ION-EXCHANGE AND REVERSE OSMOSIS TECHNOLOGY FOR WATER DEFLUORIDATION, WATER DENITRIFICATION AND WATER DESALINATION

REPORT TO THE:

WATER RESEARCH COMMISSION

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WRC Report No KV 121/99 (Project No 220)

PRETORIA
APRIL 2000

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SUMMARY

Many borehole waters in rural areas are unfit for human consumption, because the fluoride (>1,5 mg/ℓ); nitrate-nitrogen (>6 mg/ℓ); and salinity (>1 500 mg/ℓ) concentrations are too high. Dental fluorosis occurs in North West, North and other Provinces. Dental fluorosis is especially serious in the North West Province. Skeletal fluorosis is also experienced. Dental fluorosis is costing the government large amounts of money through dental health services annually.

High fluoride concentrations are experienced in borehole waters in the Manke (approximately 14 mg/ℓ), Moretele (4 to 5 mg/ℓ), and Taung districts (approximately 5 mg/ℓ). These waters are not fit for human consumption, and must be defluoridated prior to use.

High nitrate concentrations are experienced in borehole waters in the Moretele (173 m/ℓ) and Kudumane (130 mg/ℓ) districts. These high nitrate concentrations have the potential of causing metahaemoglobemia in babies. The water also does not comply with drinking-water standards.

High TDS concentrations occur in borehole waters in the Kudumane and Taung districts (3 000 to 6 000 mg/ℓ). These waters also contain high fluoride and nitrate concentrations, in some cases, and are not fit for human consumption.

Ion-exchange (IX) and reverse osmosis (RO) technology are available that can be used for water defluoridation, water denitrification and water desalination. However, methodology and guidelines for the use of these technologies in rural areas are not available. The following information is lacking:

(a) Regeneration conditions.
(b) The most suitable adsorbents to use.
(c) The most suitable low and high pressure RO membranes to use.
(d) Water pretreatment requirements.
(e) Frequency of membrane cleaning.
(f) Bacterial contamination of adsorbents and membranes.
(g) Design of IX and RO systems to protect them from vandalism, and
(h) Economics of these processes.

Defluoridation of water will reduce dental caries among children and fluorosis in adults and animals, with positive health effects. Nitrate-nitrogen removal from water supplies will protect babies from metahaemoglobemia. Desalination of brackish water will supply potable water to communities. Job creation can take place where rural people will be willing to desalinate water to sell to communities. Therefore, desalination of brackish water supplies holds numerous advantages.

The main objectives of this investigation were to develop methodology and guidelines for water

defluoridation, water denitrification and water desalination in rural areas. The sub-objectives were to:

(a) Demonstrate the use of the activated alumina process for water defluoridation in rural areas.

(b) Demonstrate the use of strong base anion-exchange for nitrate removal in rural areas.

(c) Demonstrate the use of low and high pressure RO for brackish water desalination (F, NO_3 and TDS removal) in rural areas.

(d) Determine the economics of IX and RO technology for water desalination in rural areas.

The following conclusions can be made as a result of this investigation:

Water defluoridation

The activated alumina process is an established process for water defluoridation. This process can be successfully used to defluoridate water from boreholes in the feed water concentration range from approximately 4 to 20 mg/ℓ to potable standards (<1,5 mg/ℓ F). Five to 10 bedvolumes regenerant (1% NaOH) can be used for regeneration. The activated alumina, however, should always be neutralised with a dilute solution of sulphuric acid (15 BVs 0,05 N) prior to loading.

The waste regenerant comprises approximately 4% of the treated water. This waste regenerant should be disposed of safely, preferably into lined fenced evaporation ponds. This brine disposal method, however, may be too expensive for application in a rural area. An alternative disposal method may be to conduct the regeneration off-site at a large municipal sewerage works, where enough dilution water is available to absorb the high fluoride concentration.

The activated alumina process should only be considered for water defluoridation where the TDS concentration is less than approximately 1 500 mg/ℓ. The activated alumina process is not a desalination process, and will only remove fluoride from the water. Therefore, water containing high TDS (>1 500 mg/ℓ), and high fluoride concentrations (>4 mg/ℓ), should be treated with RO.

Water denitrification

Strong base anion-exchange is an established process for the removal of nitrates from water. Borehole waters with nitrate-nitrogen concentrations in the range from 10 to 50 mg/ℓ can be successfully treated with strong base anion-exchange for nitrate removal (<6 mg/ℓ NO_3-N in product water).

High sulphate concentrations, however, will reduce the efficiency of strong base ion-exchange resins for water denitrification, because the sulphate will be removed preferentially which will result in a reduced output for nitrate-nitrogen removal. However, nitrate selective resins are available that can be used on waters with high sulphate concentrations.

The waste regenerant comprises approximately 4% of the treated water. This waste regenerant consists mainly of spent sodium chloride solution. This brine should be disposed of safely, preferably in lined evaporation pounds. This method of brine disposal, however, may also be too expensive for application in rural areas. An alternative way of brine disposal may be to dispose of the brine at a large sewage works where enough dilution water is available.

The ion-exchange process should work effectively for water denitrification when the TDS of the water is low (<1 500 mg/ℓ). The ion-exchange process, as the activated alumina process, is not a desalination process. Therefore, only nitrates will be removed. The removal of high TDS concentrations (>1 500 mg/ℓ) in the presence of high nitrate concentrations (>10 mg/ℓ NO_3-N) will require RO desalination.

Water defluoridation, water denitrification and water desalination with RO

Both low (approximately 4 bar) and high pressure (approximately 15 to 20 bar) RO can be successfully applied for water defluoridation, water denitrification and water desalination. Fluoride in the feed water concentration range from 4 to approximately 20 mg/ℓ can be effectively defluoridated to potable standards (<1,5 mg/ℓ) with RO. Nitrate-nitrogen in the feed water concentration range from 10 to 50 mg/ℓ nitrate-nitrogen can also be effectively denitrified with RO to potable standards (<6 mg/ℓ NO_3-N). TDS in feed waters can be effectively reduced from 10 000 mg/ℓ to less than 500 mg/ℓ.

Reverse osmosis brine should be disposed of safely in lined evaporation ponds. This, however, may be expensive in a rural area. An alternative way of brine disposal may be to use the brine for stock watering. This might be possible in the case of high TDS and high nitrate-nitrogen concentrations waters. Water recovery, however, should be kept sufficiently low to make this possible. This, however, might not be possible with high fluoride-containing waters.

Reverse osmosis membranes for water defluoridation, water denitrification and water desalination are available from a large variety of membrane suppliers. Desalination experts, however, should always be consulted prior to the selection of membranes for water desalination. The same applies for adsorbents to be used for water defluoridation and water denitrification.

Water pretreatment prior to RO desalination should be kept as simple as possible. Filtration of borehole water through a multi-media filter should remove most of the suspended material in the feed water. The remaining suspended material should be removed with a 5 micron cartridge filter prior to desalination. The cartridge filter should be cleaned or replaced when the pressure drop across the cartridge filters exceeds 1 bar.

Generic guidelines

- The chemical composition of the borehole water should always be determined to determine whether potential foulants (Fe, Mn, Ba, Sr, H_2S, Ca, SO_4, F, etc.) are present, and to determine at which safety water recovery levels the units can be operated at.

- The bacteriological composition of the borehole should also be determined to identify any faecal pollution.

- The yield of the borehole water should be established to ensure a long, steady supply of water.

- The product water should be chlorinated prior to distribution.

- Raw and product water tanks should be closed to prevent dust and plant material contaminating the water.

- The high pressure RO pump should be protected from damage by simple safety devices.

- The ion-exchange or RO plant should be housed in a construction that can be locked.

- The ion-exchange or RO plant, feed and product storage tanks should be protected from damage by intruders by a wire fence.

- Desalination equipment should be protected from direct sunlight to prevent degradation of PVC and other plastic components.

- Taps should be provided where untreated borehole water can be collected for non-potable uses, such as washing of clothes, dishes, stock watering, brick manufacturing, etc.

- Chemicals (acids, bases, anti-scalants, etc.) should be stored in a separate locked storeroom in the desalination plant housing.

- Plant operators should always wear gloves and glasses when preparing chemical make-up.

- Enough spare parts and chemicals should be kept in stock on site to prevent long down times.

- Technical people should be identified who can help with mechanical and electrical problems, if they should occur.

- A higher form of supervision over a water treatment scheme in a rural area will always be necessary. This task can be conducted by a suitable consultant.

Demonstration Studies

It was demonstrated that:

- The activated alumina process can remove fluoride in the feed concentration range from approximately 4 to 20 mg/ℓ to less than 1,5 mg/ℓ. Therefore, water of a potable quality can be produced with this process. The capital cost for a household defluoridation unit was determined at approximately R5 000. Operational cost in the feed water concentration range from 4, 8, and 20 mg/ℓ was determined at 0,43;1,14 and R3,99/kℓ water treated.

- A strong base anion exchanger can remove nitrate-nitrogen from approximatelhy 4,4 mg/ℓ to less than 2 mg/ℓ. The capital cost of a household denitrification unit was determined at approximately R5 000. Operational cost at a feed concentration of approximately 44 mg/ℓ nitrate-nitrogen was determined at R3,18/kℓ water treated.

- Fluoride can be removed with low pressure RO in the feed water concentration range from 10 to 17 mg/ℓ to approximately 0,2 mg/ℓ in the RO permeate.

- Fluoride can be removed with high pressure RO from approximately 17 mg/ℓ in the feed water to approximately 0,2 mg/ℓ in the RO permeate.

- Nitrate-nitrogen can be removed with high pressure RO from approximately 45 mg/ℓ nitrate-nitrogen in the RO feed to approximately 2 mg/ℓ in the RO permeate.

- A feed water containing 3,90 mg/ℓ fluoride and 1 624 mg/ℓ TDS can be desalinated with low pressure RO to contain almost zero fluoride and 580 mg/ℓ TDS in the RO permeate.

- A feed water containing 6,6 mg/ℓ fluoride and 4 156 mg/ℓ TDS can be desalinated with low pressure RO to contain less than 0,2 mg/ℓ fluoride and 188 mg/ℓ TDS in the RO permeate.

- The capital cost of a small RO unit to produce approximately 50 ℓ/d defluoridated water is estimated at approximately R3 000. Operational cost is estimated at approximately R3,00/kℓ. The capital cost of an RO unit to produce approximately 5 kℓ/d desalinated water is estimated at approximately R20 000. Operational cost is estimated at approximately R1,69/kℓ. The capital cost of an RO unit to produce approximately 50 kℓ/d denitrified water is estimated at approximately R150 000. Operational cost is estimated at approximately R2,17/kℓ.

ACKNOWLEDGMENTS

The study was undertaken at Environmentek, CSIR, and in the North West and Northern Provinces.

I would like to thank:

- The Water Research Commission, the Department of Water Affairs and Forestry (DWAF), and the CSIR for their financial support.
- Operators from DWAF in the Northern Province for their ability to operate and maintain a first-world reverse osmosis technology in a rural area.
- Dr James Meyer from the Department of Animal and Wildlife Sciences, Faculty of Biological and Agricultural Sciences, University of Pretoria, for his valuable advice regarding water quality requirements for stock watering.
- Institutions which made sites available for the study.

1. INTRODUCTION

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(c) Demonstrate the use of low and high pressure RO for brackish water desalination (F, NO_3 and TDS removal) in rural areas.

(d) Determine the economics of IX and RO technology for water desalination in rural areas.

2. EXPERIMENTAL

2.1 Fluoride Removal with Activated Alumina

A glass fibre reinforced plastic vessel with a diameter of 400 mm and height of 1 400 mm was purchased from a local supplier of ion-exchange equipment. The vessel was loaded with 60 ℓ activated alumina with a particle size of 0,5 to 1,0 mm. The activated alumina was regenerated with 10 bedvolumes (BV) 1% sodium hydroxide solution. Excess sodium hydroxide was removed by rinsing the activated alumina with approximately 15 BV water. The activated alumina was then neutralised with 15 BV 0,05 N sulphuric acid prior to loading. A schematic diagram of the defluoridation vessel is shown in Figure 1.

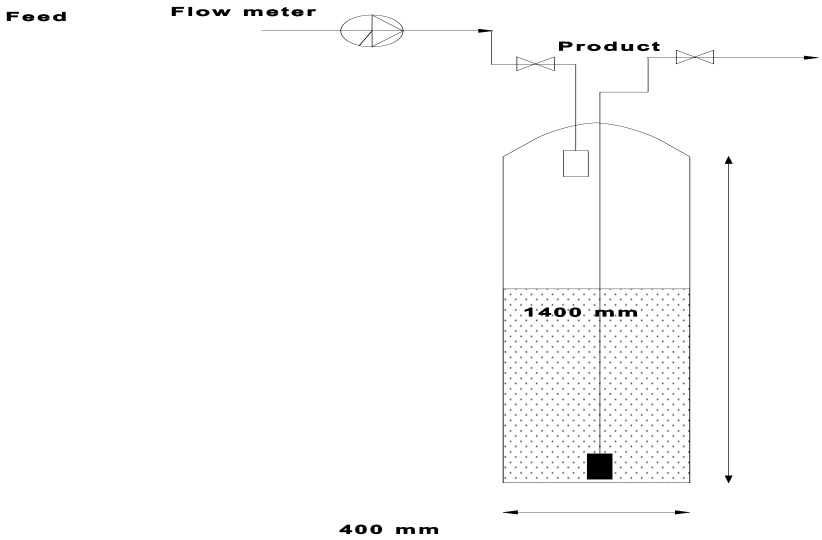

Figure 1. Schematic diagram of defluoridation vessel.

Water defluoridation was conducted on two ground waters in rural areas. The fluoride concentration of the one water was approximately 8 mg/ℓ, and that of the other water approximately 20 mg/ℓ. Ground water was passed through the activated alumina vessels at a flow rate of approximately 2 to 3ℓ/minute.

The performance of the activated alumina process was determined by measuring the fluoride concentration of the feed and the product water (defluoridated water) regularly. Fluoride measurements were conducted either spectrophotometrically or with a specific fluoride electrode. Breakthrough curves were established. Elution curves were also established after regeneration of the spent activated alumina. The bacteriological quality of the defluoridated water was also measured periodically.

2.2 Nitrate-Nitrogen Removal with Strong-Base-Ion-Exchange

The same type of vessel that was used for the defluoridation studies was also used for the nitrate removal studies. The vessel was loaded with 60 litres (1 BV) Lewatit M504 strong base resin. The resin was first converted into the chloride form by regeneration with 5 BV 10% sodium chloride. Excess sodium chloride was removed by rinsing with 10 BV denitrified water, whereafter loading was conducted with a water containing 45 mg/ℓ nitrate-nitrogen, at a flow rate of 15 BV per hour. Several loading and regeneration runs were conducted and breakthrough and elution curves were established.

2.3 TDS, Fluoride and Nitrate-Nitrogen Removal with Reverse Osmosis

Low and high pressure RO were used in the experimental studies. A typical diagram of an RO unit is shown in Figure 2.

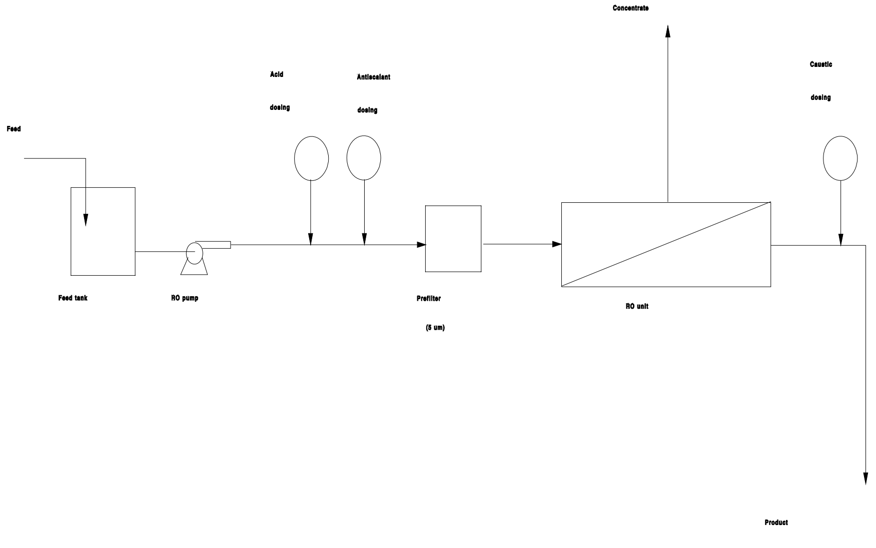

Figure 2. Simplified flow diagram of an RO unit.

Low pressure RO was conducted at approximately 4 bar and high pressure RO at approximately 20 bar. Feed water from a borehole was pressurised and passed through a 5 micron cartridge filter prior to RO desalination. Filmtec 2 x 20 inch (low pressure - 4 bar), 4 x 40 inch (high pressure - 20 bar) and Hydranautics 4 x 80 inch (high pressure - 13 bar) membranes were used in the investigation.

3. RESULTS

3.1 Water Defluoridation with Activated Alumina

3.1.1 Performance of the activated alumina defluoridation unit when defluoridating a water containing approximately 8 mg/ℓ fluoride

Ground water with a fluoride concentration of 8 mg/ℓ was passed through the vessel for approximately 3 hours each day at a flow rate between 1 and 2 litre per minute. The defluoridation results are shown in Figure 3. Approximately 300 BVs defluoridated water with a fluoride concentration of less than 1,5 mg/ℓ could be produced.

The chemical composition of the feed and the defluoridated water is shown in Table 1. Fluoride was reduced from approximately 8 mg/ℓ to less than 1,5 mg/ℓ.

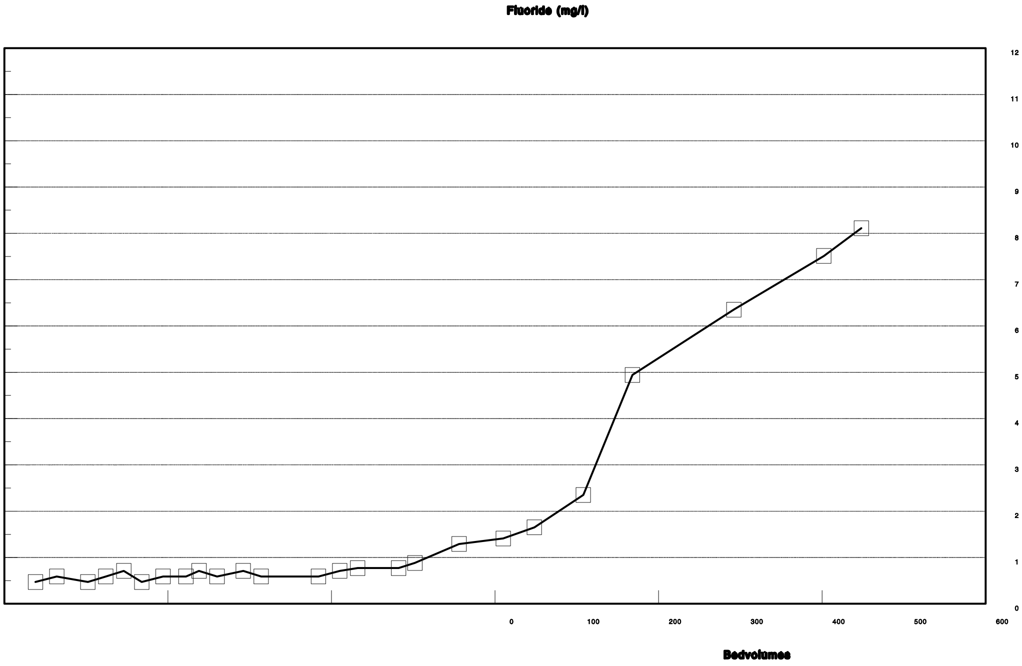

Figure 3. Performance of defluoridation unit as a function of bedvolumes of product water produced. 1 BV = 60 ℓ.

Table 1. Chemical composition of the feed and product water.

Constituent	**Concentration (mg/ℓ)**	
	Feed	**Product**
Sodium	42	44
Potassium	3	2
Calcium	125	18
Magnesium	59	6
Nitrate (as N)	10,1	12,7
Sulphate	492	379
Chloride	39	42
Alkalinity (as $CaCO_3$)	49	65
Fluoride	7,2	0,5
pH	7,1	7,2

3.1.2 Performance of the activated alumina defluoridation unit when defluoridating a water containing approximately 20 mg/ℓ fluoride

Ground water with a fluoride concentration of approximately 20 mg/ℓ was passed through the vessel for approximately 2 hours each day at a flow rate between 1 and 2 litre per minute. The defluoridation results are shown in Figure 4. The fluoride concentration in the feed was reduced to approximately 0,1 mg/ℓ. Approximately 85 BVs product water was produced at 1,5 mg/ℓ fluoride breakthrough.

The bacteriological quality of the defluoridated water was investigated when the unit had been in operation for a number of months. Total coliforms, faecal coliforms and a standard plate count were conducted. Total and faecal coliforms were 60 and 0 counts per 100 mℓ, respectively (maximum allowable counts for total and faecal coliforms per 100 mℓ are 5 and 0, respectively). The total plate count per millilitre was determined at 25 000 (DWT recommends a maximum count of 1 000). Therefore, total coliforms and the total plate count of the defluoridated water were too high, and the water should be disinfected before use. The water can be disinfected with HTH before use.

The chemical composition of the feed and defluoridated water is shown in Table 2. Alkalinity and silica are also removed from the feed water with activated alumina. Sulphate is added to the product water through displacement from the activated alumina by adsorbing species such as fluoride, alkalinity and silica. The sodium concentration of the water is high. Activated alumina, however, does not remove sodium. The fluoride concentration of the product water was determined at 0,07 and 1,23 mg/ℓ after 56,5 and 85 BVs had been passed through the vessel, respectively.

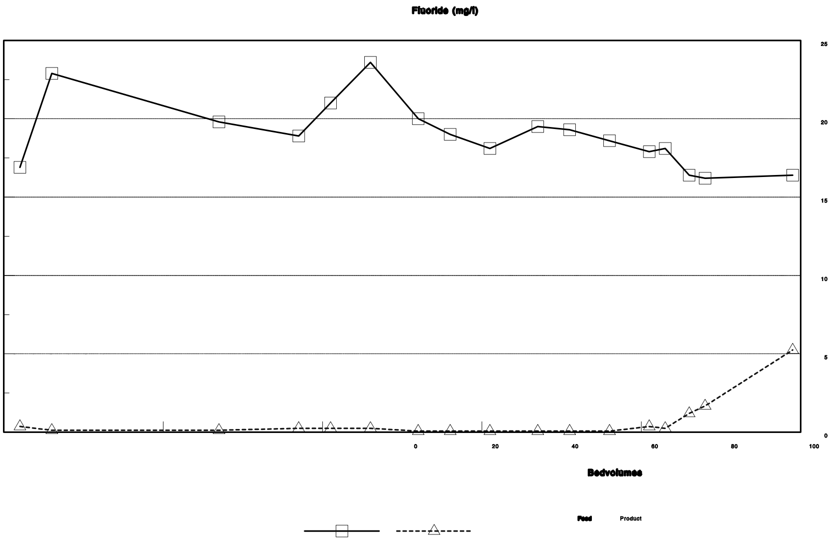

Figure 4. Performance of defluoridation unit as a function of bedvolumes of product water produced. 1 BV = 60 ℓ.

Table 2. Chemical composition of feed and product water.

Constituent	Concentration (mg/ℓ)			
	Feed	**Product***	**Feed**	**Product****
Sodium	162	140	122	119
Potassium	3	3	2	2
Calcium	2	<1	6	7
Magnesium	1	1	2	2
Nitrate-nitrogen	0,4	0,3	0,3	0,2
Silica	8,3	0,4	-	-
Sulphate	10	51	9	23
Chloride	59	51	59	54
Alkalinity (as $CaCO_3$)	253	201	209	202
Fluoride	19,0	0,07	16,4	1,23
pH	8,1	7,8	8,7	7,7

* Sample after 56,5 BVs had been produced.

** Sample after 85 BVs had been produced.

Defluoridation runs were conducted on another ground water with a fluoride concentration of approximately 19 mg/ℓ. The results are shown in Figure 5. Approximately 141 BV of product water could be produced after the first run. However, the bedvolumes of product water decreased to approximately 83 bedvolumes after the second run. The reduction in output of defluoridated water produced can be ascribed to an incomplete regeneration of the activated alumina after the first rum. Regeneration was conducted with 5 bedvolumes 1 per cent caustic soda solution (Figure 6). However, it appears that better results should be obtained when 10 bedvolumes caustic soda (1%) are used for the regeneration of the activated alumina. It is clear from Figure 6 that the regeneration was not complete.

The activated alumina feed and product water quality are shown in Table 3. Fluoride was reduced from 18,5 to 1,28 mg/ℓ in the product. No significant changes were experienced in the concentrations of the other cations and anions present in the water.

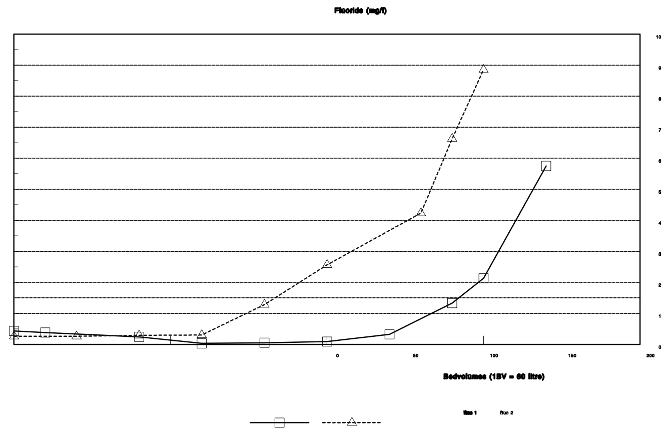

Figure 5. Performance of defluoridation unit as a function of bedvolumes of product water produced. 1 BV = 60 ℓ.

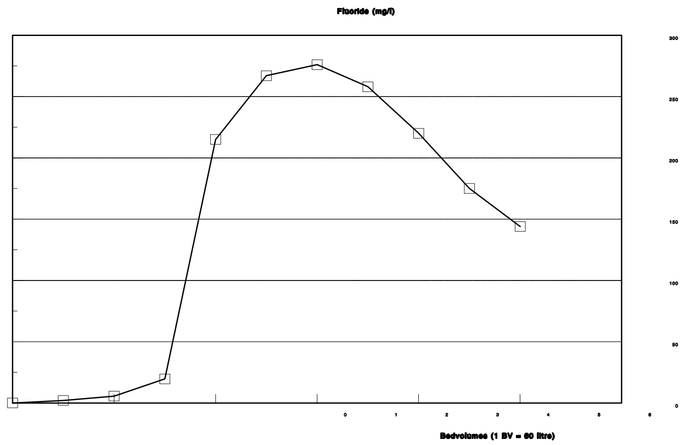

Figure 6. Elution curve.

Table 3. Chemical composition of feed and product water.

Constituents*	Feed water	Product water
pH	7,91	7,88
Conductivity (mS/m)	110	110,2
Nitrate as N	0,06	0,05
Chloride	55,63	43,45
Fluoride	18,5	1,28
Alkalinity as $CaCO_3$	457,5	455,5
Sulphate	28	73
TDS	696	708
Potassium	3,61	3,52
Sodium	206	199
Magnesium	1,66	1,19
Calcium	7,12	4,84

* Concentration in mg/ℓ, unless stated otherwise.

3.1.3 Defluoridation cost.

The capital and operational costs to treat different fluoride feed concentrations are shown in Table 4.

Table 4. Capital and operational cost to treat different fluoride concentration feed waters.

Defluoridation method	**Capital cost (R)**	**Operational cost* (chemicals)**		
		4 mg/ℓ F R/m³	**8 mg/ℓ F R/m³**	**20 mg/ℓ F R/m³**
Household defluoridation unit	5 000	0,43 (1)	1,14 (2)	3,99 (3)

* H_2SO_4: R300/ton NaOH: R2 800/ton.
(1) = 800 BVs (2) = 300 BVs (3) = 90 BVs

3.2 Water Denitrification with a Strong Base Ion-Exchanger.

3.2.1 Performance of the ion-exchange denitrification unit when denitrifying a water containing approximately 44 mg/ℓ nitrate-nitrogen

Borehole water with a nitrate-nitrogen concentration of approximately 45 mg/ℓ was passed at a rate of 15 BV/h (1 BV = 60 ℓ) through the resin (Lewatit M504). The breakthrough curves are shown in Figure 7. The bedvolumes of product water produced with a nitrate-nitrogen concentration of less than 6 mg/ℓ varied between 89 and 135 for three runs that were conducted.

The elution curves are shown in Figure 8. Most of the nitrate-nitrogen was removed with 5 BV of regenerant. Therefore, less than 5 BV regenerant, approximately 4 BV, should be sufficient for regeneration of the resin.

The nitrate-nitrogen was reduced from 44,1 to zero when the sample was taken (Table 5). The chloride concentration in the product water shows an increase, because chloride is displaced by nitrate in the feed water. The TDS, therefore, also shows an increase.

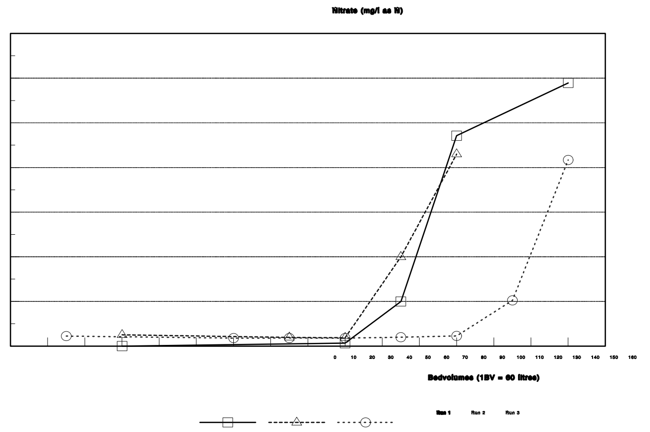

Figure 7. Performance of ion-exchange denitrification unit as a function of bedvolumes of product water produced. (1 BV = 60 ℓ).

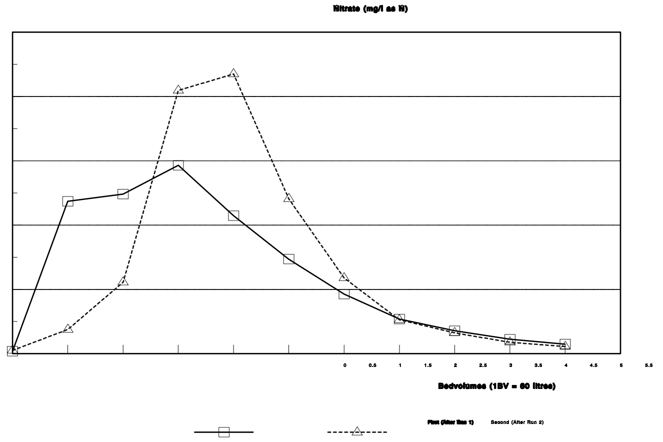

Figure 8. Elution curve.

The chemical composition of the feed and product water is shown in Table 5.

Table 5. Chemical composition of feed and ion-exchange treated water.

Constituents*	Feed water	Product water
pH	7,46	7,50
Conductivity (mS/m)	181	187,5
Nitrate as N	44,09	0
Chloride	155,3	328,2
Alkalinity as $CaCO_3$	365	323
Sulphate	100	1
TDS	1 024	1 304
Potassium	4,17	3,14
Sodium	130,8	124
Magnesium	78,6	76,5
Calcium	112	128

* Concentration in mg/ℓ, unless otherwise stated.

3.2.2 Denitrification cost

The capital and operational costs to treat a water containing approximately 45 mg/ℓ nitrate-nitrogen are shown in Table 6.

Table 6. Capital and operational cost to treat a water containing approximately 45 mg/ℓ nitrate-nitrogen.

Defluoridation method	**Capital cost (R)**	**Operational cost* (chemicals) 110 BV, 45 mg/ℓ NO_3-N R/m^3**
Household defluoridation unit	5 000	3,18

* NaCl 70 c/kg.

3.3 Water defluoridation with Reverse Osmosis.

3.3.1 Low pressure RO.

Borehole water with a fluoride concentration of approximately 17 mg/ℓ was desalinated in a rural area (Filmtec 2 x 20 inch membranes). The operational data are shown in Appendix A.

The electrical conductivity of the RO feed, permeate and brine are shown in Figure 9. The percentage conductivity and fluoride removals are shown in Figure 10 and Table 7. The permeate flux through the RO membranes is shown in Figure 11.

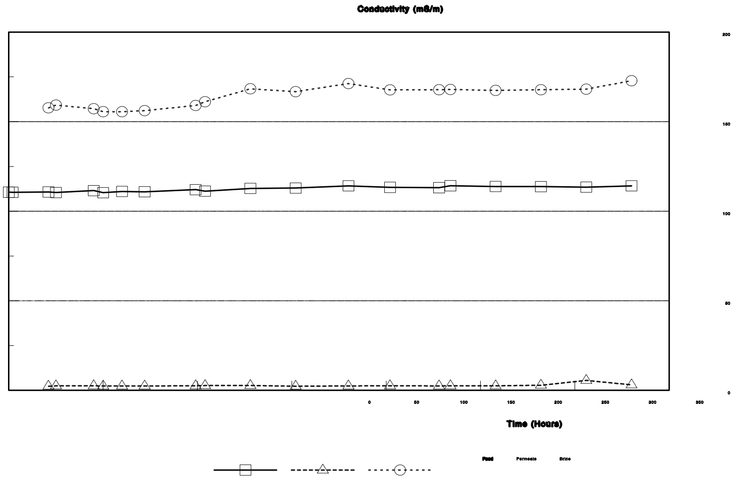

Figure 9. Electrical conductivity of RO feed, permeate and brine as a function of time.

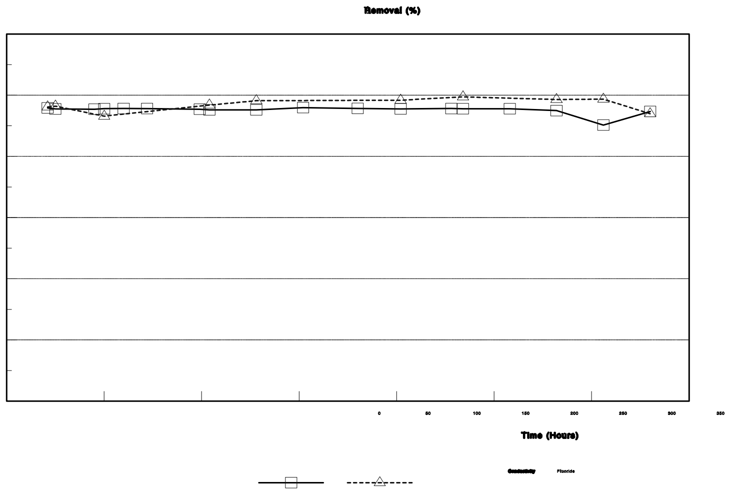

Figure 10. Percentage electrical conductivity and fluoride removals as a function of time.

Table 7. Fluoride removal with RO.

	Fluoride concentration (mg/ℓ)			
Time (hours)	**Feed**	**Permeate**	**Brine**	**Removal (%)**
2	16,7	0,32	26,2	98,08
25	16,7	0,30	27,6	98,20
50	16,7	0,57	34,3	96,59
99	16,1	0,26		98,39
128	17,7	0,16		99,10
202	18,3	0,15	27,8	99,18
234	17,9	0,05	27,5	99,72
282	18,2	0,13	27,1	99,29
306	18,4	0,12		99,35
330	18,6	0,56	28,9	96,99

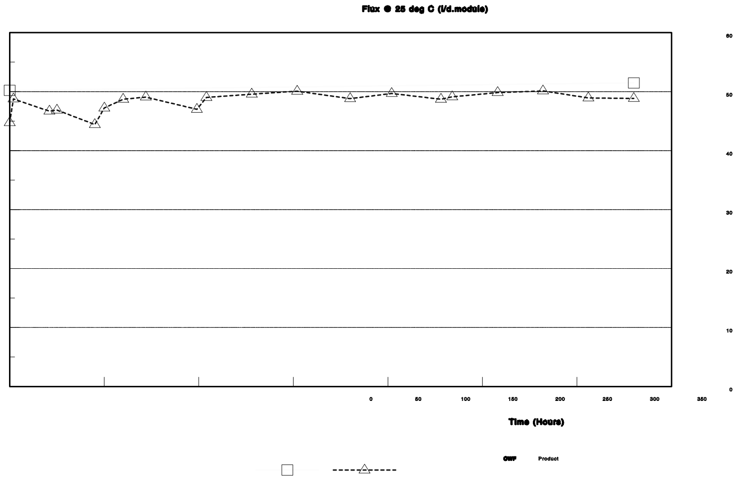

Figure 11. Permeate flux through RO membranes as a function of time.

Fluoride could be very effectively removed form approximately 17 mg/ℓ to less than 0,5 mg/ℓ in the permeate (97 to 99% removal) (Table 7). Excellent electrical conductivity removals were also obtained (97%) (Figure 10). The permeate flux through the membrane module was approximately 50 ℓ module.d (Figure 11). The recovery varied between 30 and 33% (Appendix A). The flux could be maintained during the run. Therefore, membrane fouling should not be problem during water defluoridation.

Another borehole water with a fluoride concentration of approximately 10 mg/ℓ was desalinated with RO. The detailed experimental results are shown in Appendix B.

The fluoride concentration in the RO feed, product and brine is shown in Figure 12. Fluoride was removed from approximately 10 mg/ℓ to approximately 0,2 mg/ℓ.

The electrical conductivity of the RO feed, permeate and brine is shown in Figure 13. The electrical conductivity was removed from approximately 80 mS/m to approximately 5 mS/m.

The permeate flux as a function of time is shown in Figure 14. Permeate flux remained at approximately 50 ℓ/module.d (water recovery approximately 30%).

The pH of the RO feed, permeate and brine is shown in Figure 15. The pH of the RO permeate is low due to alkalinity removal from the permeate. Lime or caustic soda should be added to the permeate to increase its pH to approximately 7 prior to drinking.

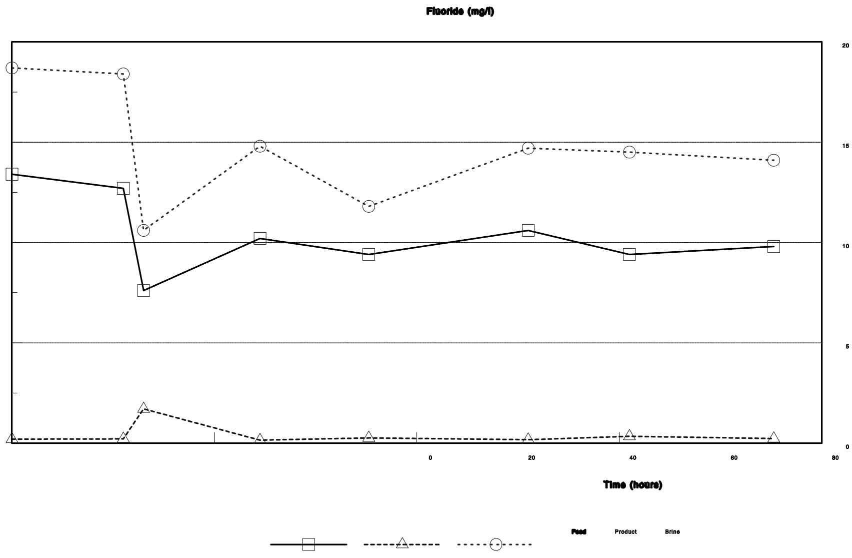

Figure 12. Fluoride concentration in RO feed, product and brine as a function of time.

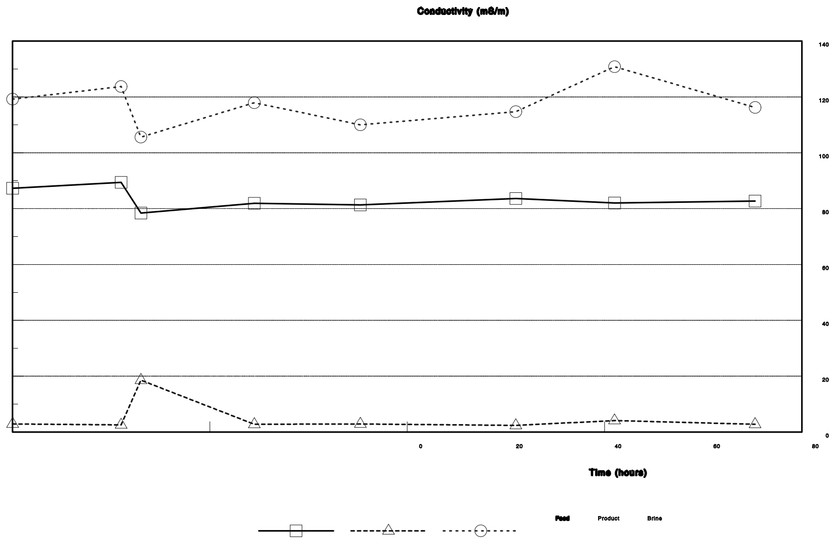

Figure 13. Electrical conductivity of RO feed, permeate and brine as a function of time.

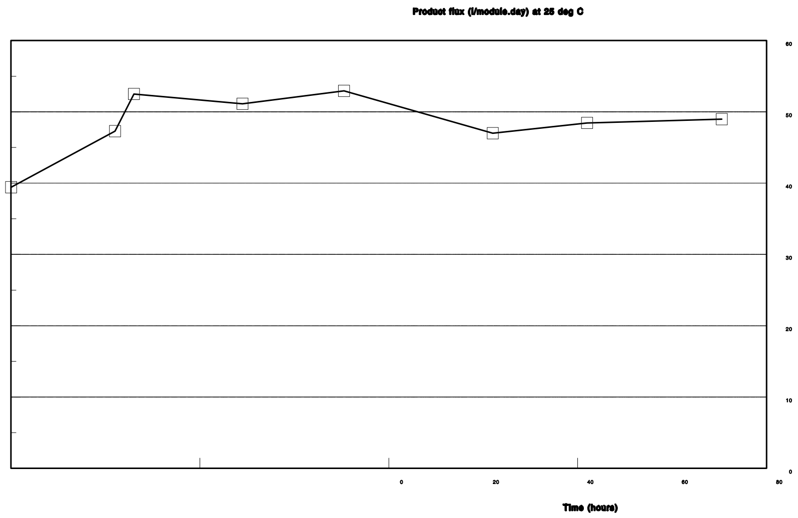

Figure 14. Permeate flux as a function of time.

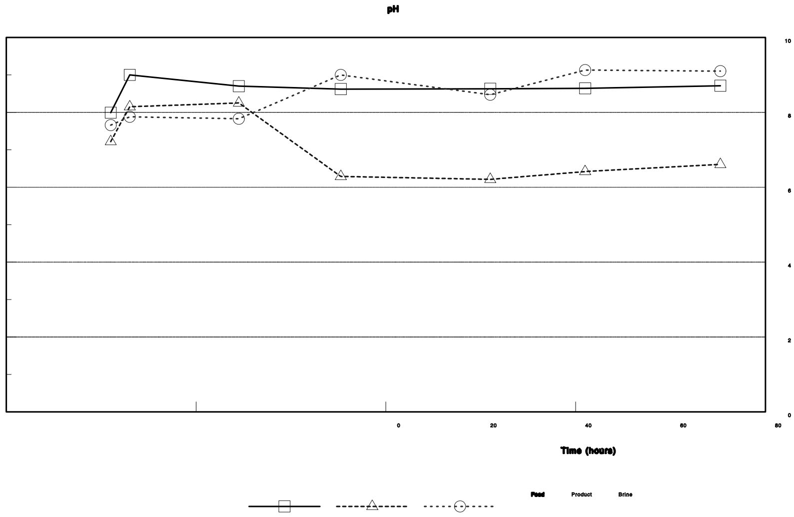

Figure 15. pH of RO feed, permeate and brine as a function of time.

3.3.2 *High pressure RO*

3.3.2.1 Water defluoridation

A borehole water containing approximately 20 mgℓ fluoride was desalinated with an EPRO unit (20 bar feed inlet pressure, Filmtec 4 x 40 inch membranes). The detailed results are shown in Appendix C. The fluoride concentration in the RO feed, permeate and brine is shown in Figure 16. Fluoride was removed from approximately 20 mg/ℓ in the feed to approximately 0,2 mg/ℓ in the permeate.

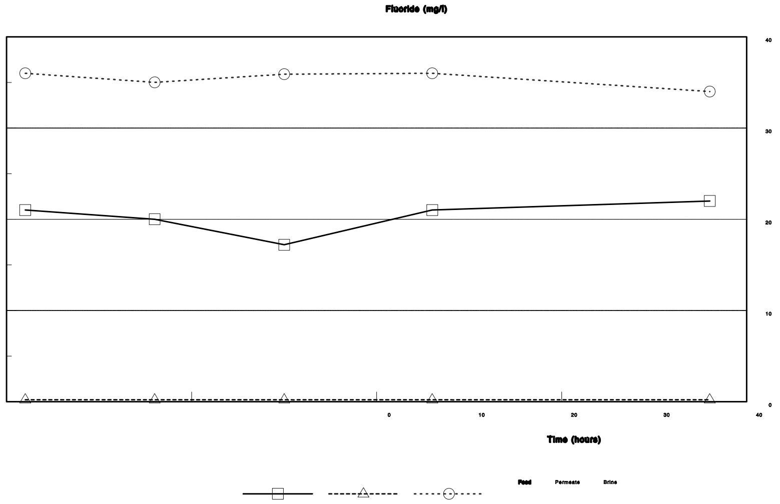

Figure 16. Fluoride concentration in the RO feed, permeate and brine as a function of time. The electrical conductivity of the RO feed, permeate and brine is shown in Figure 17.

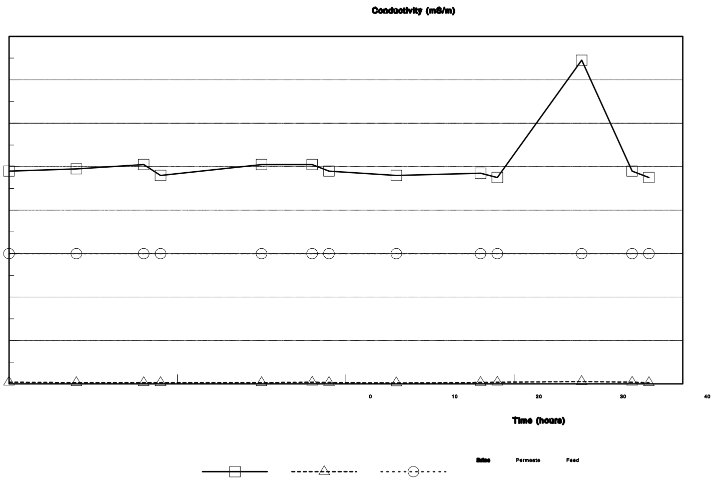

Figure 17. Electrical conductivity of the RO feed, permeate and brine as a function of time.

The electrical conductivity of the RO feed was reduced from approximately 60 mS/m to 0,8 mS/m in the permeate.

The permeate flux through the membranes as a function of time is shown in Figure 18.

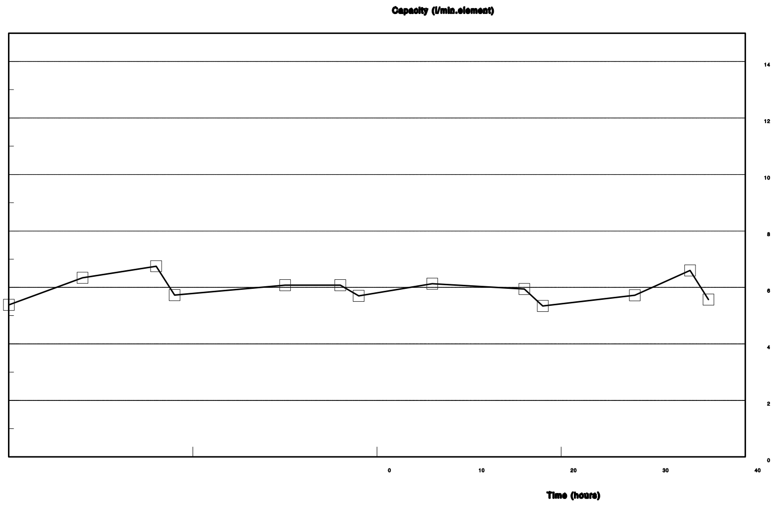

Figure 18. Permeate flux as a function of time.

The permeate flux remained at approximately 6 ℓ/min.element for the duration of the run. This shows that membrane fouling should not be a problem during treatment of the water with RO.

The chemical composition of the RO feed, permeate and brine is shown in Table 8.

Table 8. Chemical composition of RO feed, permeate and brine.

Constituent*	Feed	Permeate	Brine	% Rejection
COD	5,0	1,0	1,0	
Ammonia	0,0	0,0	0,0	
Nitrate	0,0	0,0	0,0	80,00
Phosphate	0,1	0,4	0,1	
Sulphate	0,0	0,0	0,0	
TDS	180	4,0	205	
Cadmium	0,0	0,0	0,0	97,78
Iron	0,0	0,0	0,0	
Potassium	2,5	0,1	3,8	
Sodium	157	1,3	2,1	96,00
Magnesium	1,0	0,1	1,4	99,15
Calcium	3,3	0,2	5,0	95,05
Fluoride	17,2	0,2	35,9	94,29
Conductivity (mS/m)	80,0	0,5	96,0	98,84
pH	7,1	6,9	7,2	99,33

* Concentration in mg/ℓ, unless otherwise stated.

Fluoride was reduced from 17,2 mg/ℓ in the RO feed to only 0,2 mg/ℓ in the RO permeate. The TDS of the RO feed was reduced from 180 mg/ℓ to only 4 mg/ℓ in the RO permeate.

3.3.2.2 Water denitrification

A borehole water containing approximately 45 mg/ℓ nitrate-nitrogen was desalinated with RO (13 bar feed inlet pressure, Hydranautics membranes). The detailed results are shown in Appendix D. The nitrate-nitrogen concentration in the RO feed, permeate and brine is shown in Figure 19. The nitrate-nitrogen concentration in the RO feed was reduced from approximately 45 mg/ℓ to approximately 2 mg/ℓ (97 removal%). The initial water recovery was approximately 35%, and was increased to approximately 50% after 23 hours of operation.

The electrical conductivity of the RO feed, permeate and brine is shown in Figure 20. The electrical conductivity of the RO feed was reduced from approximately 180 mS/m to between 10 and 20 mS/m in the RO permeate (97% removal). The electrical conductivity of the brine was approximately 320 mS/m.

The chemical composition of the RO feed, permeate and brine is shown in Table 9. The RO product water complies with the quality requirements for potable water. The quality of the RO brine may be suitable for stock watering, depending on certain conditions (see Appendix E).

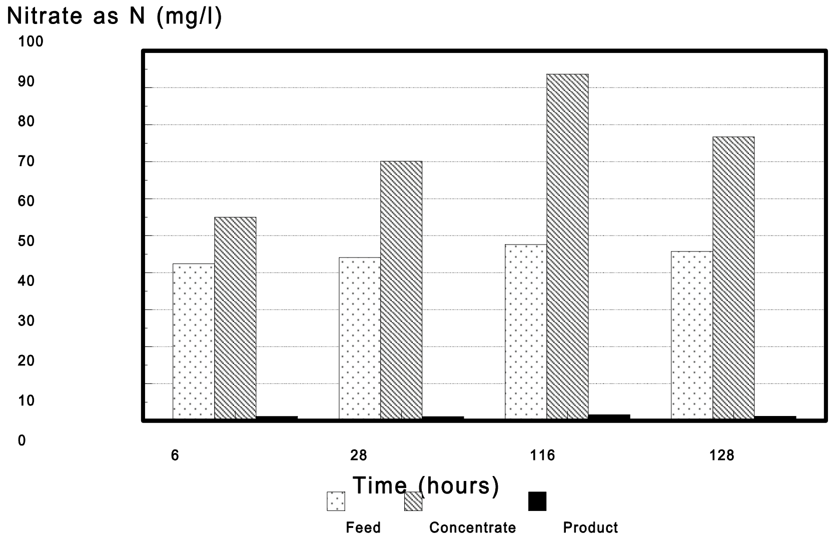

Figure 19. Nitrate-nitrogen concentration of RO feed, permeate and concentrate over the test period.

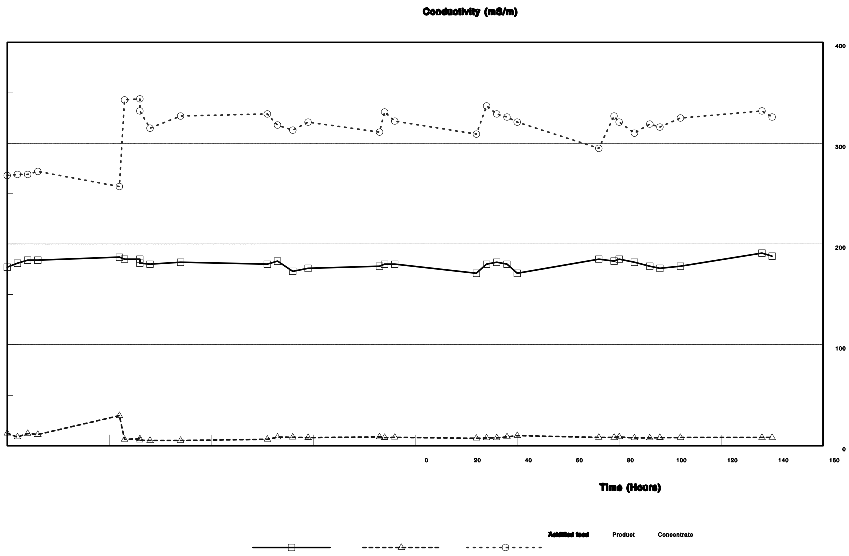

Figure 20. Electrical conductivity of the RO feed, permeate and concentrate as a function of time.

Table 9. Chemical composition of RO feed, product and brine (128 hours of operation, 27/03/1997).

Constituents*	**Raw feed**	**pH adjusted feed**	**Product**	**Concentrate**	**% removal**
pH	7,06	6,93	6,12	7,27	
Conductivity (mS/m)	176	179	8	316	95,45
COD	0	-	-	-	-
TKN as N	5,04		1,01	1,35	79,96
Ammonia	-	-	-	-	-
Nitrate as N	45,73		1,18	76,7	97,42
Chloride	181,8		4,60	346,2	97,47
Fluoride	0,84		0,03	1,54	96,43
Alkalinity as $CaCO_3$	368		38,5	635,5	89,54
Sulphate	70	120	1	180	98,57
TDS	1 276		88	2 444	93,10
Iron	0		0	0,01	-
Manganese	0,07		0	0,12	100,00
Potassium	3,57		0,15	5,4	95,80
Sodium	96		11,6	171	87,72
Magnesium	79,4		0,24	211	99,70
Calcium	108		0,45	206	99,58
Barium	0,144		<0,03	0,27	-
Strontium	0,8		<0,03	1,5	-
Silica	52,4		0,7	108	98,66
Aluminium	<0,1		<0,1	<0,1	-

* Concentration in mg/ℓ, unless stated otherwise.

3.3.2.3 Water desalination and water defluoridation

An EPRO desalination unit was used to demonstrate desalination and defluoridation of typical waters obtained in borehole waters in rural areas (Filmtec 4 x 40 inch membranes). The salinity and fluoride concentrations were 1 624 and 3,8 mg/ℓ, respectively, in one case. In another case, the salinity and fluoride concentrations were 4 156 and 6,6 mg/ℓ, respectively. Typical results are shown in Figures 21 and 22, and Table 10.

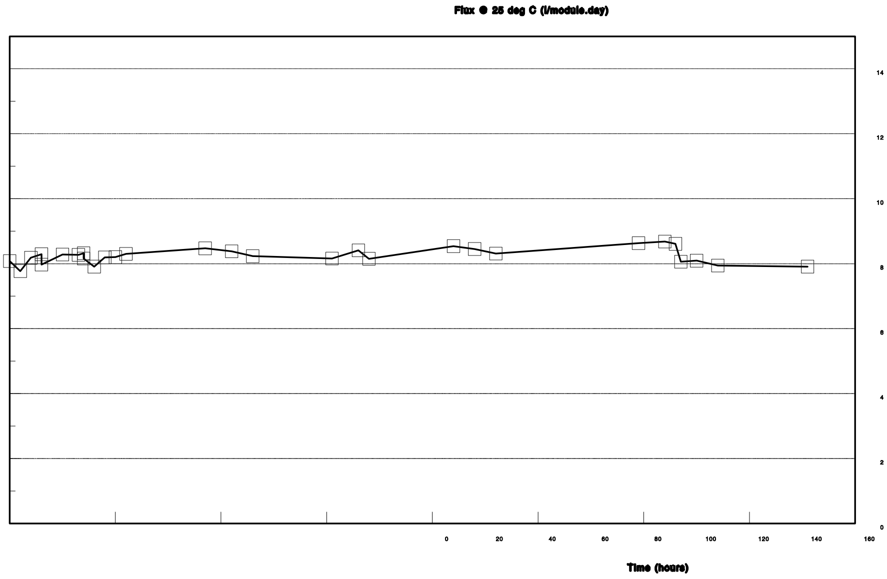

Figure 21. Permeate flux as a function of time (1 600 mg/ℓ TDS).

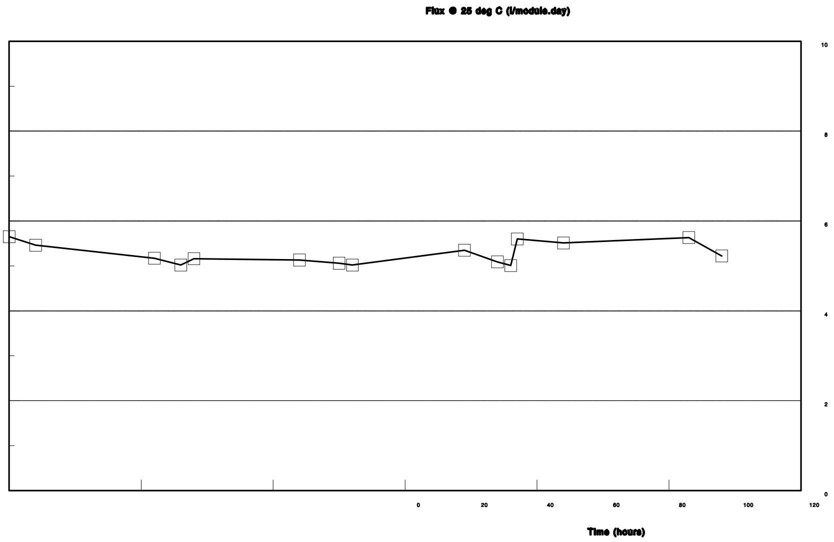

Figure 22. Permeate flux as a function of time (4 156 mg/ℓ TDS).

Excellent fluoride removals were obtained. Fluoride removals varied between 98 and 100 per cent (Table 10). Excellent TDS removals were also obtained. TDS removals varied between 92 and 95 per cent. Therefore, RO should be very effectively applied for water desalination and water defluoridation in rural areas.

The permeate flux remained almost constant (Figures 21 and 22). Therefore, it appears that membrane fouling should not be a problem.

Table 10. Reverse osmosis desalination and defluoridation results.

Constituents*	**Feed water**	**Permeate**	**Brine**	**Removal (%)**
EPRO feed, permeate and brine at 50 hours. TDS approximately 1 624 mg/ℓ.				
pH	6,97	5,61	7,35	
Conductivity (mS/m)	297	7,07	951	97,62
Chloride	679,2	16,69	2 078	97,54
Fluoride	3,98	0	14,9	100,00
TDS	1 624	136	580	91,53
Sodium	397	11,3	1 430	97,15
EPRO feed, permeate and brine at 50 hours. TDS approximately 4 200 mg/ℓ.				
pH	7,17	5,75	7,47	
Conductivity (mS/m)	743	38,4	2 160	94,83
Chloride	1 850	99,93	5 856	94,60
Fluoride	6,6	0,14	20,4	97,88
TDS	4 156	188	13 120	95,48
Sodium	1 249	63	390	94,95
Alkalinity as $CaCO_3$	67	8,5	208,5	87,31

* Concentration in mg/ℓ, unless otherwise stated.

3.3.3 Costs

The capital cost of a small RO unit to produce approximately 50 ℓ/d defluoridated water is estimated at approximately R3 000. Operational costs is estimated at approximately R3,00/m³. The capital cost of an RO unit to produce approximately 5 kℓ/d water is estimated at approximately R20 000. Operational cost is estimated at approximately R1,69/kℓ. The capital cost of an RO unit to produce approximately 50 kℓ/d denitrified water is estimated at approximately R150 000. Operational cost is estimated at approximately R2,17/kℓ.

4. METHODOLOGY AND GUIDELINES FOR WATER DEFLUORIDATION, WATER DENITRIFICATION AND WATER DESALINATION IN RURAL AREAS

4.1 Water Defluoridation

The activated alumina process is an established process for water defluoridation. This process can be successfully used to defluoridate water from boreholes in the feed water concentration range from approximately 4 to 20 mg/ℓ to potable standards (<1,5 mg/ℓ F). Five to 10 bedvolumes regenerant (1% NaOH) can be used for regeneration. The activated alumina, however, should always be neutralised with a dilute solution of sulphuric acid (15 BVs 0,05 N) prior to loading.

The waste regenerant comprises approximately 4% of the treated water. This waste regenerant should be disposed of safely, preferably into lined fenced evaporation ponds. This brine disposal method, however, may be too expensive for application in a rural area. An alternative disposal method may be to conduct the regeneration off-site at a large municipal sewerage works, where enough dilution water is available to absorb the high fluoride concentration.

The activated alumina process should only be considered for water defluoridation where the TDS concentration is less than approximately 1 500 mg/ℓ. The activated alumina process is not a desalination process, and will only remove fluoride from the water. Therefore, water containing high TDS (>1 500 mg/ℓ), and high fluoride concentrations (>4 mg/ℓ), should be treated with RO.

4.2 Water Denitrification

Strong base anion-exchange is an established process for the removal of nitrates from water. Borehole waters with nitrate-nitrogen concentrations in the range from 10 to 50 mg/ℓ can be successfully treated with strong base anion-exchange for nitrate removal (<6 mg/ℓ NO_3-N in product water).

High sulphate concentrations, however, will reduce the efficiency of strong base ion-exchange resins for water denitrification, because the sulphate will be removed preferentially which will result in a reduced output for nitrate-nitrogen removal. However, nitrate selective resins are available that can be used on waters with high sulphate concentrations.

The waste regenerant comprises approximately 4% of the treated water. This waste regenerant consists mainly of spent sodium chloride solution. This brine should be disposed of safely, preferably in lined evaporation pounds. This method of brine disposal, however, may also be too expensive for application in rural areas. An alternative way of brine disposal may be to dispose of the brine at a large sewage works where enough dilution water is available.

The ion-exchange process should work effectively for water denitrification when the TDS of the water is low (<1 500 mg/ℓ). The ion-exchange process, as the activated alumina process, is not a desalination process. Therefore, only nitrates will be removed. The removal of high TDS concentrations (>1 500 mg/ℓ) in the presence of high nitrate concentrations (>10 mg/ℓ NO_3-N) will require RO desalination.

4.3 Water Defluoridation, Water Denitrification and Water Desalination with RO

Both low (approximately 4 bar) and high pressure (approximately 15 to 20 bar) RO can be successfully applied for water defluoridation, water denitrification and water desalination. Fluoride in the feed water concentration range from 4 to approximately 20 mg/ℓ can be effectively defluoridated to potable standards (<1,5 mg/ℓ) with RO. Nitrate-nitrogen in the feed water concentration range from 10 to 50 mg/ℓ nitrate-nitrogen can also be effectively denitrified with RO to potable standards (<6 mg/ℓ NO_3-N). TDS in feed waters can he effectively reduced from 10 000 mg/ℓ to less than 500 mg/ℓ.

Reverse osmosis brine should be disposed of safely in line evaporation ponds. This, however, may be expensive in a rural area. An alternative way of brine disposal is to use the brine for stock watering. This should be possible in the case of high TDS and high nitrate-nitrogen concentrations waters. Water recovery, however, should be kept sufficiently low to make this possible. This, however, should not be possible with high fluoride-containing waters.

Reverse osmosis membranes for water defluoridation, water denitrification and water desalination are available from a large variety of membrane suppliers. Desalination experts, however, should always be consulted prior to the selection of membranes for water desalination

Water pretreatment prior to RO desalination should be kept as simple as possible. Filtration of borehole water through a multi-media filter should remove most of the suspended material in the feed water. The remaining suspended material should be removed with a 5 micron cartridge filter prior to desalination. The cartridge filter should be cleaned or replaced when the pressure drop across the cartridge filters exceeds 1 bar.

4.4 Generic Guidelines

- The chemical composition of the borehole water should always be determined to determine whether potential foulants (Fe, Mn, Ba, Sr, H_2S, Ca, SO_4, F, etc.) are present, and to determine at which safety water recovery levels the units can be operated at.

- The bacteriological composition of the borehole should also be determined to identify any faecal pollution.

- The yield of the borehole water should be established to ensure a long, steady supply of water.

- The product water should be chlorinated prior to distribution.
- Raw and product water tanks should be closed to prevent dust and plant material contaminating the water.
- The high pressure RO pump should be protected from damage by simple safety devices.
- The ion-exchange or RO plant should be housed in a construction that can be locked.
- The ion-exchange or RO plant, feed and product storage tanks should be protected from damage by intruders by a wire fence.
- Desalination equipment should be protected from direct sunlight to prevent degradation of PVC and other plastic components.
- Taps should be provided where untreated borehole water can be collected for non-potable uses, such as washing of clothes, dishes, stock watering, brick manufacturing, etc.
- Chemicals (acids, bases, anti-scalants, etc.) should be stored in a separate locked storeroom in the desalination plant housing.
- Plant operators should always wear gloves and glasses when preparing chemical make-up.
- Enough spare parts and chemicals should be kept in stock on site to prevent long down times.
- Technical people should be identified who can help with mechanical and electrical problems, if they should occur.
- A higher form of supervision over a water treatment scheme in a rural area will always be necessary. This task can be conducted by a suitable consultant.

5. CONCLUSIONS

5.1 Methodology and Guidelines for Water Defluoridation, Water Denitrification and Water Desalination in Rural Areas

5.1.1 Water defluoridation

The activated alumina process is an established process for water defluoridation. This process can be successfully used to defluoridate water from boreholes in the feed water concentration range from approximately 4 to 20 mg/ℓ to potable standards (<1,5 mg/ℓ F). Five to 10 bedvolumes regenerant (1% NaOH) can be used for regeneration. The activated alumina, however, should always be neutralised with a dilute solution of sulphuric acid (15 BVs 0,05 N) prior to loading.

The waste regenerant comprises approximately 4% of the treated water. This waste regenerant should be disposed of safely, preferably into lined fenced evaporation ponds. This brine disposal method, however, may be too expensive for application in a rural area. An alternative disposal method may be to conduct the regeneration off-site at a large municipal sewerage works, where enough dilution water is available to absorb the high fluoride concentration.

The activated alumina process should only be considered for water defluoridation where the TDS concentration is less than approximately 1 500 mg/ℓ. The activated alumina process is not a desalination process, and will only remove fluoride from the water. Therefore, water containing high TDS (>1 500 mg/ℓ), and high fluoride concentrations (>4 mg/ℓ), should be treated with RO.

5.1.2 Water denitrification

Strong base anion-exchange is an established process for the removal of nitrates from water. Borehole waters with nitrate-nitrogen concentrations in the range from 10 to 50 mg/ℓ can be successfully treated with strong base anion-exchange for nitrate removal (<6 mg/ℓ NO_3-N in product water).

High sulphate concentrations, however, will reduce the efficiency of strong base ion-exchange resins for water denitrification, because the sulphate will be removed preferentially which will result in a reduced output for nitrate-nitrogen removal. However, nitrate selective resins are available that can be used on waters with high sulphate concentrations.

The waste regenerant comprises approximately 4% of the treated water. This waste regenerant consists mainly of spent sodium chloride solution. This brine should be disposed of safely, preferably in lined evaporation pounds. This method of brine disposal, however, may also be too expensive for application in rural areas. An alternative way of brine disposal may be to dispose of the brine at a large sewage works where enough dilution water is available.

The ion-exchange process should work effectively for water denitrification when the TDS of the water is low (<1 500 mg/ℓ). The ion-exchange process, as the activated alumina process, is not a desalination process. Therefore, only nitrates will be removed. The removal of high TDS concentrations (>1 500 mg/ℓ) in the presence of high nitrate concentrations (>10 mg/ℓ NO_3-N) will require RO desalination.

5.1.3 Water defluoridation, water denitrification and water desalination with RO

Both low (approximately 4 bar) and high pressure (approximately 15 to 20 bar) RO can be successfully applied for water defluoridation, water denitrification and water desalination. Fluoride in the feed water concentration range from 4 to approximately 20 mg/ℓ can be effectively defluoridated to potable standards (<1,5 mg/ℓ) with RO. Nitrate-nitrogen in the feed water concentration range from 10 to 50 mg/ℓ nitrate-nitrogen can also be effectively denitrified with RO to potable standards (<6 mg/ℓ NO_3-N). TDS in feed waters can be effectively reduced from 10 000 mg/ℓ to less than 500 mg/ℓ.

Reverse osmosis brine should be disposed of safely in lined evaporation ponds. This, however, may be expensive in a rural area. An alternative way of brine disposal may be to use the brine for stock watering. This might be possible in the case of high TDS and high nitrate-nitrogen concentrations waters. Water recovery, however, should be kept sufficiently low to make this possible. This, however, might not be possible with high fluoride-containing waters.

Reverse osmosis membranes for water defluoridation, water denitrification and water desalination are available from a large variety of membrane suppliers. Desalination experts, however, should always be consulted prior to the selection of membranes for water desalination. The same applies for adsorbents to be used for water defluoridation and water denitrification.

Water pretreatment prior to RO desalination should be kept as simple as possible. Filtration of borehole water through a multi-media filter should remove most of the suspended material in the feed water. The remaining suspended material should be removed with a 5 micron cartridge filter prior to desalination. The cartridge filter should be cleaned or replaced when the pressure drop across the cartridge filters exceeds 1 bar.

5.1.4 Generic guidelines

- The chemical composition of the borehole water should always be determined to determine whether potential foulants (Fe, Mn, Ba, Sr, H_2S, Ca, SO_4, F, etc.) are present, and to determine at which safety water recovery levels the units can be operated at.

- The bacteriological composition of the borehole should also be determined to identify any faecal pollution.

- The yield of the borehole water should be established to ensure a long, steady supply of water.

- The product water should be chlorinated prior to distribution.

- Raw and product water tanks should be closed to prevent dust and plant material contaminating the water.

- The high pressure RO pump should be protected from damage by simple safety devices.

- The ion-exchange or RO plant should be housed in a construction that can be locked.

- The ion-exchange or RO plant, feed and product storage tanks should be protected from damage by intruders by a wire fence.

- Desalination equipment should be protected from direct sunlight to prevent degradation of PVC and other plastic components.

- Taps should be provided where untreated borehole water can be collected for non-potable uses, such as washing of clothes, dishes, stock watering, brick manufacturing, etc.

- Chemicals (acids, bases, anti-scalants, etc.) should be stored in a separate locked storeroom in the desalination plant housing.

- Plant operators should always wear gloves and glasses when preparing chemical make-up.

- Enough spare parts and chemicals should be kept in stock on site to prevent long down times.

- Technical people should be identified who can help with mechanical and electrical problems, if they should occur.

- A higher form of supervision over a water treatment scheme in a rural area will always be necessary. This task can be conducted by a suitable consultant.

5.2 Demonstration Studies

It was demonstrated that:

- The activated alumina process can remove fluoride in the feed concentration range from approximately 4 to 20 mg/ℓ to less than 1,5 mg/ℓ. Therefore, water of a potable quality can be produced with this process. The capital cost for a household defluoridation unit was determined at approximately R5 000. Operational cost in the feed water concentration range from 4, 8, and 20 mg/ℓ was determined at 0,43;1,14 and R3,99/kℓ water treated.

- A strong base anion exchanger can remove nitrate-nitrogen from approximatelhy 4,4 mg/ℓ to less than 2 mg/ℓ. The capital cost of a household denitrification unit was determined at approximately R5 000. Operational cost at a feed concentration of approximately 44 mg/ℓ nitrate-nitrogen was determined at R3,18/kℓ water treated.

- Fluoride can be removed with low pressure RO in the feed water concentration range from 10 to 17 mg/ℓ to approximately 0,2 mg/ℓ in the RO permeate.

- Fluoride can be removed with high pressure RO from approximately 17 mg/ℓ in the feed water to approximately 0,2 mg/ℓ in the RO permeate.

- Nitrate-nitrogen can be removed with high pressure RO from approximately 45 mg/ℓ nitrate-nitrogen in the RO feed to approximately 2 mg/ℓ in the RO permeate.

- A feed water containing 3,90 mg/ℓ fluoride and 1 624 mg/ℓ TDS can be desalinated with low pressure RO to contain almost zero fluoride and 580 mg/ℓ TDS in the RO permeate.

- A feed water containing 6,6 mg/ℓ TDS can be desalinated with low pressure RO to contain less than 0,2 mg/ℓ fluoride and 188 mg/ℓ fluoride and 4 156 mg/ℓ TDS in the RO permeate.

- The capital cost of a small RO unit to produce approximately 50 ℓ/d defluoridated water is estimated at approximately R3 000. Operational cost is estimated at approximately R3,00/kℓ. The capital cost of an RO unit to produce approximately 5 kℓ/d desalinated water is estimated at approximately R20 000. Operational cost is estimated at approximately R1,69/kℓ. The capital cost of an RO unit to produce approximately 50 kℓ/d denitrified water is estimated at approximately R150 000. Operational cost is estimated at approximately R2,17/kℓ.

APPENDIX A

Table A1. Reverse osmosis water defluoridation operational data.

Time (h)	Flux (25°C) (l/m^2.mod)	Temperature (°C)	Flux (ml/2 min)	Brine (ml/min)	Recovery (%)	Feed		Permeate		Brine		Rejection EC* (%)	Pressure		
						pH	EC* (mS/m)	pH	EC* (mS/m)	pH	EC* (mS/m)		Filter (kPa)$_{in}$	Filter (kPa)$_{out}$	Membrane (kPa)$_{in}$
CWF	50,22	20	62	-	-		34,7		1,41			95,94			
0	44,75	24,9	62	70	30,69	-	110,6	-	-	-	-		390	400	400
2	48,76	26,3	70	72	32,71	-	110,5	-	-	-	-		390	400	400
21	46,69	25,7	66	74	30,84	7,94	110,7	6,28	2,31	8,06	157,7	97,91	390	400	400
25	46,87	27,8	70	74	32,11	7,82	110,4	6,52	2,49	7,90	159,2	97,75	390	400	400
45	44,42	24,3	62	72	30,10	7,91	111,5	6,18	2,55	8,05	157,2	97,71	390	400	400
50	47,23	24,0	64	72	30,77	7,85	110,3	6,28	2,43	8,01	155,5	97,80	390	400	400
60	48,71	24,0	66	72	31,43	7,65	111,0	6,38	2,41	7,85	155,5	97,83	390	400	400
72	49,08	24,9	68	72	32,08	7,89	110,8	6,25	2,43	7,99	156,1	97,81	390	400	400
99	47,00	27,7	70	72	32,71	7,88	112,0	6,42	2,57	8,00	159,0	97,71	375	400	400
104	49,00	30,1	78	76	33,91	7,71	111,2	6,68	2,67	7,97	161,1	97,60	390	400	400
128	49,56	29,7	78	76	33,91	-	112,7	-	2,71	-	168,3	97,60	390	400	400
152	50,07	28,4	76	76	33,33	-	112,9	-	2,30	-	166,7	97,96	390	400	400
180	48,82	31,1	80	78	33,90	-	114,1	-	2,46	-	171,2	97,84	390	400	400
202	49,68	30,5	80	76	34,48	7,87	113,3	6,52	2,54	7,96	167,7	97,76	390	400	400
228	48,71	29,4	76	76	33,33	-	113,1	-	2,46	-	167,8	97,83	390	400	400
234	49,12	27,1	72	78	31,58	-	114,2	-	2,55	-	167,9	97,77	390	400	400
258	49,84	29,5	78	74	34,57	7,91	113,8	6,37	2,51	8,02	167,4	97,79	390	400	400
282	50,12	29,3	78	74	34,51	-	113,7	-	2,85	-	167,8	97,49	390	400	400

Time (h)	Flux (25°C) (l/m².mod)	Temperature (°C)	Flux (ml/2 min)	Brine (ml/min)	Recovery (%)	Feed		Permeate		Brine		Rejection EC^* (%)	Pressure		
						pH	EC^* (mS/m)	pH	EC^* (mS/m)	pH	EC^* (mS/m)		Filter $(kPa)_{in}$	Filter $(kPa)_{out}$	Membrane $(kPa)_{in}$
306	48,93	29,7	77	76	33,62	-	113,4	-	5,55	-	168,1	95,11	390	400	400
330	48,84	32,7	84	76	35,59	7,95	114,1	6,39	3,05	8,08	172,8	97,33	390	400	400

APPENDIX B

Table B1. Reverse osmosis water defluoridation operational data.

Date	Time (h)	Time (cumulative) (h)	Product volume (ℓ)	Product volume (cumulative) (ℓ)	Product flux (mℓ/min)	Temperature (°C)	Product flux at 25°C (ℓ/module.day)	Brine flow rate (mℓ/min)	Water recovery (%)
10/01/95	0		0		28	25,9	39,41	72	28,00
13/01/95	11	11,00	27	27,00	33	25,2	47,28	73	31,13
19/01/95	2	13,00	5	32,00	36	24,5	52,49	86	29,51
27/01/95	11,5	24,50	28,5	60,50	40	29,5	51,12	88	31,25
03/02/95	10,75	35,25	27,5	88,00	38	26,3	52,94	88	30,16
10/02/95	15,75	51,00	37	125,00	32	24,2	47,00	80	28,57
17/02/95	10	61,00	25	150,00	34,5	26	48,44	80	30,13
24/02/95	14,25	75,25	36	186,00	34	25	48,96	80	29,82

Date	Time (h)	Fluoride (mg/ℓ)				Conductivity (mS/m)				pH		
		Feed	Product	Brine	Rej, (%)	Feed	Product	Brine	Rej, (%)	Feed	Product	Brine
10/01/95	0	13,4	0,20	18,7	98,51	87,3	2,9	119,2	96,68	-	-	-
13/01/95	11	12,7	0,21	18,4	98,35	89,4	2,59	123,7	97,10	7,99	7,22	7,66
19/01/95	13	7,6	1,71	10,6	77,50	78,4	18,6	105,6	76,28	9,00	8,15	7,88
27/01/95	24,5	10,2	0,15	14,8	98,53	81,9	2,8	117,9	96,58	8,70	8,25	7,83
03/02/95	35,25	9,4	0,26	11,8	97,23	81,3	2,9	110	96,43	8,62	6,29	9,00

10/02/95	51	10,6	0,17	14,7	98,40	83,6	2,4	114,7	97,13	8,63	6,21	8,47
17/02/95	61	9,4	0,34	14,5	96,38	82,0	4,1	130,8	95,00	8,64	6,42	9,13
24/02/95	75,25	9,8	0,23	14,1	97,65	82,7	2,8	116,2	96,61	8,71	6,61	9,10

APPENDIX C

Table C1. Reverse osmosis water defluoridation operational data.

Time (h)	Perm 1/min	Brine 1/min	Temp (°C)	Brine mS/m	Perm mS/m	% Rej	Temp Cor.	Cor. Capac. 1/min/elem.
0	4,68	14,61	19	98	0,8	99,2	1,2	5,38
4	5,40	14,4	18	99	0,6	99,4	1,2	6,34
8	6,00	15,84	20	101	0,6	99,4	1,1	6,75
9	4,68	14,64	16	96	0,6	99,4	1,2	5,73
15	5,40	14,40	20	101	0,6	99,4	1,1	6,08
18	5,40	14,40	20	101	0,8	99,2	1,1	6,08
19	4,56	13,50	15	98	0,7	99,3	1,3	5,70
23	5,22	13,80	18	96	0,5	99,4	1,2	6,13
28	5,40	16,44	21	97	0,7	99,3	1,1	5,94
29	4,27	14,94	15	95	0,8	99,1	1,3	5,34
34	5,58	12,72	24	149	1,1	99,3	1,0	5,72
37	6,00	18,00	21	98	0,8	99,2	1,1	6,60
38	4,20	15,00	12	95	0,6	99,4	1,3	5,57

Fluoride Concentration levels (mg/ℓ).

Hours	Feed	Perm.	Brine	% Rej.
1	21,0	0,2	36,0	99,05
8	20,0	0,2	35,0	99,00
15	17,2	0,2	35,9	98,84
23	21,0	0,2	36,0	99,05
38	22,0	0,2	34,0	99,00

APPENDIX D

Table D1. Reverse osmosis water denitrification operational data.

Time (h)	Pressure (kPa)								Flow rate (ℓ/h)		Reco very (%)	Raw feed			Acid feed			Permeate			Concentrate		Rej (%)
	Prefilter		Pump	Conc	Feed 1	Feed 2	Feed 3	Perm	Perm	Conc		mS/m	°C	pH	mS/m	°C	pH	mS/m	°C	pH	mS/m	pH	
	in	out																					
Pretoria tap water																							
0	100	85	1500	1100	950	850	600	12,5	31	56	35,6				34,9	19,9	5,66			4,3			
1	100	85	1500	1100	950	850	600	12	31	56	35,6				34	20,3	5,74	1,14		4,4	52,5	5,91	96,65
2	100	85	1500	1100	950	850	600	12	31	56	35,6				35,4	20,8	5,72	1,09		4,4	53,2	5,90	96,9
5	100	85	1500	1100	950	850	650	15	34	52	39,5				36,9	23,3	5,91	1,52		4,4	58,0	6,11	95,9
11	100	75	1500	1100	975	875	700	17	38	48	44,2				35,9	25,1	5,82	1,55		4,5	59,0	6,13	95,7
16	100	75	1500	1100	975	875	750	17	38	44	46,3				41,3	27,3	5,81	1,95		4,6	68,8	6,04	95,3
Zava high nitrate water																							
26/02/97																							
0	210	195	1550	1100	950	875	650	27,5	32	56	36,4	177	28,9	7,62	177		6,96	12,2		6,93	268		93,1
2	200	190	1550	1100	950	850	650	25	32	56	36,4	181	30	7,44	181		6,99	8,5		6,56	269	7,59	95,3
4	200	190	1500	1100	950	850	625	25	32	56	36,4	184	29,9	7,17	184		7,07	12			269	7,61	93,5
6	200	160	1500	1100	950	850	625	25	32	56	36,4	184	30	7,24	184		7,07	11		6,60	272	7,60	94
Wash prefilter due to pressure drop																							
21	200	84	Wash prefilter due to pressure drop																				
22	200	170	1500	1100	925	825	560	22,5	28	62	31,1	183	25,4	7,17	187		7,08	29,8		6,22	257	7,30	84,1
23	200	126	Wash prefilter due to pressure drop																				
Preserve membranes in 0,25% sodium metabisulfite. Install sandfilters as pretreatment to RO unit.																							
11/03/97																							
23	230	220	1600	1325	1200	1100	975	37,5	42	44	48,8	185	29,6	7,00	186		6,90	6,19		6,05	343	7,43	96,7
26	230	220	1600	1300	1150	1050	925	35	42	44	48,8	185	30	7,00	186		6,90	6,79		6,04	344	7,40	96,3

Time (h)	Pressure (kPa)								Flow rate (ℓ/h)		Reco very (%)	Raw feed			Acid feed			Permeate			Concentrate		Rej (%)
	Prefilter		Pump	Conc	Feed 1	Feed 2	Feed 3	Perm	Perm	Conc		mS/m	°C	pH	mS/m	°C	pH	mS/m	°C	pH	mS/m	pH	
	in	out																					
26	250	230	1650	1400	1275	1175	1050	40	40	44	47,6	181	24,9	6,77	182		6,67	5,42		5,79	332	7,20	97
28	230	220	1625	1375	1250	1150	1025	40	40	44	47,6	180	25,8	6,85	181		6,67	5,1		5,68	315	7,18	97,2
34	240	225	1650	1375	1250	1150	1025	40	40	44	47,6	182	26,5	6,72	180		6,39	5,08		5,86	327	6,87	97,2
51	230	220	1650	1375	1250	1150	1025	40	40	44	47,6	180	25,9	6,70	181		6,68	6,28		5,67	329	7,13	96,5
53	230	220	1650	1375	1250	1150	1025	39	40	44	47,6	183	26,6	6,83	181		6,63	8,4		6,16	318	7,10	95,4
*56	230	205	1625	1375	1250	1150	1025	40	41	43	48,8	173	27,4	6,87	175		6,61	8,31		6,06	313	7,12	95,3
59	225	205	1625	1375	1250	1150	1025	40	41	44	48,2	176	27,1	6,88	174		6,68	7,98		6,19	321	7,13	95,4
73	230	210	1650	1375	1270	1175	1050	40	40	45	47,1	178	25,3	6,99	177		6,79	8,6		6,32	311	7,34	95,1
73	220	200	1650	1375	1250	1150	1025	37,5	39	43	47,6												
74	220	200	1650	1375	1250	1175	1050	38	41	42	49,4	180	27,2	7,10	178		7,01	8,01		6,22	331	7,40	95,5
76	230	210	1650	1375	1250	1175	1050	38	41	43	48,8	180	27,1	7,12	178		7,02	8,21		6,31	322	7,38	95,4
92	230	210	1625	1375	1260	1180	1060	39	40	43	48,2	171	26,6	7,10	172		6,99	7,3		6,49	309	7,55	95,8
94	230	205	1625	1375	1260	1180	1060	40	41	43	48,8	180	26,8	7,10	180		6,99	7,6		6,34	337	7,58	95,8
96	230	205	1625	1375	1250	1175	1050	38	41	43	48,8	182	27,5	7,00	181		7,06	7,7		6,48	329	7,52	95,7
98	225	200	1600	1375	1250	1175	1050	38	41	43	48,8	180	27,7	6,96	181		7,03	8,7		6,48	326	7,52	95,2
100	220	190	1600	1375	1260	1175	1060	40	42	40	51,2	171	27,9	6,98	174		6,80	10		6,24	321	7,43	94,3
116	225	200	1650	1375	1250	1175	1050	40	40	44	47,6	185	26,1	6,99	186		6,76	8,15		6,30	295	7,52	95,6
119	200	190	1600	1375	1250	1175	1060	40	42	40	51,2	183	27	7,12	183		7,02	8,2		6,29	327	7,41	95,5
120	210	190	1600	1375	1250	1150	1025	37,5	40	44	47,6	185	28,3	7,15	186	28,3	6,96	8,7		6,66	321	7,43	95,3
123	220	190	1600	1375	1250	1150	1025	35	40	44	47,6	182	28,1	7,10	183	28,1	6,89	7,6		6,43	310	7,33	95,8
126	240	210	1650	1375	1225	1150	1025	36	38	46	45,2	178	26	7,14	179	25,9	6,84	7,6		6,20	319	7,32	95,8
128	230	200	1600	1375	1250	1175	1050	40	40	44	47,6	176	27,1	7,06	176	27,3	6,93	8,0		6,12	316	7,27	95,5
132	220	180	1600	1375	1250	1150	1025	39	41	43	48,8	178	28	7,11	178	28,2	6,87	8,1		6,22	325	7,30	95,4

Time (h)	Pressure (kPa)								Flow rate (ℓ/h)		Reco very (%)	Raw feed			Acid feed			Permeate			Concentrate		Rej (%)
	Prefilter		Pump	Conc	Feed 1	Feed 2	Feed 3	Perm	Perm	Conc		mS/m	°C	pH	mS/m	°C	pH	mS/m	°C	pH	mS/m	pH	
	in	out																					
148	210	170	1600	1375	1250	1150	1050	38	40	44	47,6	191	26,5	7,22	191	26,8	7,03	8,1		6,30	332	7,40	95,8
150	210	170	1600	1375	1250	1175	1050	37,5	40	44	47,6	188	26,6	7,19	188	26,9	7,01	8,1		6,38	326	7,38	95,7

APPENDIX E

CONDITIONS FOR THE USE OF RO BRINE FOR STOCK WATERING

Introduction

When assessing the fitness for use of water destined for livestock watering, three norms must be considered. They are:

- **Health implications for the animals consuming the water**. This addresses toxicological and palatability effects.

- **Consumer health hazards and product quality**. This deals with the fitness for use of the animal product, and depends on the context of use. In terms of rural, communal subsistence production systems, the possible adverse health risk for humans by the consumption of milk, meat and various organs and tissues, is the primary issue.

- **Livestock watering systems**. This applies to adverse effects such as scaling, corrosion, blockage of emitters, and any effect on the water delivery system that may have a financial implication for the livestock producer.

Risk assessment

There are two distinct methods for conducting a risk assessment. The first, a generic guideline application, makes use of static tabulated guidelines in the form of a mg/ℓ basis. The second, a specific guideline application, makes use of an ingestion rate in mg water quality constituent (WQC)/Body Weight/day, and uses site-specific information. The generic guideline system is independent of the environment, actual intake of potentially hazardous constituents, and desired production level, and may therefore be overly conservative in risk estimation.

In communities which rely on livestock for subsistence in a localised geographical production system context, the second norm concerning human health becomes increasingly important due to the greater dependency on local food and water sources (Plant *et al*, 1996). Potential hazards are increased further by the greater sensitivity of the user groups, usually pregnant women, children and older persons (WHO, 1993). There is also an increased risk of bioaccumulation and bioconcentration in animal tissues due to soil and plants contributing to higher mineral loading in animals. **RO brine may not be classed as fit for use for livestock watering without first assessing the potential risk to both animal health and subsequent human health hazards.**

Due to the potentially toxic nature of many of the trace minerals which may occur naturally in groundwater, and which may be present in elevated concentrations in brine water, it is essential that the trace mineral content of the RO brine be known. It is recommended that the following water quality constituent detail be obtained:

F; NO_2; NO_3; Cl; SO_4; TDS; Ca; Mg; Na; B; pH; Be; V; Cr; Mn; Co; Ni; As; Cu; Br; Se; Sr; Mo;

Cd; Sb; Sn; Te; Th; Ti; Au; Hg; Pb and U.
(For those WQC not underlined, a semi-quantitative scan is sufficient initially)

Risk assessment due to RO Brine water
Based on Table 9, only two WQCs pose a potential hazard.

The first is TDS, which although below the guideline level for mature ruminants, may cause an adverse palatability response on first access.

It is recommended that the stock be exposed to a TDS concentration of 1 000 mg/ℓ for at least 3 days prior to being allowed access to the brine.

It must be noted that should RO brine contain potentially hazardous concentrations of trace minerals which are cumulative toxins, and have a TDS concentration in excess of 3 000 mg/ℓ, the resultant increase in water intake by livestock due to sodium related thirst signals, can significantly increase the ingestion of those potentially hazardous constituents. This may occur despite concentrations in water that are within a target water quality guideline range.

The second is NO_3. A nitrate ion concentration of greater than 100 mg NO_3/ℓ may cause adverse chronic effects in monogastric livestock (pigs and horses), and possibly acute effects in pregnant monogastric livestock. The reported RO brine concentration is approximately 340 mgNO_3/ℓ (Table 9). At this concentration ruminant livestock are at risk due to chronic effects, whilst pregnant ruminants, and all monogastric species, are at risk due to acute effects. Livestock can however adapt to high nitrate concentrations. The ability for stock to adapt to high nitrate levels is dependant on an incremental exposure to nitrate, allowing for nitrite reducing microorganisms to increase to a large enough population size.

It is recommended that all stock be exposed to nitrate levels of 100 mgNO_3/ℓ initially, for a period of at least 3 days, before being allowed access to the RO brine. Note that pregnant animals may still abort, or have stillborn foetuses, with associated complications. Once exposure is in effect, it is recommended that it be continuous, and not intermittent. As conditions such as overcast weather and drought can lead to a significant increase in plant nitrate levels, it is important that stock remain adapted to nitrate ingestion.

Note that the HCO_3- concentration (Table 9), despite exceeding the recommended guideline, should not pose any significant health hazard.

TDS and Palatability

It should be noted that only with sufficient adaptation is it suitable for stock to consume high TDS water (12000mg/ℓ) without serious adverse effects. Stock must be adapted incrementally, to increasing TDS levels, and it is imperative that the ratios of Cl:SO_4:TDS are maintained within a palatability zone of preference. This zone is different for sheep, cattle and goats. Where high TDS RO brine is used for stock watering, the calculation of the required addition of Na_2SO_4 or NaCl to RO brine in order to improve the palatability, may be done using the software program

CIRRA, Vers 1.03, developed for the WRC. For further detail the reader should be referred to WRC report K5/644 and K5/857.

Note that the strontium concentration (Table 9) of the concentrate is considered to be an antagonistic variable (AV) with regard to chronic fluorosis. Strontium values in excess of 0.1 mg/ℓ are classed as AVs as they have the potential to increase the incidence of chronic fluorosis, with specific reference to skeletal effects. This can lead to an increase in chronic fluorosis at F concentrations of less than 6 mg/ℓ. This is exacerbated by the increased F concentrations in the concentrate, but will be partially mitigated by the increased Ca, Mg and TDS in the concentrate. It is recommended that feed and/or water source manipulation be used to mitigate for the potential F hazard. The relevant adverse effects are applicable to the animal health norm mainly, as F does not pose a significant health hazard in soft tissues, although dependent on species, milk levels may increase.

Mitigation

When RO brine yields concentrations of water quality constituents which exceed the recommended guidelines, and when site-specific analysis reveals that risk may be increased for the community in terms of hazards attributable to the use of animal products, there are several mitigation options.

- Dilution of RO brine with feed water

- Incremental adaptation for certain WQCs

- Improvement of water palatability by the addition of specific salts to RO brine

- Correction of induced mineral toxicities, imbalances and/or deficiencies, via manipulation of water and/or feed mineral content

- A possible mitigation effect may be obtained by increasing the recovery from the RO raw water to increase the TDS, Ca and Mg concentrations in situations of increased F, Sr and Mo concentrations (proportionately more TDS, Ca and Mg, than associated F, Sr and Mo in the concentrate). For F concentrations of >4 mg/ℓ, TDS, Ca and Mg concentrations should be at 3000 – 6000, 1000 and 500 mg/ℓ respectively. Increasing B levels to approximately 25 mg/ℓ is also recommended (this may apply to lower F concentrations dependent on species involved, altitude, ambient temperature and feed and soil F concentrations).

Generic guidelines applicable to livestock watering

The following Table is provided as a generic guide to the WQC concentrations that apply to livestock watering. However, it must be noted that for localised geographic communities relying on subsistence production systems, a site-specific approach is required for an accurate risk assessment.

Table E1. Generic guidelines for livestock watering[a].

Water quality constituent	Target Water Quality Range (mg/ℓ)*
Al	0 – 5
As	0 - 0.6
B	0 – 5
Cd	0 - 0.01
Ca	0 – 1000
Cl	0 – 1500 / 0 – 3000 (species dependent)
Cr	0-1
Co	0 – 1
Cu	0 - 0.5 / 0 – 5 (species dependent)
F	0 – 2 / 0 – 6 (species dependent)
Fe	0 – 10
Pb	0 - 0.05
Mg	0 – 500
Mn	0 – 10
Hg	0 - 0.001
Mo	0 - 0.01
Ni	0 – 1
NO_3 (as NO_3	0 – 100
Se	0 - 0.05
Na	0 – 1000
SO_4	0 – 1000
TDS	0 – 1000 / 0 - 3000 (species dependent)
V	0 - 0.1
Zn	0 – 20

[a] Adapted from: Casey & Meyer (1996), updated in WRC Report 857/1/2000 (in press).

* Guideline Tables for species differences and types of effects may be found in WRC Report 857/1/2000.

Whilst the Specific Guideline Risk assessments for livestock can be conducted utilising a software program developed for the Water Research Commission, CIRRA Version 1.03 (Casey *et al.*, 1998), for humans, risk assessments need to use local and international guidelines currently in use, including DWA&F (1996), Quality of Water for Domestic Supplies (1998), USEPA (1998) and the WHO (1993). This is to cater for the absence of many known potentially hazardous trace minerals in the South African guidelines (Mills, 1996; TEMA 10, 1999; Underwood & Suttle, 1999).

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