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Nitrate removal with reverse osmosis in a rural area in South Africa

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Abstract

The nitrate-nitrogen concentration (>6 mg/l) and the salinity (>1000 mg/l TDS) of many borehole waters in rural areas in South Africa are too high for human consumption. Therefore, an urgent need for water denitrification and water desalination exists in these areas. Reverse osmosis (RO), electrodialysis (ED), ion-exchange (IX) and certain biological technologies can be very effectively applied for water denitrification. Each of these technologies, however, has its own advantages and disadvantages. Reverse osmosis technology, however, has been selected for this study because the technology is well known in South Africa and because it can be very effectively applied for water desalination. The objectives of this study were: (a) to transfer RO technology through process demonstration performance for water denitrification and water desalination to people living in rural areas; (b) to build capacity regarding the operation and maintenance of an RO application in a rural area; (c) to produce a preliminary operational and maintenance manual for the operation of an RO unit in a rural environment; (d) to train local operators to operate and maintain an RO plant in a rural environment; (e) to evaluate stock watering as brine disposal option; and (f) to determine the preliminary economics of the process. The following conclusions were drawn. It was demonstrated that the RO process could be very effectively applied for water denitrification and water desalination in a rural area. Nitrate-nitrogen was reduced from 42.5 mg/l in the RO feed to only 0.9 mg/l in the RO product water. The TDS of the RO feed was reduced from 1292 mg/l to 24 mg/l in the RO permeate. Therefore, an excellent quality water could be produced for potable purposes. The RO brine at approximately 50% water recovery should be suitable for stock watering if the conditions for stock watering are met in terms of nitrate-nitrogen concentration, TDS and other constituent concentrations. The capital cost for an approximately 50 m^3/d output RO plant is approximately US $29,900. Preliminary cost estimates have shown that the operational cost for water denitrification is approximately US $0.50/m^3$. This cost, however, should be significantly reduced by optimisation of the chemical dosing and by blending borehole water with RO product water.

Keywords: Reverse osmosis; Nitrate removal; Brine disposal; Stock watering; Treatment costs

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1. Introduction

Many borehole waters in rural areas in South Africa are not fit for human consumption because the nitrate-nitrogen (>6 mg/l) and salinity (>1000 mg/l TDS) concentration levels are too high [1]. High nitrate-nitrogen concentration levels in drinking water can cause an illness, called "Blue-Baby", in small children. High salinity levels in drinking water can cause diarrhoea, high blood pressure and other health-related problems for people drinking such water. Therefore, an urgent need exists for water denitrification and water desalination in rural areas in South Africa to provide potable water to people living in these areas.

Reverse osmosis (RO), electrodialysis (ED), ion-exchange (IX) and biological technologies can be very effectively applied for water denitrification [2]. Each of these technologies has its own advantages and disadvantages. RO technology, however, has been selected for this study because it is well known in South Africa and because it can be very effectively applied for water desalination.

The disposal of brine generated by a desalination process is always problematic. Brine can comprise between approximately 20% to 50% of the treated water volume, depending on the raw water quality. Brine is usually disposed of in lined evaporation ponds. This is very expensive [3]. Other brine disposal options are [4]:

- discharge into sewage treatment plants
- biodegradation of the concentrated waste
- volume reduction in an ED plant
- field irrigation

Another brine disposal option is stock watering [1]. This can be a very convenient way of brine disposal, especially in a rural area.

The objectives of the study were:

- to transfer RO technology through process demonstration performance for water denitrification and water desalination to people living in rural areas
- to build capacity regarding the operation and maintenance of an RO application in a rural area
- to produce a preliminary operational and maintenance manual for the operation of an RO unit in a rural environment
- to train local operators to operate and maintain an RO plant in a rural environment
- to evaluate stock watering as a brine disposal option
- to determine the preliminary economics of the process.

2. Nitrogen sources

Organic wastes in soil contain nitrogen in protein form. Their first transformation step is protein degradation (proteolysis and ammonia fixation of molecules) into ammonia-nitrogen by microorganisms [2]. The second step is the nitrification (two phases) performed by autotropic bacteria:

- NH_4^+ is oxidised into NO_2^- by nitrosomonas
- NO_2^- is oxidised into nitrate (nitration) by nitrobacter.

It is believed that organic matter in soil is the nitrogen source in many cases in South Africa where borehole waters in rural areas are contaminated with nitrates. Other nitrogenous sources include agriculture, waste water and domestic water [2]. However, it is doubtful whether any of these sources contribute significant quantities of nitrates to ground water in rural areas in South Africa.

3. Effects caused by nitrates

The norm used in the South African guideline for nitrate and nitrite is human health. There are no direct aesthetic impacts [5].

Upon absorption, nitrite combines with oxygen-carrying red blood pigment, haemo-

Table 1a
Effects of nitrate-nitrite on human health [5]

Nitrate/nitrite range (as mg/l N)	Effects
Target water quality range 0–6	No adverse effects
6–10	Rare instances of methaemoglobinaemia in infants; no effects in adults; concentrations in this range are generally well tolerated
10–20	Methaemoglobinaemia may occur in infants; no effects in adults
>20	Methaemoglobinaemia occurs in infants; occurrence of mucous membrane irritation in adults

Table 1b
Nitrate + nitrite (as N) [6]

Nitrate + nitrite range mg/l as N or mg/l as NO_3	Drinking		Food preparation	Bathing	Laundry
	Health	Aesthetic			
<6 mg/l as N (<26 mg/l as NO_3)	Negligible health effects	No aesthetic effects	Negligible health effects	No effects	No effects
6–10 mg/l as N (26–44 mg/l as NO_3)	Insignificant risk	No aesthetic effects	Insignificant risk	No effects	No effects
10–20 mg/l as N (44–89 mg/l as NO_3)	Slight chronic risk to some babies	No aesthetic effects	Slight chronic risk to some babies	Insignificant risk	No effects
20–40 mg/l as N (89–177 mg/l as NO_3)	Possible chronic risk to some babies	No aesthetic effects	Possible chronic risk to some babies	Slight risk to babies only	No effects
>40 mg/l as N (<177 mg/l as NO_3)	Increasing acute health risk to babies	No aesthetic effects	Increasing acute health risk to babies	Possible health risk to babies	No effects

globin, to form methaemoglobinaemia [5]. The reaction of nitrite with haemoglobin can be particularly hazardous to infants under 3 months of age, and is compounded when the intake of vitamin C is inadequate.

Metabolically, nitrates may react with secondary and tertiary amines and amides, commonly derived from food, to form nitro-amines which are known carcinogens.

A diet, adequate in vitamin C, partially protects against the adverse effects of nitrate-nitrite. Methaemoglobinaemia in infants can only be mitigated by blood transfusion.

The effects of nitrate-nitrite on human health, food preparation, bathing and laundry, are shown in Tables 1(a) and 1(b).

4. Nitrate removal methods

A number of water treatment methods are available for nitrate removal, but R&D work is still needed to improve both process performance and economics [2,7]. In fact, the challenge between different technologies (Table 2) depends on desired water quality, plant capacity, process automation or access to manpower of suitable skill [7].

Nitrate removal by means of biological denitrification is usually the preferred solution for nitrate removal because it is transformed in gaseous nitrogen with a very high yield and low process cost.

Biological denitrification, however, shows some drawbacks in process control and output

Table 2
Nitrate removal methods

Method	Removal efficiency, %
Biodentifrication	70–95
Algae harvesting	50–90
Ion-exchange	80–99
Electrodialysis	30–50
Chemical reduction	33–90
Reverse osmosis	50–96
Distillation	90–98
Land application	5–15

water quality. Nitrites are formed if insufficient carbon or energy is available and substrate is in excess. This problem, especially when random changes in the feed composition occur, can also be complicated by the presence of excess biomass (bacteria) or dead biomass in the final water. Therefore, post-treatment, disinfection and oxygenation of product water are generally needed. Biological treatment is preferred for large plants.

Processes based on IX, RO and ED have a lower efficiency if compared with biological denitrification, but they seem to be very interesting for medium and small applications. Better economics, larger automation possibilities, lower level in feed and process parameters control and no need for extensive post-treatment (in the case of RO) are advantages of these processes.

A comparison made between IX and RO states the higher cost of the latter process [8], but data refer to traditional membranes for desalination with a nitrate rejection as low as 70%. New membranes with high nitrate rejection can improve RO costs [7].

5. Brine disposal

Four different possibilities can be considered for brine disposal [4]:

- In most cases, discharge into a sewage treatment plant is possible.
- Direct biodegradation of the concentrated nitrate.
- Volume reduction in an ED plant with downstream evaporation or transport to a sewage treatment plant.
- Field irrigation; however, this possibility requires a certain brine quality such as nitrate portion, chloride concentration, sodium adsorption ratio (SAR) and residual sodium carbonate (RSC).
- Stock watering; this possibility, however, also requires a certain brine quality [1].

6. RO plant layout and operation

The RO plant (Delta 10, Environmental Products USA; 4040-LHA-CPA2 membrane; array, 2 × 2, 2 × 2, 1 × 2; membrane area 79 m^2) layout in the rural area in Zava, Giyani, is shown in Fig. 1. The plant layout consists of a building containing the RO plant, RO feed tanks (F1, F2 and F3) and an intermediate product water storage tank (P1), sand filters, product storage reservoir (approximately 160 m^3 capacity), RO brine disposal into a dry river bed via a cement crib, and three boreholes located at different locations in the area of the plant. The boreholes are equipped with electrical driven pumps which are controlled by the water level in the RO feed tanks. Denitrified and desalinated water stored in the concrete reservoir are used by the community at Zava for potable purposes. Provision has been made for the blending of untreated borehole water with RO product water to increase the water yield and to reduce desalination costs.

Feed water to the RO unit is stored in three 10 m^3 plastic tanks, filtered through three dual-media sand filters to remove suspended material from the water, and pumped through the RO plant at a flow rate and inlet pressure of approximately 85 l/min and 230 kPa, respectively (Fig. 2). Sulphuric acid (10 l 98% acid/50 l product water) and anti-scalant (5 l anti-scalant/50 l product water) are added to the feed water at

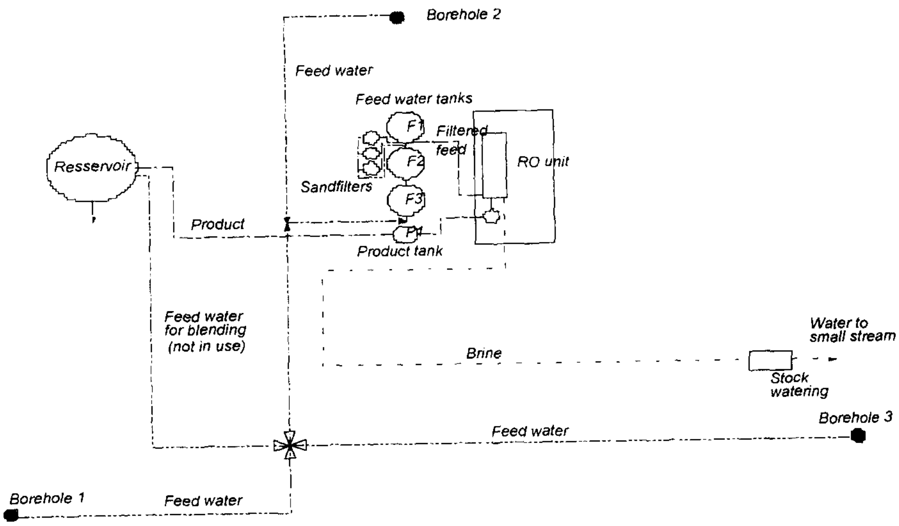

Fig. 1. Reverse osmosis plant layout at Zava.

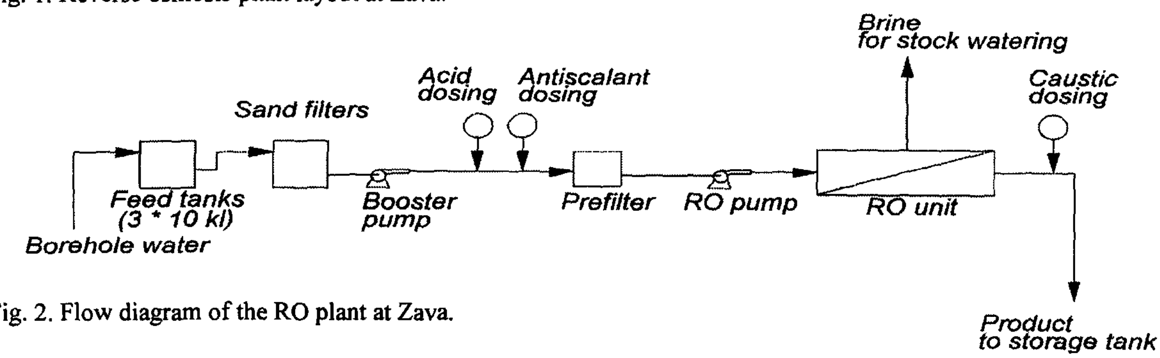

Fig. 2. Flow diagram of the RO plant at Zava.

flow rates of approximately 9 and 8.8 ml/min, respectively. The feed water is then filtered through a 5 micron cartridge filter prior to RO treatment to protect the membranes from plugging. Caustic soda (10 l 45% caustic soda/ 50 l product water) is added to the RO permeate at a flow rate of approximately 14 ml/min to raise the pH of the product water to approximately 7 prior to use as drinking water by the community.

The RO plant is operated at constant pump and concentrate pressures of 1600 and 1375 kPa, respectively. Plant output is approximately 55 m^3/d product water at a water recovery of approximately 50%. The plant was operated for approximately 150 h during the commissioning period.

7. Results and discussion

7.1. Electrical conductivity and nitrate-nitrogen concentration of the RO feed, permeate and brine

The electrical conductivity of the RO feed, product (permeate) and brine (concentrate) over approximately 3000 h of operation is shown in Fig. 3. The electrical conductivity of the RO feed varied between approximately 170 and 190 mS/m, while the electrical conductivity of the RO permeate varied between approximately 10 and 20 mS/m. Salinity of the RO concentrate varied between approximately 210 and 390 mS/m.

The nitrate-nitrogen concentration in the RO feed, permeate and brine as a function of time is

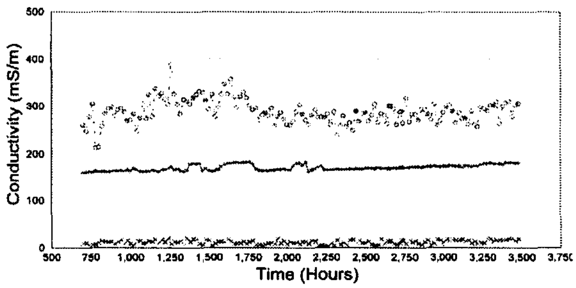

Fig. 3. Electrical conductivity of the RO feed, product and brine as a function of time.

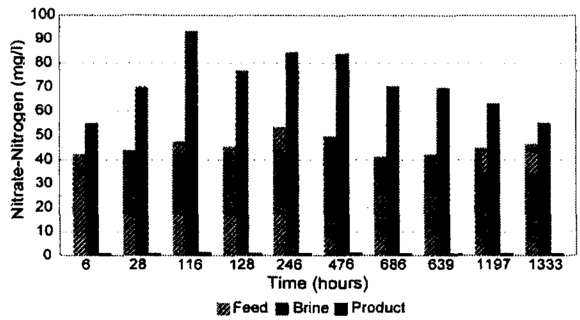

Fig. 4. Nitrate-nitrogen concentration of the RO feed, product and brine as a function of time.

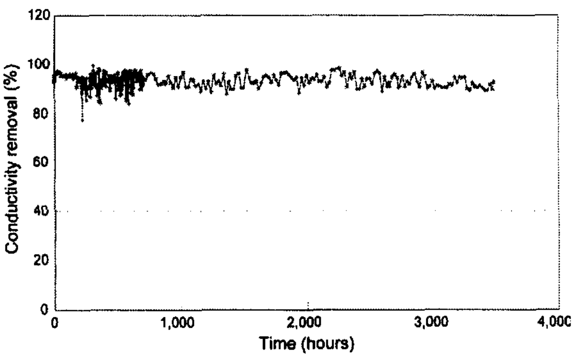

Fig. 5. Electrical conductivity removal as a function of time.

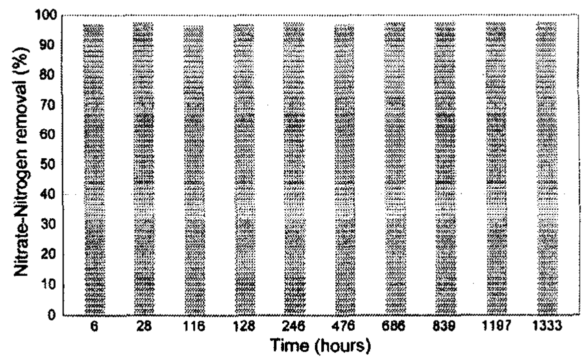

Fig. 6. Nitrate-nitrogen removal as a function of time.

shown in Fig. 4. The nitrate-nitrogen in the feed varied between 42 and 53 mg/l over the test period. Nitrate-nitrogen in the RO brine varied between 55 and 93 mg/l over the test period. The nitrate-nitrogen concentration in the RO permeate was less than 5 mg/l. Therefore, excellent nitrate-nitrogen removal could be obtained with RO desalination of the borehole water.

7.2. Electrical conductivity and nitrate-nitrogen removal as a function of time

The electrical conductivity removal as a function of time is shown in Fig. 5. Electrical conductivity removal over the test period varied between approximately 90% and 97%. Nitrate-nitrogen removal as a function of time is shown in Fig. 6. The nitrate-nitrogen removal varied between 96 and 98%.

7.3. Permeate flux as a function of time

The RO permeate flux (approximately 34.2 $l/m^2.h$) over an approximately 3000 h of operation is shown in Fig. 7. The permeate flux remained almost constant over the test period, showing that membrane fouling should not be a problem.

7.4. Water recovery

The water recovery over an approximately 3000 h of operation is shown in Fig. 8. Water recovery was deliberately kept low (40–50%) to ensure that the quality of the RO brine should be suitable for stock watering.

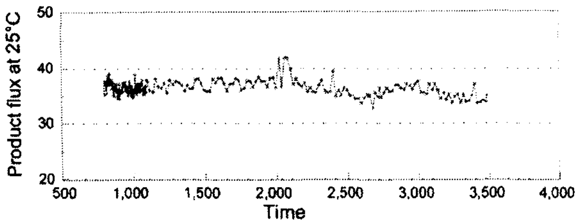

Fig. 7. Reverse osmosis permeate flux (l/min) as a function of time.

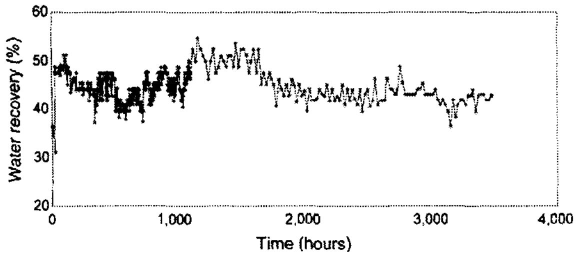

Fig. 8. Water recovery as a function of time.

7.5. Chemical composition of the RO feed, permeate and brine

The nitrate-nitrogen concentration in the RO feed, permeate and brine is shown in Table 3. The nitrate-nitrogen in the RO feed was reduced from approximately 42 mg/l to less than 1 mg/l (98% removal). Excellent TDS removals were also obtained (98.2%). The quality of the RO permeate, however, is too pure for potable purposes. Therefore, the RO permeate should be blended with the raw water to make it more suitable for potable purposes and to increase yield.

7.6. Conditions for the use of RO brine for stock watering

7.6.1. Background

Three norms must be considered when assessing the fitness for use of water destined for livestock watering [1]:

- health implications for the animals consuming the water. This addresses toxicological and potability 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 due to 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.

7.6.2. 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 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 that 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. Potential hazards are increased further by the greater sensitivity of the user groups, usually pregnant women, children and older persons. There is also an increased risk of bio-accumulation and bio-concentration in animal tissue 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

Table 3
Chemical composition of RO feed, permeate and brine and ion rejection (29/10/97, 839 h)

Constituents*	Raw feed	pH adjusted feed	Product	Concentrate	% removal
pH	7.22	6.98	6.40	7.30	
Conductivity (mS/m)	162.6	162.5	10.9	279	93.30
Nitrate as N	42.46		0.85	69.17	98.00
Chloride	169.1		1.41	309	99.17
Fluoride	0.76		0	1.33	100.00
Alkalinity as Ca CO_3	393	337	20.5	577	94.78
Sulphate	70	120	0	100	100.00
TDS	1292		24	2160	98.15
Iron	0		0	0	
Manganese	0.08		0	0.12	100.00
Potassium	4.05		0.09	5.9	97.78
Sodium	122		7.37	204	93.96
Magnesium	117		0.14	158	99.88
Calcium	135		0.18	180	99.87
Barium	0.21		<0.03	0.35	—
Strontium	0.86		<0.03	1.39	—
Silica	42.8		0.5	80.6	98.83
Aluminium	<0.1		<0.1	<0.1	—

* Constituents in mg/l unless stated otherwise.

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 ground water, and which may be present in elevated concentrations in RO brine, 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; Te; Th; Ti; Au; Hg; Pb and U. (Note: For those constituents not underlined, a semi-quantitative scan is sufficient initially.)

Based on Table 3, 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 1000 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 3000 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 nitrate. 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 306 mg NO_3/l (Table 3). 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 of stock to adapt to high nitrate levels is dependent on an incremental exposure to nitrate, allowing for nitrite-reducing micro-organisms to increase to a large enough population size.

It is recommended that all stock be exposed to nitrate levels of 100 mg NO_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.

7.6.3. TDS and palatability

It should be noted that only with sufficient adaption is it suitable for stock to consume high TDS water (12,000 mg/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 a software program CIRRA, Vers 1.03 [10].

Note that the strontium concentration (Table 3) 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 an AV as they have the potential to increase the incidence of chronic fluorosis with 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 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 tissue, although dependent on species, milk levels may increase.

7.6.4. 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 product, there are several mitigation options:

- dilution of the 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 3000–6 000, 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.)

7.6.5. Generic guidelines applicable to livestock watering

Table 4 gives 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.

While the Specific Guideline Risk assessments for livestock can be conducted utilising a software program developed for the Water Research Commission, CIRRA Version 1.03 [10,11], for humans, risk assessments need to use local and international guidelines currently in use, including the Department of Water Affairs and Forestry, Quality of Water for Domestic Supplies [11], USEPA [12] and the WHO [13]. This is to consider the absence of many known potentially hazardous trace minerals in the South African guidelines [14].

7.7. Capacity building, operational and maintenance manual and training of operators

Capacity was built amongst technical people of the Department of Water Affairs and Forestry to solve electrical and mechanical problems that occurred during the operation of the RO plant in a rural area. Learning was done through experience. Very few problems were experienced.

Procedures for the operation of the RO plant were established [15] and two local operators were taught to operate and maintain the RO plant. The project demonstrated that a first world technology could be successfully applied in a rural area if operators are reliable, well trained and under constant supervision.

The economics of the RO denitrification process is shown in Table 5.

Mixing of three parts of RO permeate with one part raw water to give a nitrate-nitrogen concentration of approximately 10.5 mg/l in the

Table 4
Generic guidelines for livestock watering [9]

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

Table 5
Economics of the RO denitrification process
(US$ = R5.02; 1999 values)

Capital cost	US$ 29,900
Operational cost (US $/m^3)	
Acid	0.01
Anti-scalant	0.10
Caustic soda	0.04
Electricity	0.12
Cartridge filters	0.07
Membranes	0.16
Total:	0.50

RO permeate, will reduce the operational cost to US\$0.37/m^3.

8. Conclusions

1. It was demonstrated that the RO process could be very effectively applied for water denitrification in a rural area. Nitrate-nitrogen could be removed from 42 mg/l to less than 1 mg/l (98% removal).

2. The RO brine should be suitable for stock watering if the water recovery is kept low (approximately 50%) and if the conditions for stock watering are met in terms of nitrate-nitrogen concentration, TDS and other constituent concentrations. Brine disposal for stock watering is a very convenient and cost-effective way of brine disposal in a rural area.

3. Operating procedures were established for the operation and maintenance of an RO unit in a rural area. These procedures were used to train local operators to operate and maintain the RO unit on their own for their own community. It was further demonstrated that a first world desalination technology could be successfully applied in a third world environment.

4. The capital and operational cost for an approximately 50 m^3/d output RO plant is estimated at US \$29,900 and US \$0.50/m^3, respectively.

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