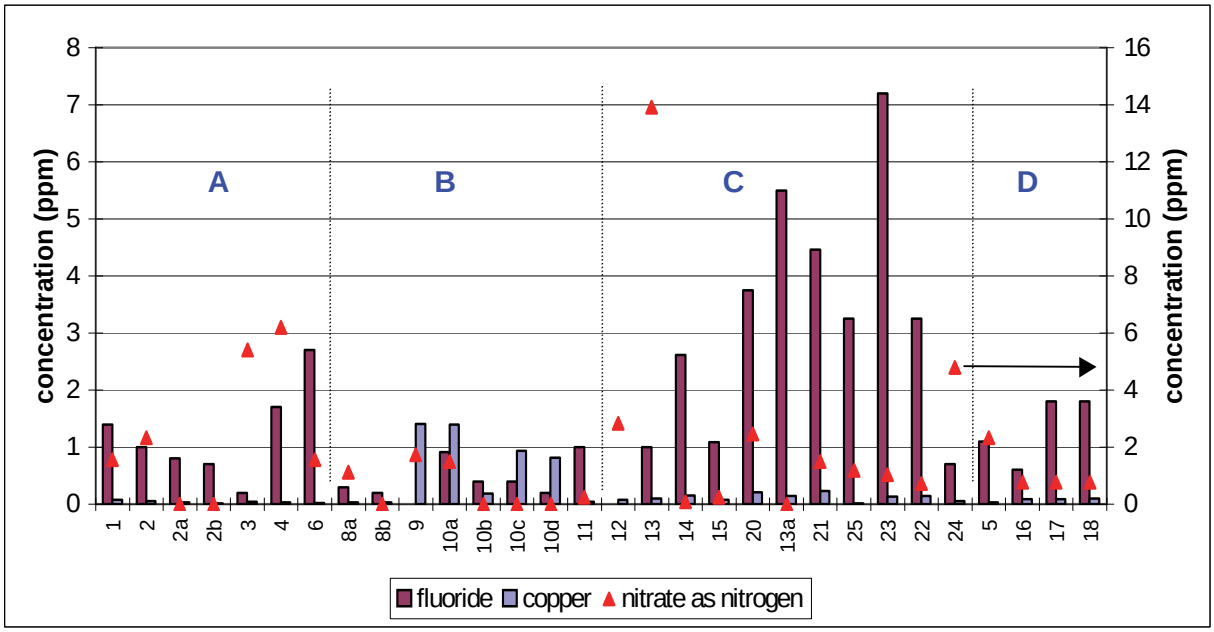
Appendix I Maximum sampling values recorded over sampling opportunities

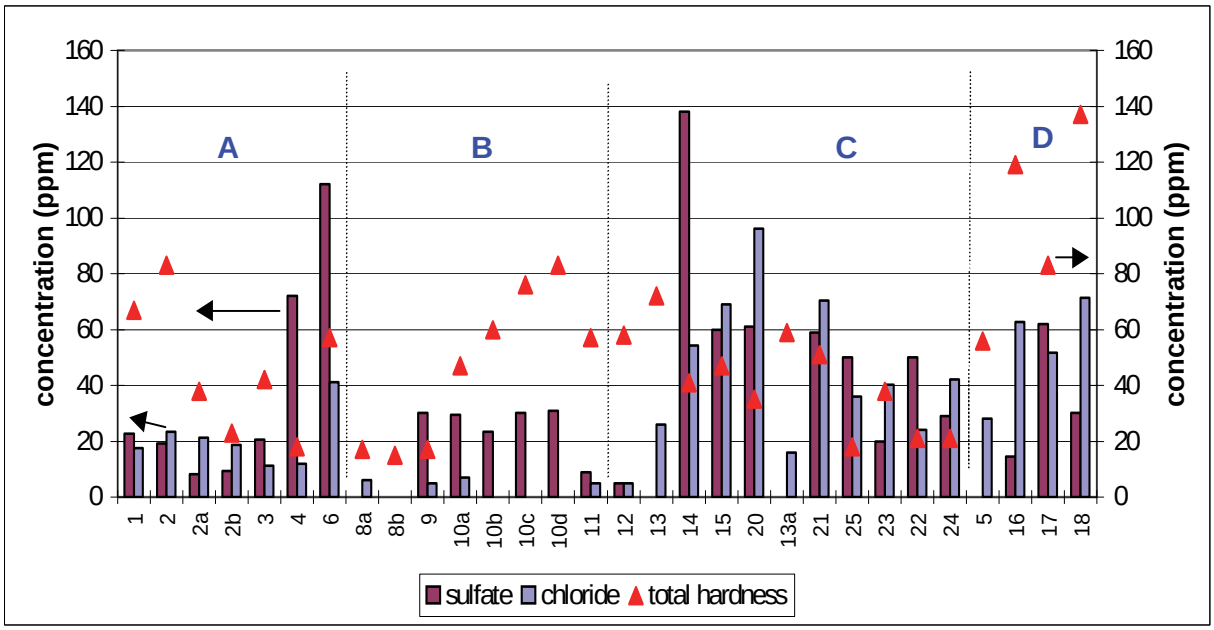
			F^- ($mg.l^{-1}$)	NO_3-N ($mg.l^{-1}$)	SO_4^{2-} ($mg.l^{-1}$)	Cl^- ($mg.l^{-1}$)	Na^+ ($mg.l^{-1}$)	TH ($mg.l^{-1}$)	Cu^{2+} ($mg.l^{-1}$)	TDS ($mg.l^{-1}$)	pH
Klerksdorp region	Mooi River	1	1.4	14.9	120	51	131	67	0.08	1300	7.4
	Potch Univ.	2	1.0	6.3	110	24	83	83	0.06	531	7.2
	Boitshoko School	2a	0.8	5.7	106	23	81	38	0.12	1341	7.3
	Sarafina	2b	0.7	1.1	114	40	62	35	0.09	3042	7.8
	Rietspruit	3	0.2	5.4	28	80	90	42	0.06	831	7.2
	Taaiboschspruit	4	1.7	6.2	83	74	140	31	0.06	631	7.6
	Orkney Vaal	6	2.7	4.1	246	50	210	63	0.03	1280	7.3
Koster region	Kaallagte 1	8a	0.8	2.5	56	17	82	28	0.06	636	7.7
	Kaallagte 2	8b	0.4	2.1	55	19	98	33	0.12	1039	7.5
	Rhenosterfontein	9	0.6	1.7	60	35	91	57	1.41	843	7.8
	Tlholego 1	10a	0.9	2.2	73	46	168	58	1.46	1882	7.1
	Tlholego 2	10b	1.2	1.2	93	35	156	79	1.41	1642	7.4
	Tlholego 3	10c	1.4	3.6	108	27	170	79	0.93	1839	7.1
	Tlholego 4	10d	1.4	1.4	72	23	166	91	0.81	1798	7.1
	Roodewal	11	1.2	2.5	104	71	62	78	0.22	1263	6.9
Rustenburg region	Rietvlei	12	0.3	3.1	63	175	63	64	0.93	1135	7.3
	Greenside	13	1.0	14.7	81	81	215	78	0.96	1753	6.6
	Mogwase	14	6.8	7.1	272	80	339	121	0.15	6468	6.6
	Beestekraal	15	1.1	1.4	183	83	143	83	0.08	5311	6.9
	Bakgatla	20	4.7	7.5	111	96	286	93	0.21	939	6.9
	Lerome 1	13a	6.5	2.9	47	42	45	59	1.52	3367	7.3
	Lerome 2	21	4.5	6.3	59	70	135	51	0.23	1300	7.0
	Lerome 3	25	5.8	8.6	55	61	93	19	0.08	899	7.6
	Ledig 1	23	8.3	3.1	68	55	138	45	0.13	831	7.5
	Ledig 2	22	5.7	5.1	58	93	142	93	0.69	1200	7.6
	Lefaragatlhe	24	6.4	4.8	70	96	168	73	0.06	781	6.9
Mafikeng	Lichtenburg	5	1.1	5.2	59	78	178	60	0.05	964	7.6
	Mmabatho	16	1.6	2.6	69	197	128	119	0.09	847	6.8
	Letlamoreng 1	17	1.8	1.1	62	402	139	83	0.09	1396	6.6
	Letlamoreng 2	18	1.8	1.0	69	451	193	137	1.52	3373	7.2

TH = Total hardness as $CaCO_3$, TDS = Total dissolved solids

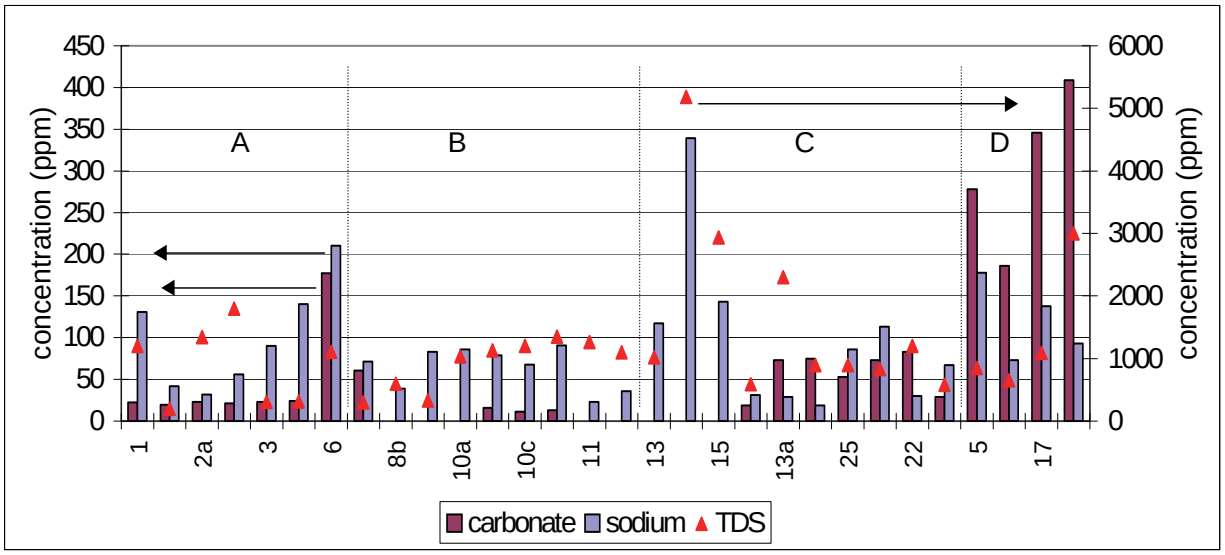
Appendix J Graphical presentation of the sampling data

First sampling: Beginning of rainy season (BRS)



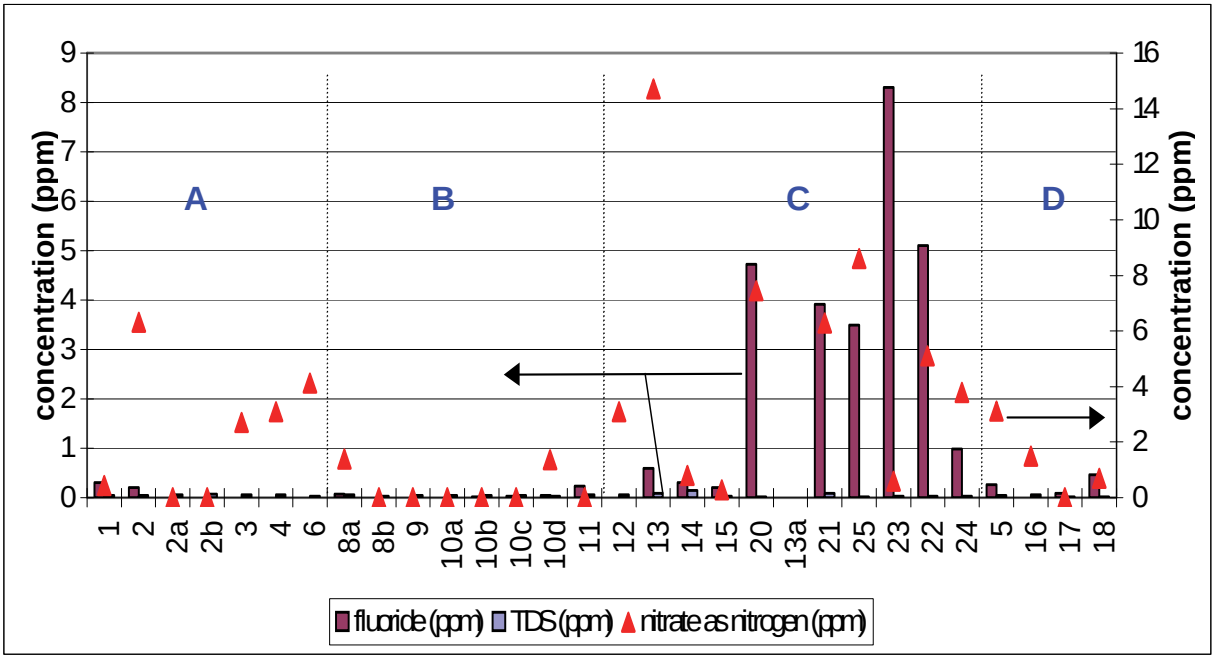


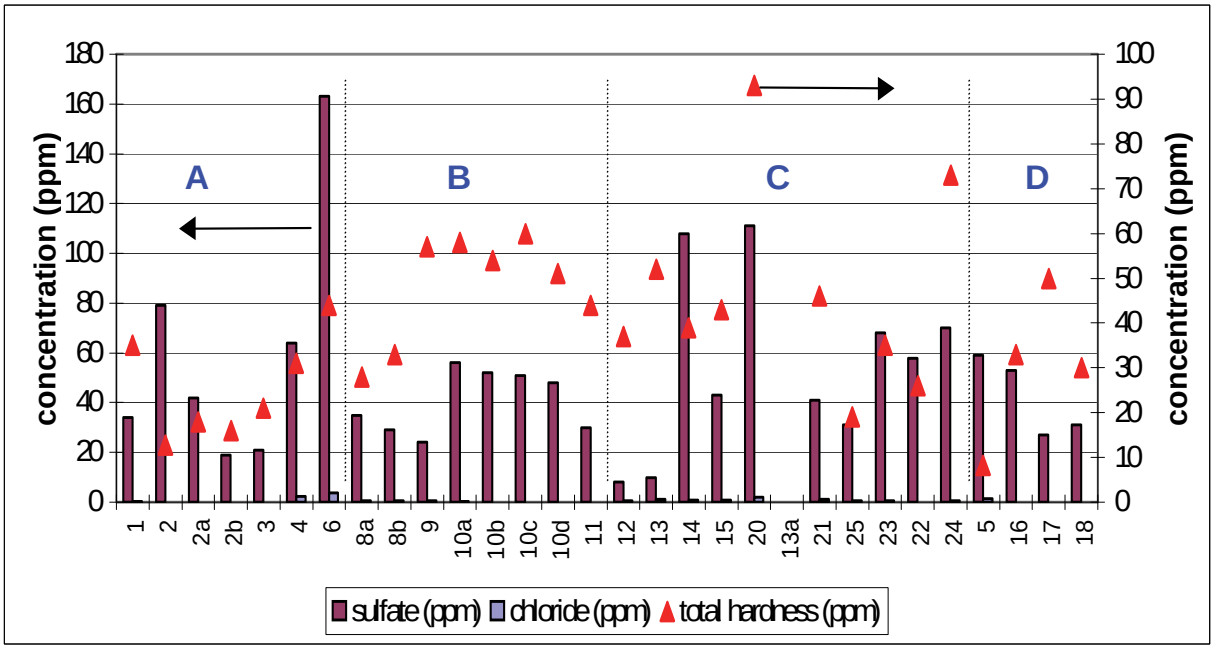
Appendix J (continued…)



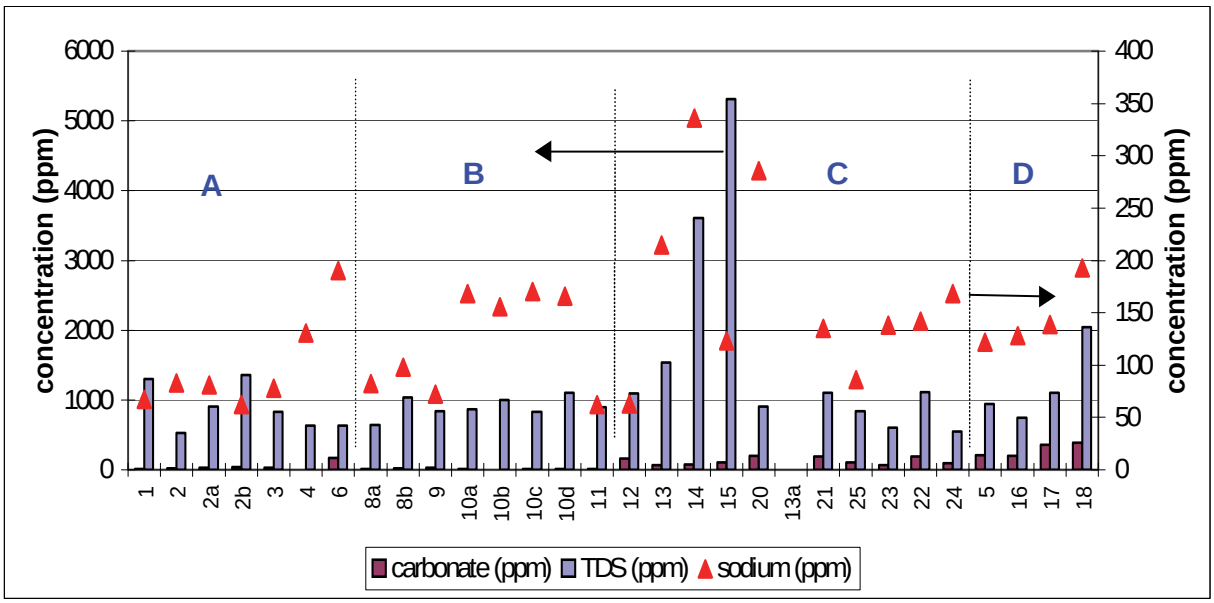
Appendix J (continued…)

Second Sampling: Middle of rainy season (MRS)



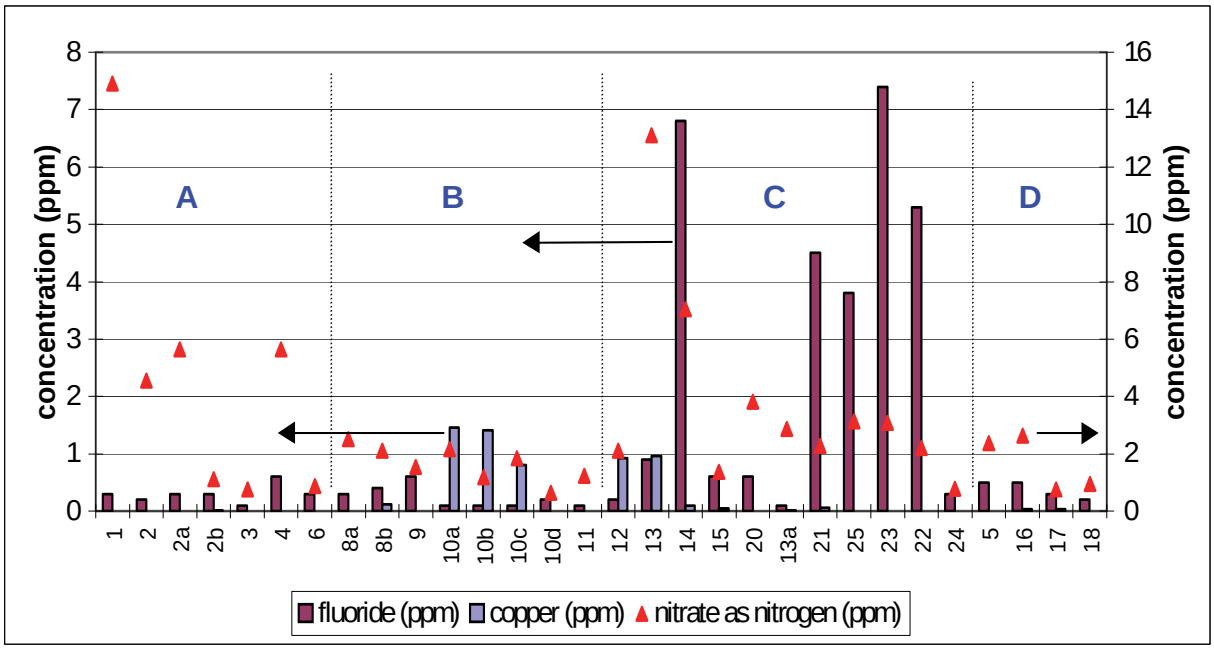


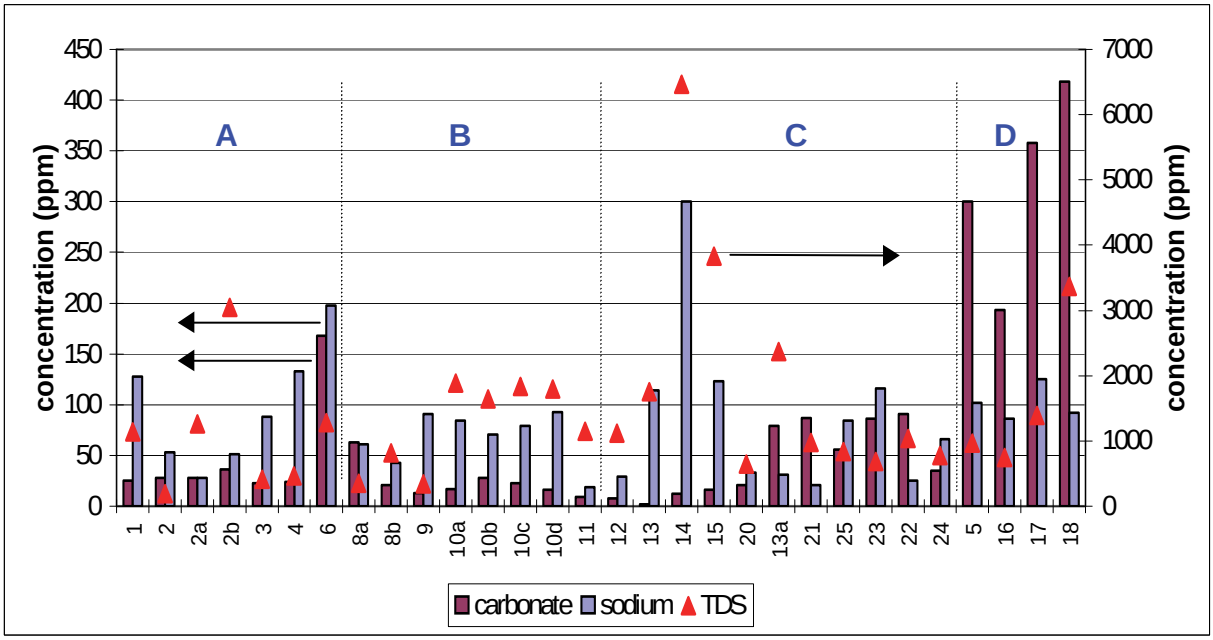
Appendix J (continued…)



Appendix J (continued…)

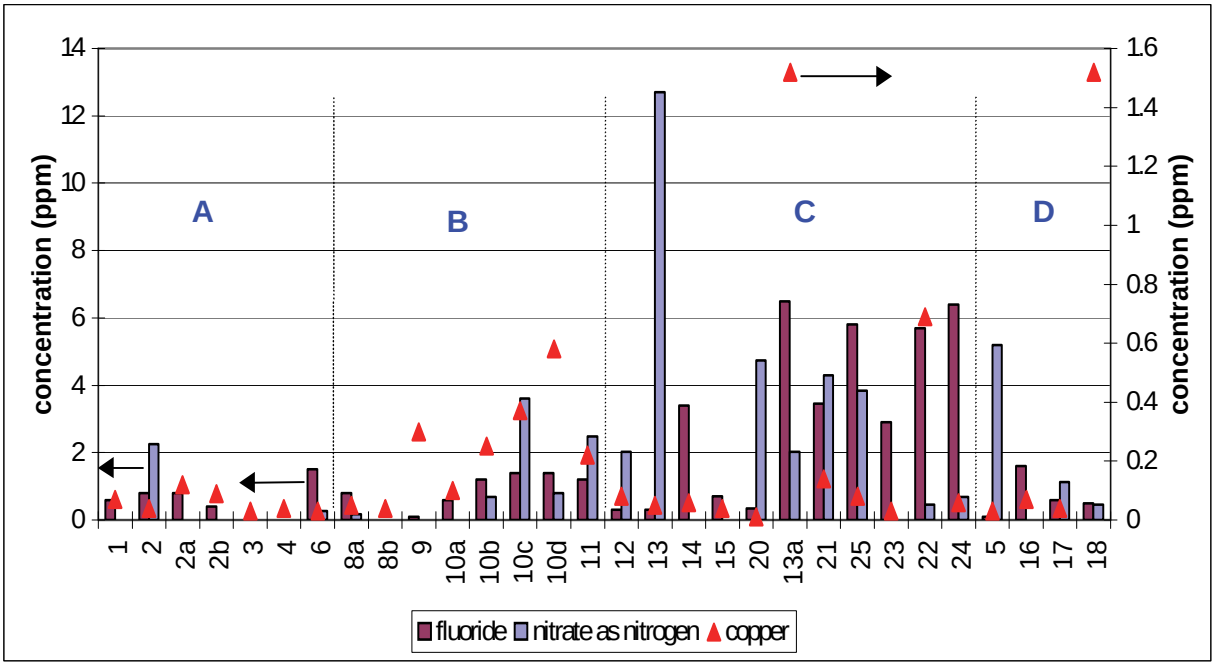
Third sampling: Beginning of dry season (BDS)

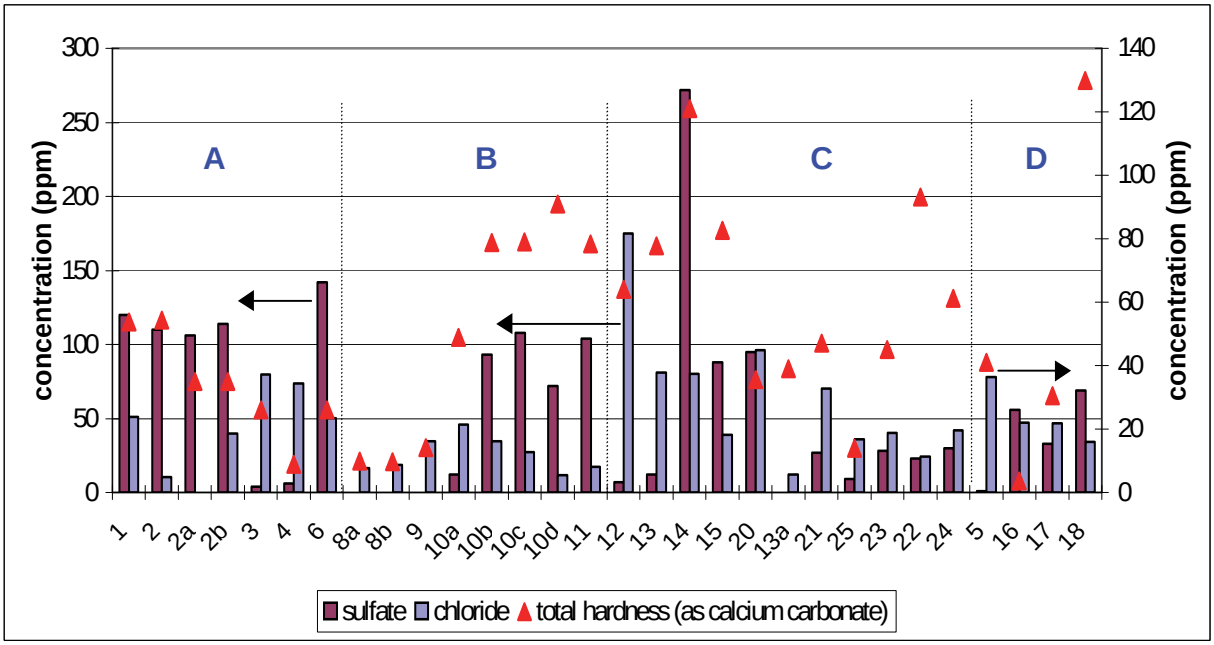




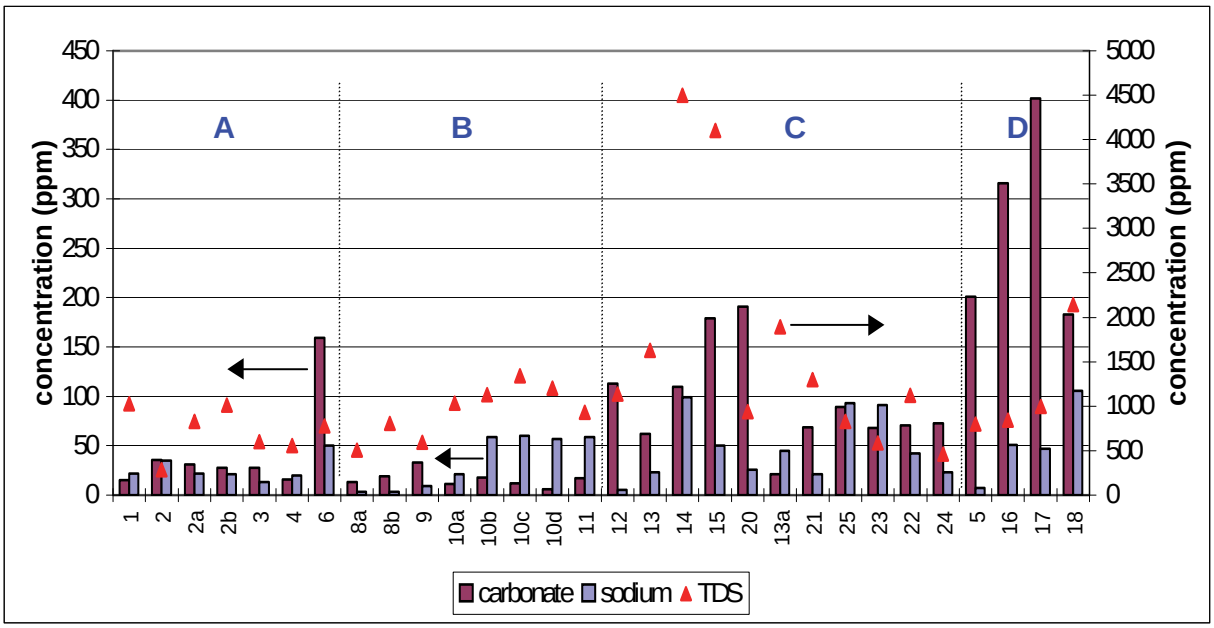
Appendix J (continued…)

Fourth sampling: Middle of dry season



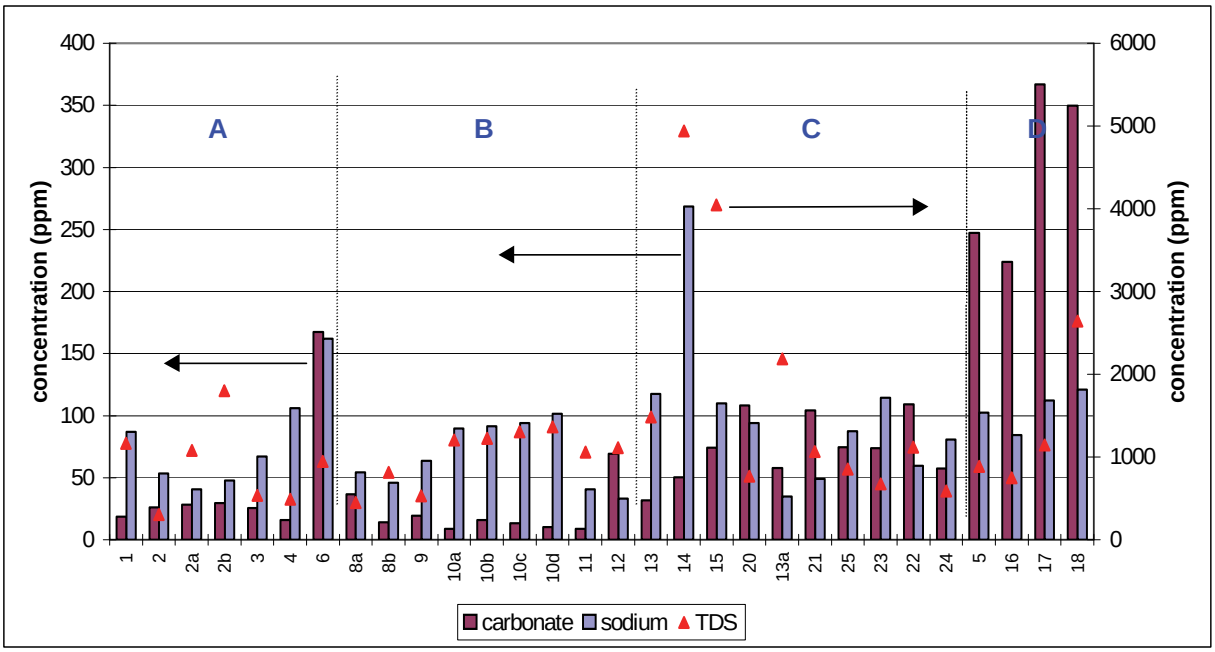


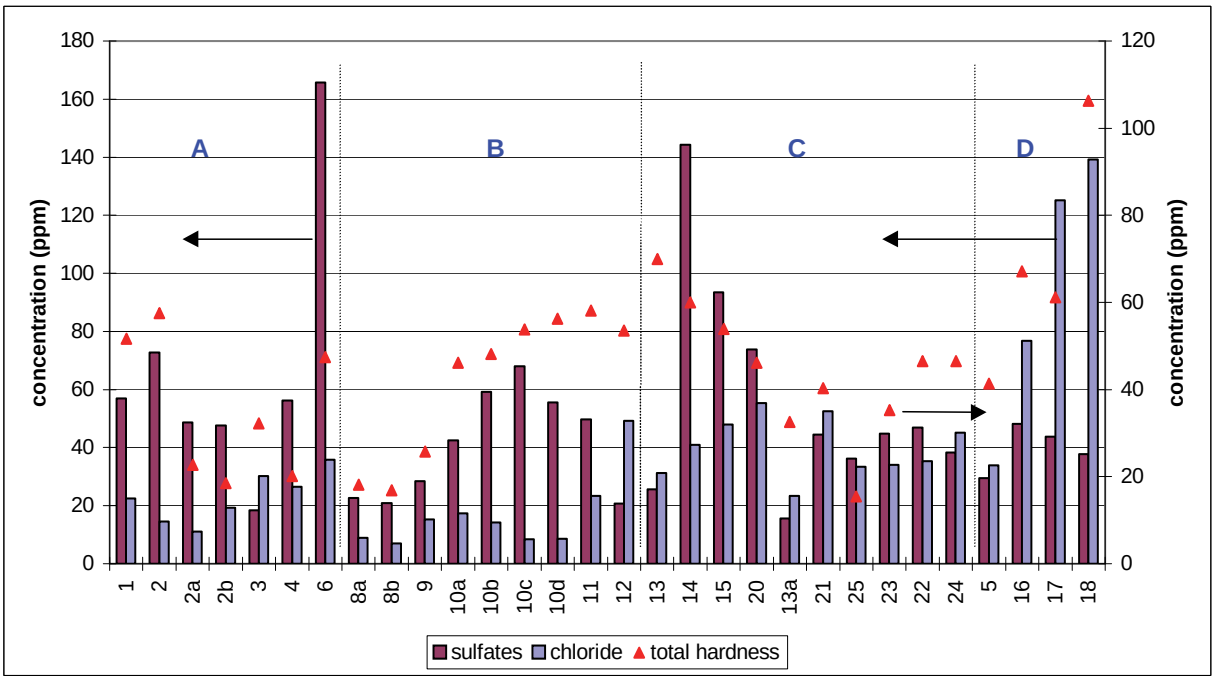
Appendix J (continued…)



Appendix J (continued…)

Averaged values





Appendix K Water classification by maximum recorded values of components in the sampled water for the Rustenburg, Klerksdorp and Koster regions

Rustenburg

		Sampling point										
		12	**13**	**14**	**15**	**20**	**13a**	**21**	**25**	**23**	**22**	**24**
Fluoride	Drinking (Health)	B	G	P	Y	P	P	P	P	P	P	P
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	G	P	Y	P	P	P	P	P	P	P
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Nitrate	Drinking Health	B	Y	G	B	G	B	G	G	B	B	B
	Drinking Aesthetic	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	Y	G	B	G	B	G	G	B	B	B
	Bathing	B	G	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Sulfate	Drinking Health	B	B	Y	G	G	B	B	B	B	B	B
	Drinking Aesthetic	B	B	Y	G	G	B	B	B	B	B	B
	Food preparation	B	B	Y	G	G	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	Y	G	G	B	B	B	B	B	B

Rustenburg

		Sampling point										
		12	**13**	**14**	**15**	**20**	**13a**	**21**	**25**	**23**	**22**	**24**
pH	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Chloride	Drinking (Health)	G	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	G	B	B	B	B	B	B	B	B	B	B
	Food preparation	G	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Sodium	Drinking (Health)	B	Y	Y	G	Y	B	G	B	G	G	G
	Drinking (Aesthetic)	B	Y	Y	G	Y	B	G	B	G	G	G
	Food preparation	B	Y	Y	G	Y	B	G	B	G	G	G
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Total hardness	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	G	B	B	B	B	B	B	B	B
	Bathing	G	G	G	G	G	G	G	B	G	G	G
	Laundry	B	B	G	B	B	B	B	Y	G	B	B
Copper	Drinking (Health)	B	B	B	B	B	Y	B	B	B	B	B
	Drinking (Aesthetic)	G	G	B	B	B	Y	B	B	B	G	B
	Food preparation	G	G	B	B	B	Y	B	B	B	G	B
	Bathing	B	B	B	B	B	Y	B	B	B	B	B
	Laundry	G	G	B	B	B	Y	B	B	B	G	B
TDS	Drinking (Health)	Y	Y	P	P	G	Y	Y	G	G	Y	G
	Drinking (Aesthetic)	Y	Y	P	P	G	Y	Y	G	G	Y	G
	Food preparation	Y	Y	P	P	G	Y	Y	G	G	Y	G
	Bathing	B	B	Y	Y	B	B	B	B	B	B	B
	Laundry	G	G	R	R	B	G	G	G	G	G	B

Appendix K (continued…)

Rustenburg

		Sampling point										
		12	**13**	**14**	**15**	**20**	**13a**	**21**	**25**	**23**	**22**	**24**
pH	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Chloride	Drinking (Health)	G	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	G	B	B	B	B	B	B	B	B	B	B
	Food preparation	G	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Sodium	Drinking (Health)	B	Y	Y	G	Y	B	G	B	G	G	G
	Drinking (Aesthetic)	B	Y	Y	G	Y	B	G	B	G	G	G
	Food preparation	B	Y	Y	G	Y	B	G	B	G	G	G
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Total hardness	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	G	B	B	B	B	B	B	B	B
	Bathing	G	G	G	G	G	G	G	B	G	G	G
	Laundry	B	B	G	B	B	B	B	Y	G	B	B
Copper	Drinking (Health)	B	B	B	B	B	Y	B	B	B	B	B
	Drinking (Aesthetic)	G	G	B	B	B	Y	B	B	B	G	B
	Food preparation	G	G	B	B	B	Y	B	B	B	G	B
	Bathing	B	B	B	B	B	Y	B	B	B	B	B
	Laundry	G	G	B	B	B	Y	B	B	B	G	B
TDS	Drinking (Health)	Y	Y	P	P	G	Y	Y	G	G	Y	G
	Drinking (Aesthetic)	Y	Y	P	P	G	Y	Y	G	G	Y	G
	Food preparation	Y	Y	P	P	G	Y	Y	G	G	Y	G
	Bathing	B	B	Y	Y	B	B	B	B	B	B	B
	Laundry	G	G	R	R	B	G	G	G	G	G	B

Appendix K (continued…)

Klerksdorp and Koster

		Sampling point													
		Klerksdorp							Koster						
		1	2	2a	2b	3	4	6	8a	8b	9	10a	10b	10c	10d
pH	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Chloride	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Sodium	Drinking (Health)	G	B	B	B	B	G	Y	B	B	B	G	G	G	G
	Drinking (Aesthetic)	G	B	B	B	B	G	Y	B	B	B	G	G	G	G
	Food preparation	G	B	B	B	B	G	Y	B	B	B	G	G	G	G
	Bathing	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Total hardness	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Bathing	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	Laundry	B	B	G	G	G	G	B	G	G	B	B	B	B	B
Copper	Drinking (Health)	B	B	B	B	B	B	B	B	Y	Y	Y	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	Y	Y	Y	G	G	B
	Food preparation	B	B	B	B	B	B	B	B	Y	Y	Y	G	G	B
	Bathing	B	B	B	B	B	B	B	B	Y	Y	Y	B	B	B
	Laundry	B	B	B	B	B	B	B	B	Y	Y	Y	G	G	B
Fluoride	Drinking (Health)	Y	G	G	G	B	R	R	G	B	B	G	Y	Y	Y
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	Y	G	G	G	B	R	R	G	B	B	G	Y	Y	Y
	Bathing	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Nitrate	Drinking (Health)	Y	G	G	B	B	G	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	Y	G	G	B	B	G	B	B	B	B	B	B	B	B
	Bathing	G	B	B	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Sulfate	Drinking (Health)	B	B	B	B	B	B	G	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	G	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	G	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	G	B	B	B	B	B	B	B
TDS	Drinking (Health)	Y	G	Y	R	G	G	Y	G	Y	G	Y	Y	Y	Y
	Drinking (Aesthetic)	Y	G	Y	R	G	G	Y	G	Y	G	Y	Y	Y	Y
	Food preparation	Y	G	Y	R	G	G	Y	G	Y	G	Y	Y	Y	Y
	Bathing	B	B	B	G	B	B	B	B	B	B	B	B	B	B
	Laundry	G	B	G	Y	B	B	G	B	G	B	G	G	G	G

Appendix L Water classification based on average recorded values over four sampling opportunities for the Rustenburg, Klerksdorp and Koster regions

Rustenburg

		Sampling point										
		12	**13**	**14**	**15**	**20**	**13a**	**21**	**25**	**23**	**22**	**24**
Fluoride	Drinking (Health)	B	G	R	B	R	R	P	P	P	P	R
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	G	R	B	R	R	P	P	P	P	R
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Nitrate	Drinking (Health)	B	Y	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	Y	B	B	B	B	B	B	B	B	B
	Bathing	B	G	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Sulfate	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B

Rustenburg

Average values		Sampling point										
		12	**13**	**14**	**15**	**20**	**13a**	**21**	**25**	**23**	**22**	**24**
pH	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Chloride	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Sodium	Drinking (Health)	B	G	Y	Y	B	B	B	B	G	B	B
	Drinking (Aesthetic)	B	G	Y	Y	B	B	B	B	G	B	B
	Food preparation	B	G	Y	Y	B	B	B	B	G	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Total hardness	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B
	Bathing	G	G	G	G	G	G	G	B	G	G	G
	Laundry	G	B	B	B	G	G	G	Y	G	G	G
Copper	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	G	B	B	B	B	B
	Food preparation	B	B	B	B	B	G	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	G	B	B	B	B	B
TDS	Drinking (Health)	Y	Y	P	P	G	Y	Y	G	G	Y	G
	Drinking (Aesthetic)	Y	Y	P	P	G	Y	Y	G	G	Y	G
	Food preparation	Y	Y	P	P	G	Y	Y	G	G	Y	G
	Bathing	B	B	Y	Y	B	B	B	B	B	B	B
	Laundry	G	G	R	R	B	G	G	B	B	G	B

Appendix L (continued…)

Rustenburg

		Sampling point										
		12	**13**	**14**	**15**	**20**	**13a**	**21**	**25**	**23**	**22**	**24**
pH	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Chloride	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Sodium	Drinking (Health)	B	G	Y	Y	B	B	B	B	G	B	B
	Drinking (Aesthetic)	B	G	Y	Y	B	B	B	B	G	B	B
	Food preparation	B	G	Y	Y	B	B	B	B	G	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B
Total hardness	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B
	Bathing	G	G	G	G	G	G	G	B	G	G	G
	Laundry	G	B	B	B	G	G	G	Y	G	G	G
Copper	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	G	B	B	B	B	B
	Food preparation	B	B	B	B	B	G	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	G	B	B	B	B	B
TDS	Drinking (Health)	Y	Y	P	P	G	Y	Y	G	G	Y	G
	Drinking (Aesthetic)	Y	Y	P	P	G	Y	Y	G	G	Y	G
	Food preparation	Y	Y	P	P	G	Y	Y	G	G	Y	G
	Bathing	B	B	Y	Y	B	B	B	B	B	B	B
	Laundry	G	G	R	R	B	G	G	B	B	G	B

Appendix L (continued…)

Klerksdorp and Koster

		Sampling point													
		Klerksdorp							Koster						
		1	**2**	**2a**	**2b**	**3**	**4**	**6**	**8a**	**8b**	**9**	**10a**	**10b**	**10c**	**10d**
pH	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Chloride	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Sodium	Drinking (Health)	B	B	B	B	B	G	G	B	B	B	B	B	G	B
	Drinking (Aesthetic)	B	B	B	B	B	G	G	B	B	B	B	B	G	B
	Food preparation	B	B	B	B	B	G	G	B	B	B	B	B	G	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Total hardness	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Bathing	G	G	B	B	G	B	G	B	B	B	G	G	G	G
	Laundry	B	B	Y	Y	G	Y	G	Y	Y	Y	G	G	B	B
Copper	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	G	B	G	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	G	B	G	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B	B	G	B
Fluoride	Drinking (Health)	B	B	B	B	B	B	Y	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	Y	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Nitrate	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Sulfate	Drinking (Health)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B	B	B	B	B	B	B
TDS	Drinking (Health)	Y	B	Y	Y	G	G	G	G	G	G	Y	Y	Y	Y
	Drinking (Aesthetic)	Y	B	Y	Y	G	G	G	G	G	G	Y	Y	Y	Y
	Food preparation	Y	B	Y	Y	G	G	G	G	G	G	Y	Y	Y	Y
	Bathing	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	Laundry	G	B	G	G	B	B	B	B	B	B	G	G	G	G

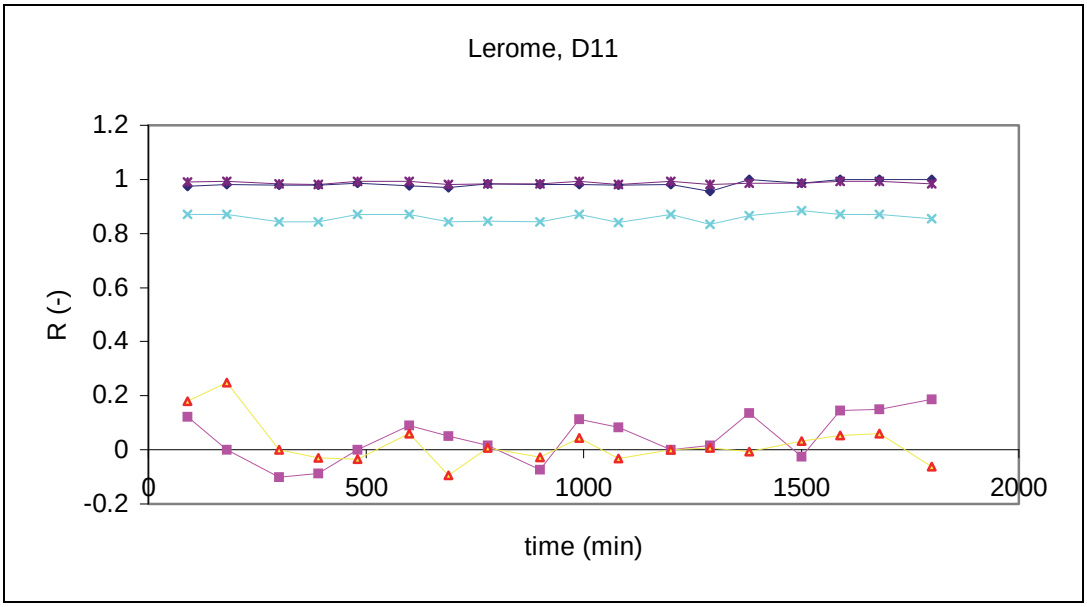
Appendix M The water classification (maximum and average values) in the Mafikeng region

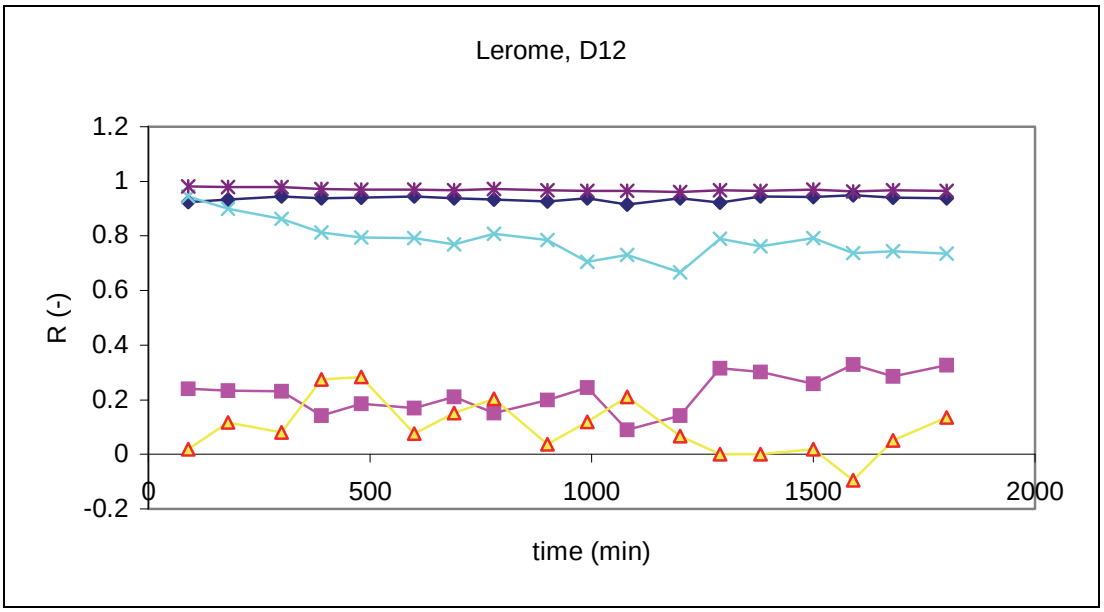
		Sampling colour classification							
		Average composition				Maximum composition			
		5	16	17	18	5	16	17	18
pH	Drinking (Health)	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B
Fluoride	Drinking (Health)	B	B	B	G	Y	R	R	R
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	G	Y	R	R	R
	Bathing	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B
Nitrate	Drinking (Health)	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B
Sulfate	Drinking (Health)	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	B	B	B	B	B
	Bathing	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B
Chloride	Drinking (Health)	B	B	G	G	B	G	Y	Y
	Drinking (Aesthetic)	B	B	G	G	B	G	Y	Y
	Food preparation	B	B	G	G	B	G	Y	Y
	Bathing	B	B	B	B	B	B	B	B
	Laundry	B	B	G	G	B	G	Y	Y
Sodium	Drinking (Health)	G	B	G	G	G	G	G	G
	Drinking (Aesthetic)	G	B	G	G	G	G	G	G
	Food preparation	G	B	G	G	G	G	G	G
	Bathing	B	B	B	B	B	B	B	B
	Laundry	B	B	B	B	B	B	B	B
Total hardness	Drinking (Health)	B	B	B	B	B	B	B	B
	Drinking (Aesthetic)	B	B	B	B	B	B	B	B
	Food preparation	B	B	B	G	B	G	B	G
	Bathing	G	G	G	G	G	G	G	G
	Laundry	G	B	B	G	B	G	B	G
Copper	Drinking (Health)	B	B	B	B	B	B	B	Y
	Drinking (Aesthetic)	B	B	B	B	B	B	B	Y
	Food preparation	B	B	B	B	B	B	B	Y
	Bathing	B	B	B	B	B	B	B	Y
	Laundry	B	B	B	B	B	B	B	Y
TDS	Drinking (Health)	G	G	Y	R	G	G	Y	R
	Drinking (Aesthetic)	G	G	Y	R	G	G	Y	R
	Food preparation	G	G	Y	R	G	G	Y	R
	Bathing	B	B	B	G	B	B	B	G
	Laundry	B	B	G	Y	B	B	G	Y

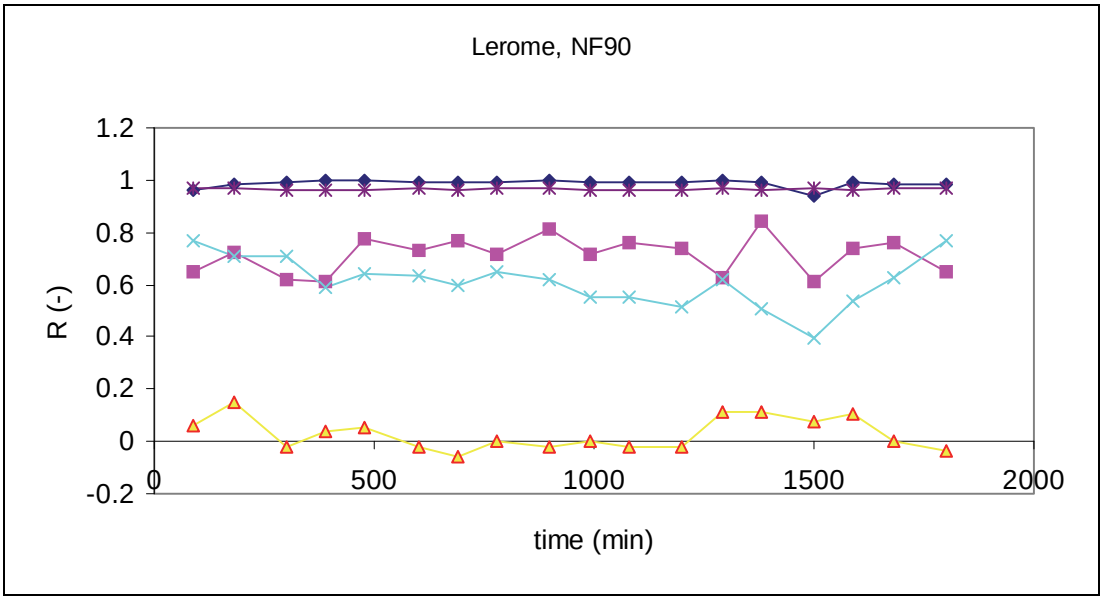
Appendix N General performance of NF membranes

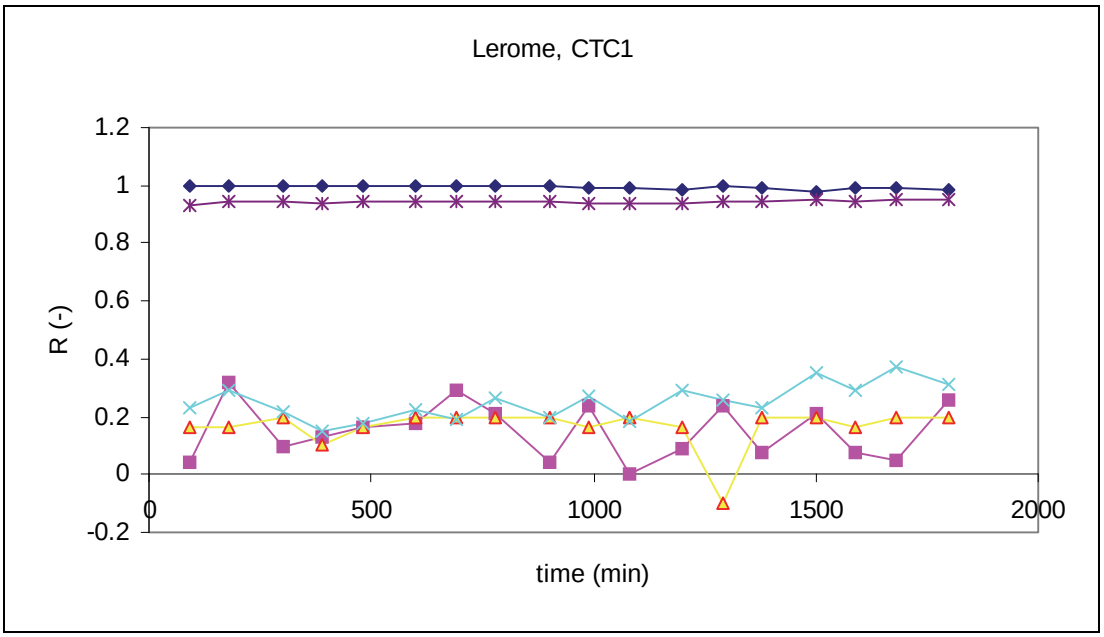
Membrane performance									
		D11	D12	NF70	NF90	TFC-S	TFC-SR	TFC-ULP	CTC-1
Lerome	Fluoride	- -	- -	+ +	- -	+ +	- -	+ +	- -
	Nitrate	- -	+	+ +	-	- -	- -	+	- -
	Overall	- -	- -	+ +	- -	-	- -	+ +	- -
	Sulfate	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +
	Calcium	- -	+ -	-	+ +	- -	+ +	- -	- -
	Magnesium	- -	- -	-	- -	-	- -	-	- -
	Overall	-	+ -	+	+ +	+ -	+ +	+ -	- -
Membrane performance									
		D11	**D12**	**NF70**	**NF90**	**TFC-S**	**TFC-SR**	**TFC-ULP**	**CTC-1**
Kaallaagte	Fluoride	+ +	- -	-	- -	- -	- -	+ +	- -
	Nitrate	- -	- -	+ +	+ +	+	- -	- -	-
	Overall	-	- -	+ -	-	-	- -	- -	- -
	Sulfate	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +
	Calcium	+ +	- -	+ +	+ -	- -	+ +	- -	+
	Magnesium	- -	-	-	- -	- -	- -	-	- -
	Overall	+	-	+ +	+ -	-	+ +	-	+ -
Membrane performance									
		D11	**D12**	**NF70**	**NF90**	**TFC-S**	**TFC-SR**	**TFC-ULP**	**CTC-1**
Rhenosterfontein	Fluoride	-	- -	- -	- -	+ +	+	- -	+ -
	Nitrate	- -	- -	+ +	- -	- -	- -	-	- -
	Overall	- -	- -	-	- -	+ -	-	- -	-
	Sulfate	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +
	Calcium	+ +	-	+ +	+ -	- -	-	+ -	+ +
	Magnesium	- -	- -	- -	- -	- -	- -	- -	- -
	Overall	+	+ -	+	-	+ -	+	+ -	+ +
Membrane performance									
		D11	**D12**	**NF70**	**NF90**	**TFC-S**	**TFC-SR**	**TFC-ULP**	**CTC-1**
Rietvlei	Fluoride	- -	- -	- -	- -	- -	- -	- -	- -
	Nitrate	- -	-	+	- -	-	- -	- -	- -
	Overall	- -	- -	-	- -	- -	- -	- -	- -
	Sulfate	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +
	Calcium	+ +	-	+ -	+ -	+ -	+ -	+ +	+ -
	Magnesium	- -	- -	+ +	- -	-	- -	- -	+ -
	Overall	+	-	+ +	+ -	+	+	+	+ +
Membrane performance									
		D11	**D12**	**NF70**	**NF90**	**TFC-S**	**TFC-SR**	**TFC-ULP**	**CTC-1**
Vaal River	Fluoride	- -	- -	+ +	- -	- -	- -	- -	- -
	Nitrate	-	-	+ -	-	+ -	-	+	+ -
	Overall	- -	-	+ +	- -	- -	-	-	- -
	Sulfate	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +
	Calcium	- -	- -	+ +	+ +	- -	+ +	-	- -
	Magnesium	- -	- -	-	- -	+ -	-	- -	- -
	Overall	- -	- -	+ +	+ -	+ -	+ +	+ -	-

Appendix O Rejection of different chemical components in the Lerome water over time (Temperature = ambient, cross-flow unit)



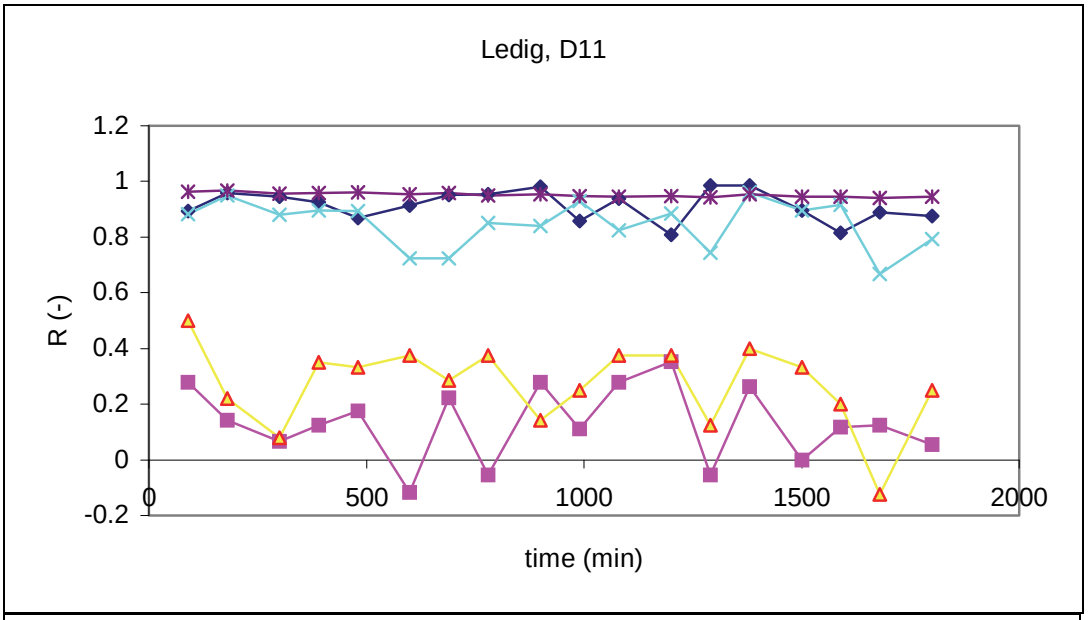


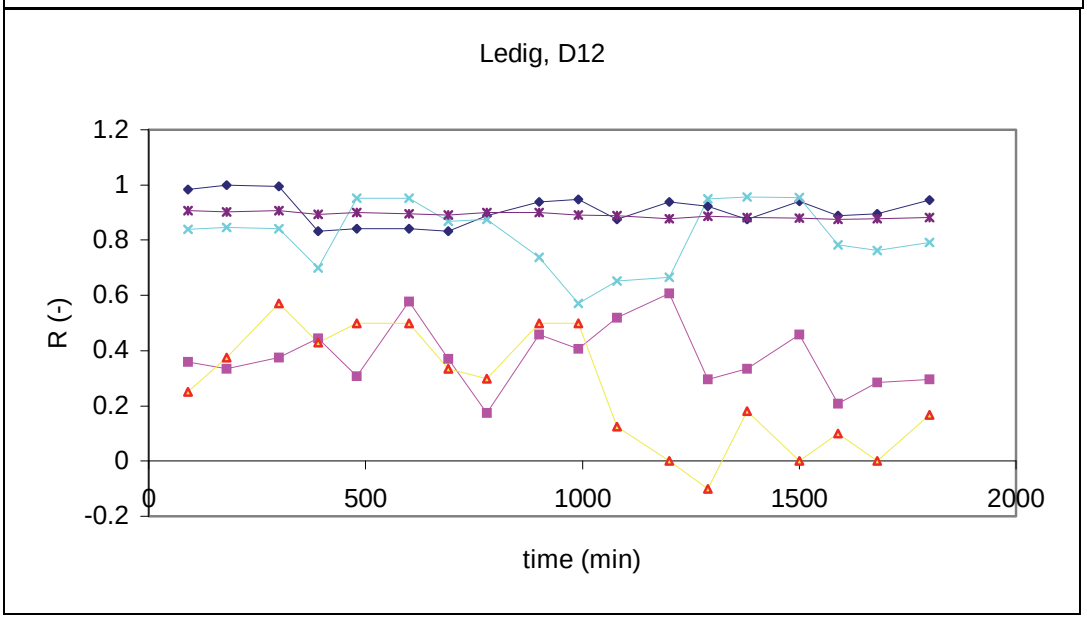


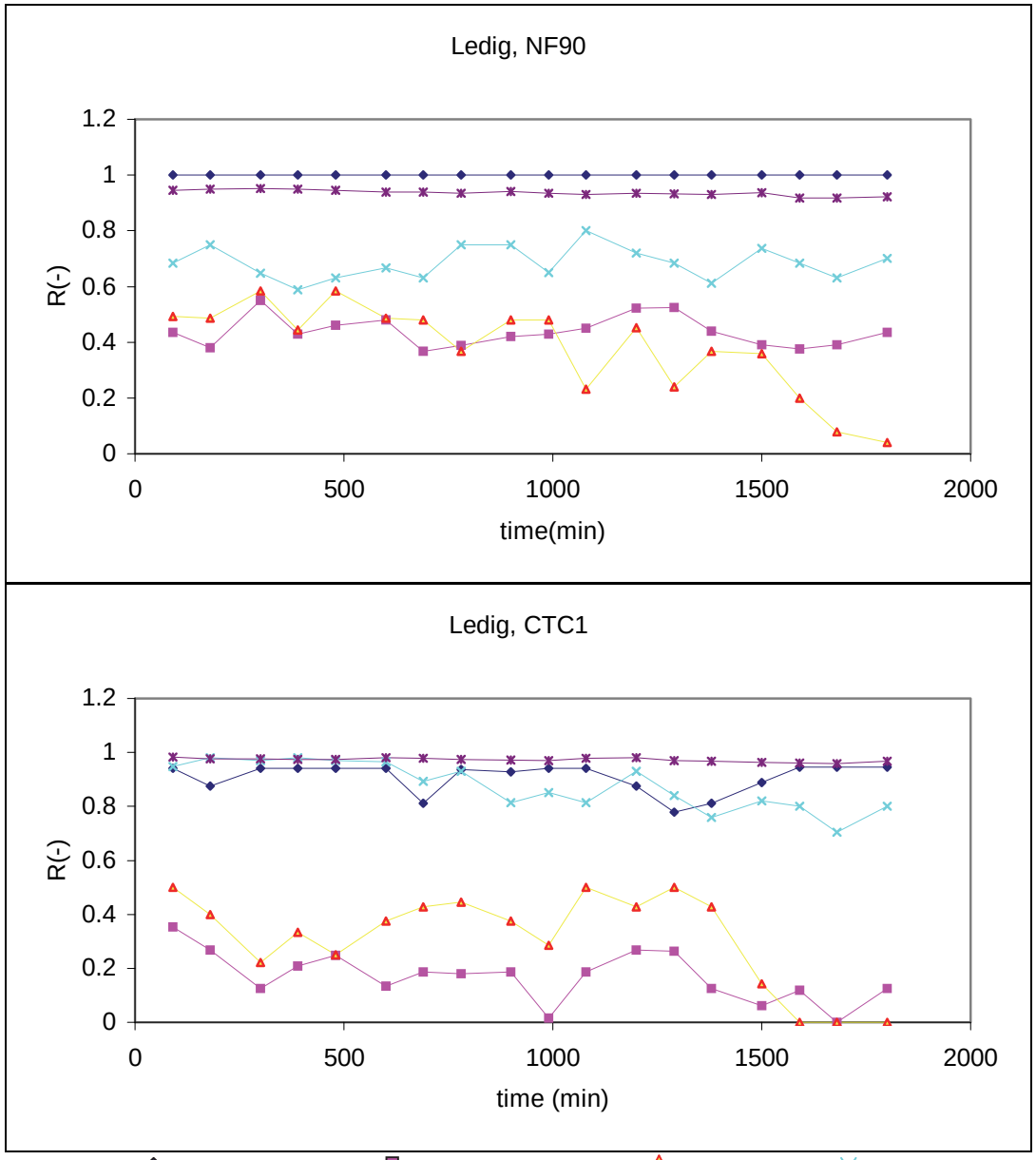


sulfate nitrate fluoride TH TDS

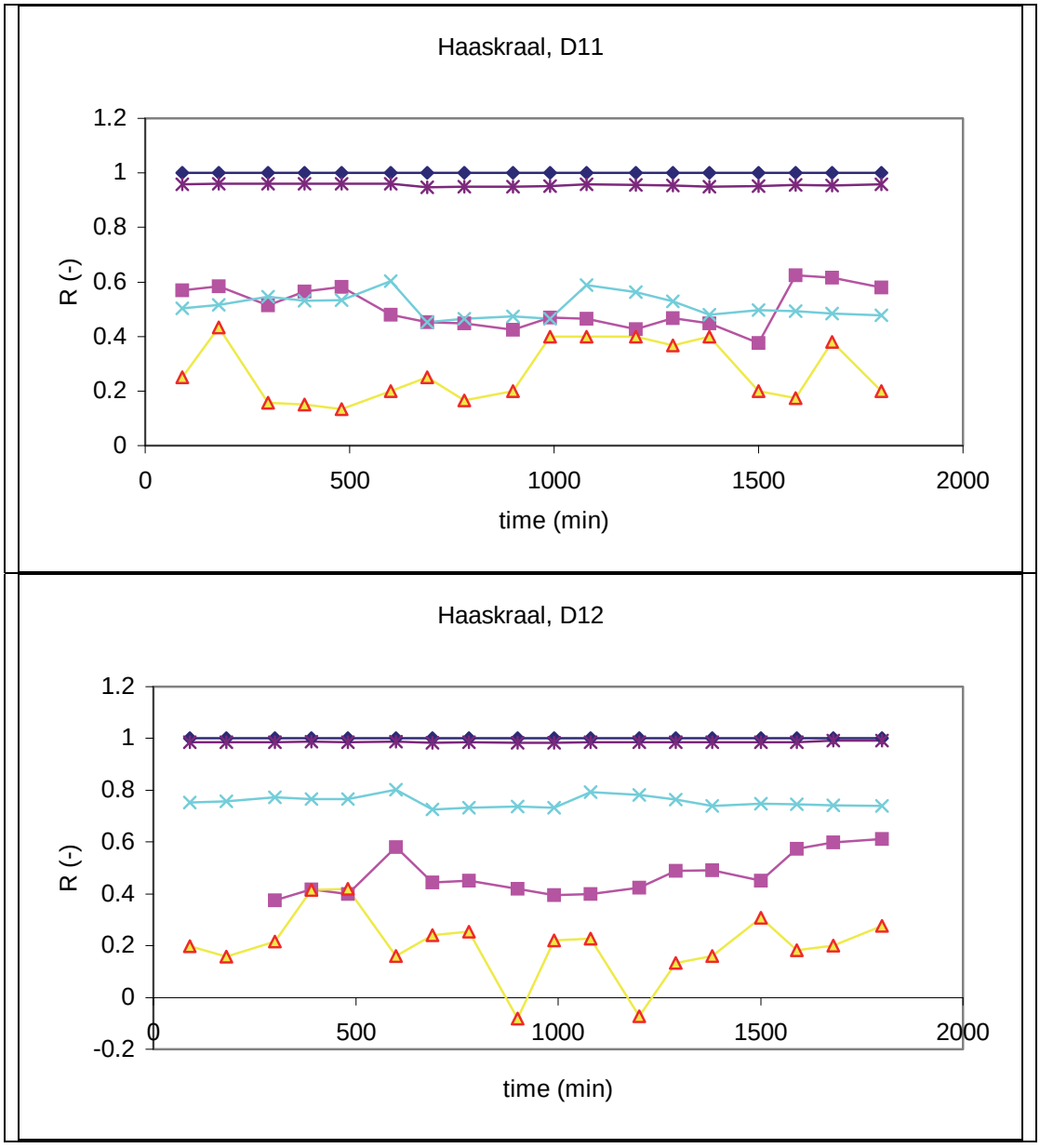
Appendix P Rejection of different chemical components on various membranes in the Ledig water over time (Temperature = ambient, cross-flow unit)

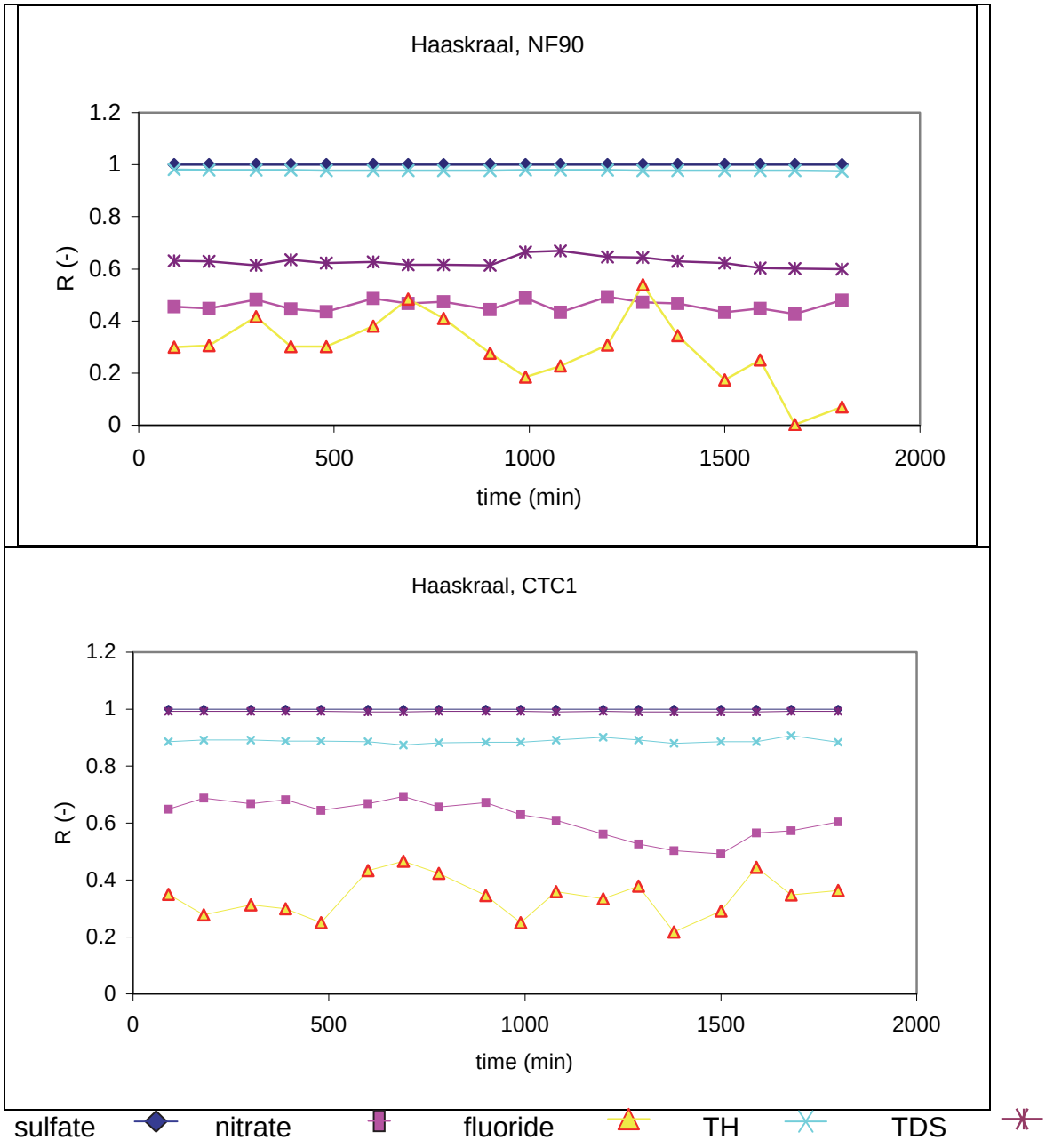




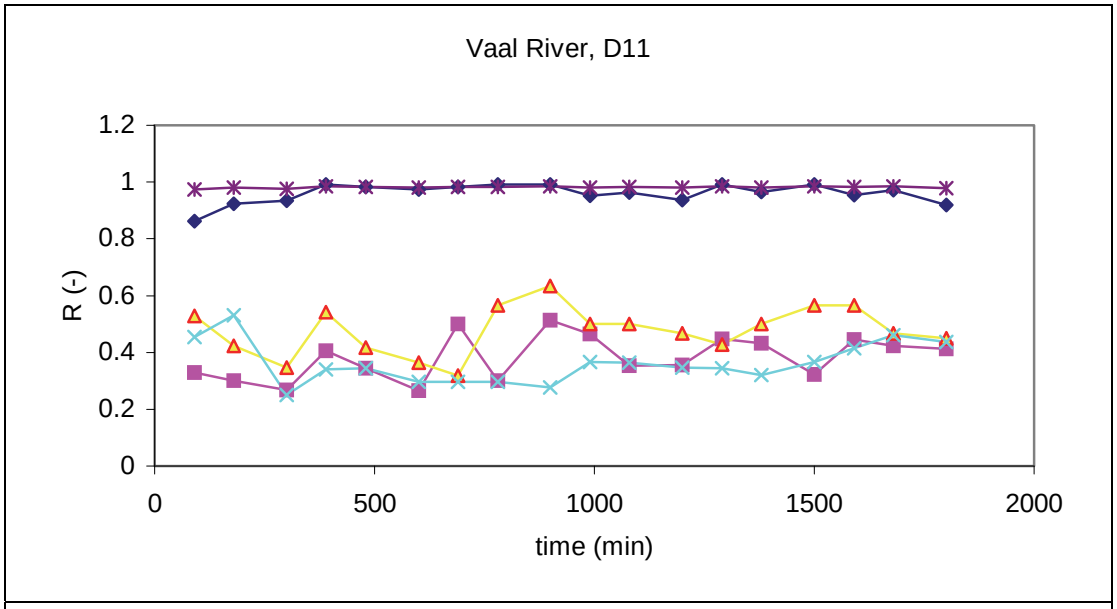

Ledig, NF90
1.2
1
0.8
0.6
0.4
0.2
0
R(-)
0
500
1000
1500
2000
time(min)
Ledig, CTC1
1.2
1
0.8
0.6
0.4
0.2
0
R(-)
0
500
1000
1500
2000
time (min)
sulfate
nitrate
fluoride
TH
TDS

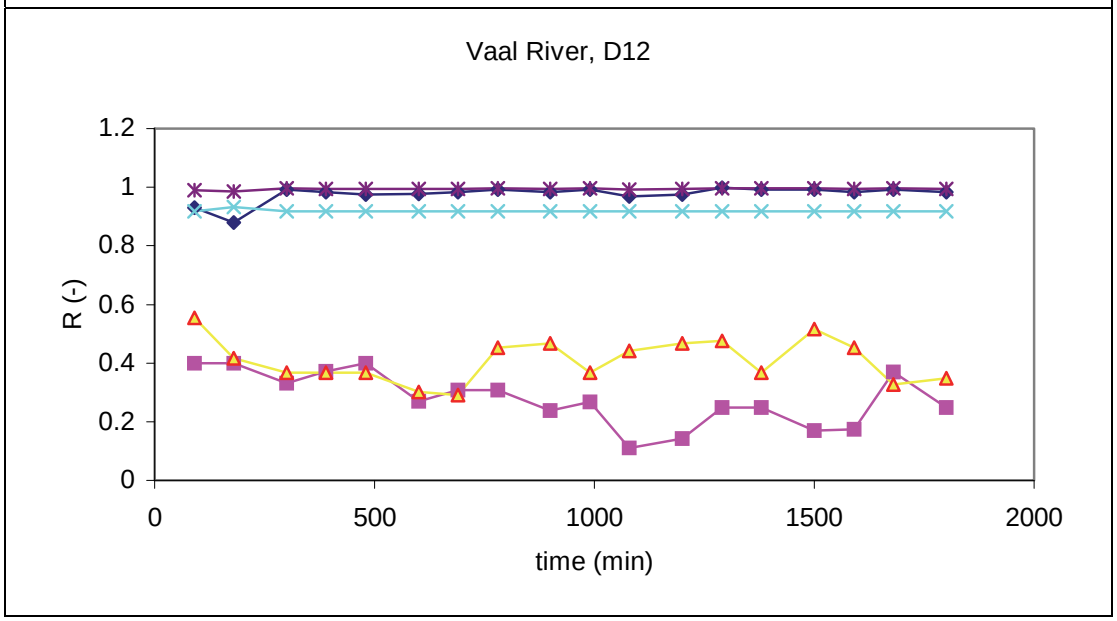
Appendix Q Rejection of different chemical components on various membranes in the Haaskraal water over time (Temperature = ambient, cross-flow unit)

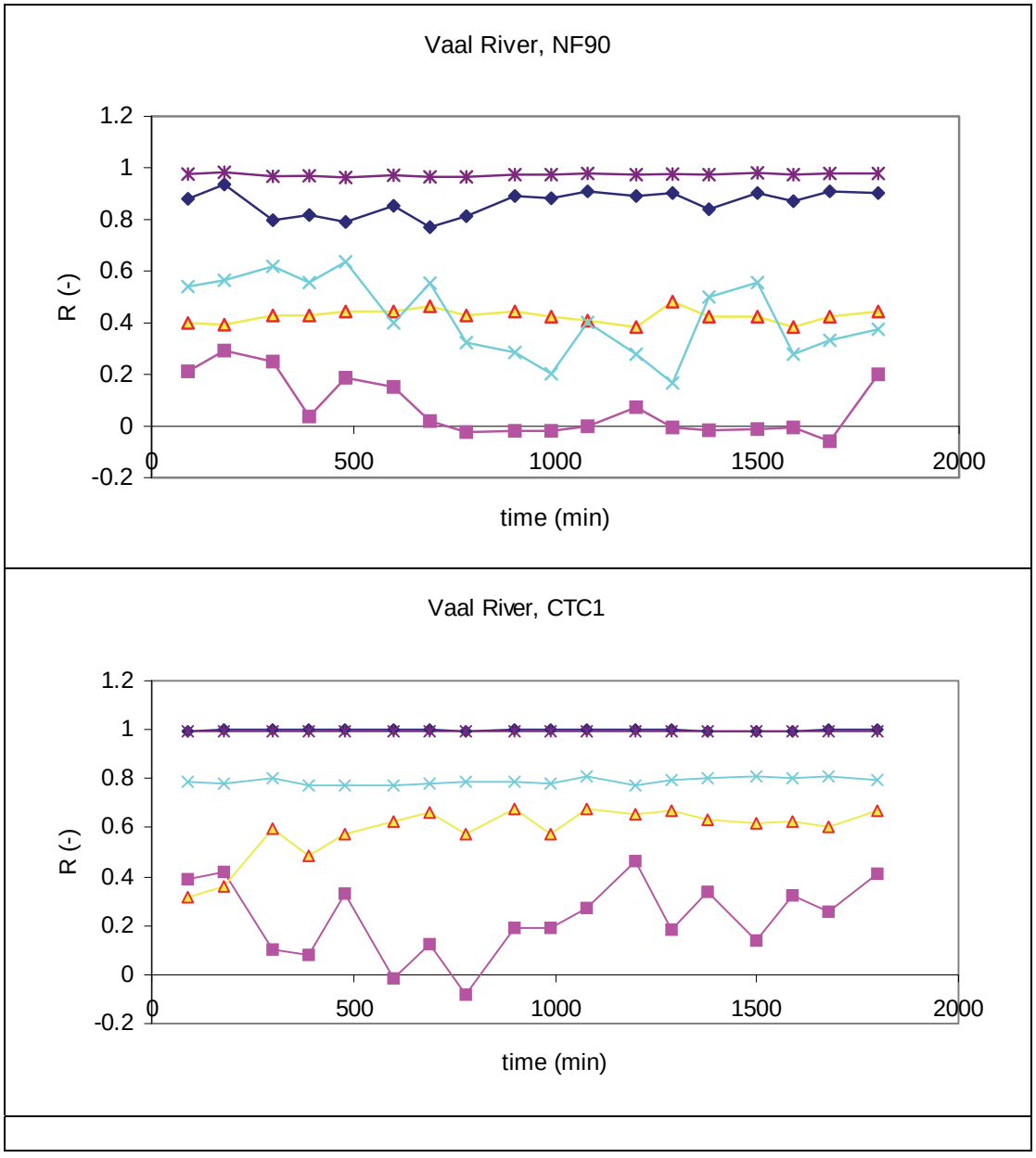



Haaskraal, NF90
1.2
1
0.8
0.6
0.4
0.2
0
R (-)
0
500
1000
1500
2000
time (min)
Haaskraal, CTC1
1.2
1
0.8
0.6
0.4
0.2
0
R (-)
0
500
1000
1500
2000
time (min)
sulfate
nitrate
fluoride
TH
TDS

Appendix R Rejection of different chemical components on various membranes in the Vaal River over time (Temperature = ambient, cross-flow unit)






Vaal River, NF90
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
R (-)
0
500
1000
1500
2000
time (min)
Vaal River, CTC1
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
R (-)
0
500
1000
1500
2000
time (min)
sulfate
nitrate
fluoride
TH
TDS

Appendix S Membrane performance in rejecting various chemical components from selected sites

Flouride								
	Lerome $[F]_o$ = 5.78ppm		Ledig $[F]_o$ = 7.23ppm		Haaskraal $[F]_o$ = 0.22ppm		Vaal River $[F]_o$ = 2.71ppm	
	Brine	Product	Brine	Product	Brine	Product	Brine	Product
D11	5.93	5.67	9.14	5.26	0.25	0.15	4.00	1.40
D12	6.36	5.23	9.07	5.33	0.23	0.17	3.81	1.59
NF90	5.17	5.63	9.94	4.46	0.26	0.14	3.83	1.57
CTC1	6.79	4.81	9.43	4.97	6.27	0.13	4.29	1.11
Nitrate								
	Lerome $[NO_3^-]_o$ = 1.21ppm		Ledig $[NO_3^-]_o$ = 1.76ppm		Haaskraal $[NO_3^-]_o$ = 13.9ppm		Vaal River $[NO_3^-]_o$ = 1.60ppm	
	Brine	Product	Brine	Product	Brine	Product	Brine	Product
D11	1.25	1.15	2.04	1.56	21.0	6.81	2.21	0.99
D12	1.47	0.93	2.48	1.12	20.1	7.37	2.05	1.15
NF90	2.05	0.35	2.59	1.01	20.4	7.37	1.71	1.49
CTC1	1.38	1.02	2.11	1.49	22.5	5.28	1.97	1.23
Sulfate								
	Lerome $[SO_4^{2-}]_o$ = 50ppm		Ledig $[SO_4^{2-}]_o$ = 20ppm		Haaskraal $[SO_4^{2-}]_o$ = 70ppm		Vaal River $[SO_4^{2-}]_o$ = 112ppm	
	Brine	Product	Brine	Product	Brine	Product	Brine	Product
D11	99.0	1.0	38.2	1.8	140	0	219	4.5
D12	96.8	3.2	38.2	1.8	140	0	222	2.2
NF90	99.4	0.7	40.0	0.0	140	0	208	15.7
CTC1	100.0	0.5	38.2	1.8	140	0	223	1.1

Appendix S (continued…)

Total Hardness (TH)								
	Lerome TH_o = 51ppm		Ledig TH_o = 18ppm		Haaskraal TH_o = 32ppm		Vaal River TH_o = 18ppm	
	Brine	Product	Brine	Product	Brine	Product	Brine	Product
D11	94.9	7.1	33.3	2.7	48.3	15.7	24.5	11.5
D12	91.0	10.9	32.6	3.4	56.3	7.7	34.6	1.4
NF90	82.1	19.9	30.2	5.8	51.8	12.2	25.6	10.4
CTC1	63.8	38.3	33.8	2.2	60.5	3.5	32.2	3.8
Total Dissolved Solids (TDS)								
	Lerome TDS_o = 899ppm		Ledig TDS_o = 831ppm		Haaskraal TDS_o = 1000ppm		Vaal River TDS_o = 1108ppm	
	Brine	Product	Brine	Product	Brine	Product	Brine	Product
D11	1789	9.0	1620	41.6	1960	40	2194	22.2
D12	1770	27.9	1570	91.4	1980	20	2204	11.1
NF90	1766	31.5	1612	49.9	1980	20	2182	33.2
CTC1	1744	53.9	1637	24.9	1990	10	2210	5.5