Treatment Options for Drinking Water Production
from Brackish Well Water at Eagle Plain Base Camp

YUKON RESEARCH CENTRE
Yukon College

This publication may be obtained from:

Yukon Research Centre, Yukon College
520 College Drive
P.O. Box 2799,
Whitehorse, Yukon
Y1A 5K4
(867) 668-8895
1-800-661-0504
yukoncollege.yk.ca/research

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

Northern Cross Yukon Ltd. is in the process of electing a treatment method for drinking water provision at their base camp situated in Eagle Plains, Yukon Territory (Canada). An experiment was conducted at the Yukon Research Centre for comparing three treatment train options that were proposed by different stakeholders.

The three treatment trains had their share of advantages and shortcomings (Figure 14, p. 39). Most notably, the ion exchange step of treatment train A had the disadvantage of requiring prohibitive quantities of inputs, the capacitive deionization step of treatment train B had the disadvantage of a low water recovery rate (volume of drinking water produced per volume of brackish water treated) and the reverse osmosis step of treatment train C had the disadvantage of requiring an anti-scalant dosage beyond regulatory standards. On the other hand, cartridge filtration proved to be the cheapest, simplest and most efficient way to remove coarser solutes; it also has a very high recovery rate and does not require any input. Similarly, nextsand™ proved very efficient at removing high concentrations of Fe and Mn. Given the information gathered from commercial suppliers, it is deemed possible to overcome the low water recovery rate of capacitive deionization when using a full-scale unit. Finally, reverse osmosis has shown very cost-effective at polishing pre-treated water down to drinking water standards.

Our recommendation thus goes towards a composite treatment train (Figure 15, p. 40) made of treatment processes gleaned from the three original treatment trains under scrutiny in this study. The recommended treatment train involves Cartridge Filtration, nextsand™ Filtration, Capacitive Deionization, and Reverse Osmosis.

1. INTRODUCTION

1.1. Context

Northern Cross Yukon Ltd. (Northern Cross) is in the process of electing a treatment method for drinking water provision at their base camp situated in Eagle Plains, Yukon Territory (Canada). Groundwater is available on site, but its brackish nature makes treatment a necessity in order to meet Canadian drinking quality guidelines (Health Canada, 2012).

The Yukon Research Centre (YRC) disposes of research facilities and possesses expertise in water treatment, commonly working in partnership with the natural resources extraction industry of the Yukon, especially the mining industry.

The Water and Wastewater Operator Programs (WWOP) of the Yukon College hold a variety of water treatment units and are keen on providing hands-on training opportunities for their students.

A partnership was thus built between Northern Cross, the YRC and the WWOP, creating bridges between the industry decision-makers, research developers and the academia, in order to look into water treatment options that could be implemented at the base camp in Eagle Plains.

1.2 Objective

The objective of this study was to provide hands-on data and comparison figures that can help Northern Cross taking an informed, science-based decision. Three water treatment train options were considered. The three options were compared and contrasted along six parameters that would be valuable in the decision-making process:

- practicality
- quality of the end-stage water
- water recovery (% volume)
- input requirements (regenerants and other chemicals)
- quality of water rejects
- energy usages

Additionally, general figures for full-scale capitalization costs were also looked into.

1.3 Format

The first part of this report is intended as a succinct overview of the theory behind the treatment processes that were used in the study. Following is the materials and methods used in this experiment, and then the results are presented and analyzed. Recommendations and suggestions that can be drawn from this study are provided in the discussion section.

1.4 Scope

Costs incurred by the implementation, maintenance and operation of treatment units are only partially presented in this work, but stricter values for full-scale deployment could be calculated from the work presented herein. Hauling costs incurred by the transport of water treatment inputs to the Eagle Plains base camp are not detailed, but they could be derived from the quantity requirements that are presented.

In the same way, a few examples of manufacturer and suppliers are presented, and full span would need further investigation. The whole question of brine management is introduced, but thorough option valuation would necessitate some more work.

2 WATER TREATMENT BASICS

2.1 Filtration

Filtration consists in the separation of water from particles by a sieving mechanism. As filtrate passes through, particles are retained on the filter matrix. Particle removal capacity depends on the pore size of the matrix, as depicted in Figure 1. For instance, sand (60-2000 µm) can be removed by granular media (e.g. cartridge filtration), but sodium ions (Na^+; 0.0037 µm) necessitate reverse osmosis, which can remove particles larger than 0.0001 µm. The smaller the pore size, the higher pressure needed to drive water through.

As particles accumulate in the filter matrix, pores can become clogged. This can be monitored by differential pressure. When a limit is attained, the filter media needs backwash or replacement. In certain cases - such as reverse osmosis - most of the particles that are sieved out by the filter matrix are evacuated in a continuous brine stream.

Cartridge filtration (e.g. 10 µm) is often used as a pre-treatment so as to remove sediments and prevent clogging of downstream units.

Sand filtration can be used for the same purpose (removing sediments and clog prevention). Conventional multi-media sand filters remove particles 12-15 µm, and nextsand™ can remove particles 5 µm and smaller.

Reverse osmosis is often used as a final stage, because it produces a very pure filtrate. However, this filtrate sometimes necessitates to be adjusted with non-treated water, in order to redeem good taste.

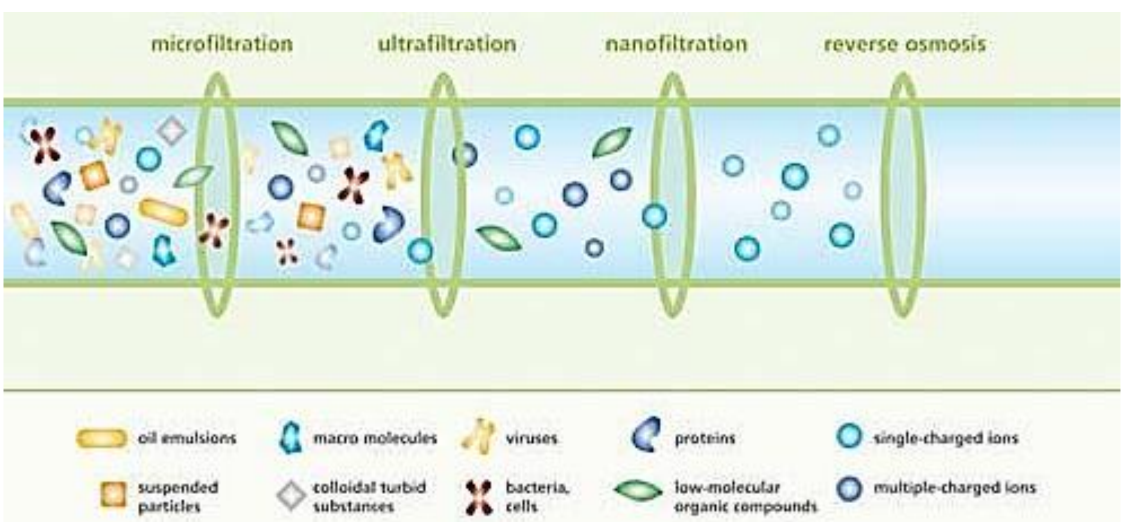

Figure 1: Particle removal capacity of filtration processes in relation to particle size.
Adapted from grunbeck (2014).

2.2 Oxidation and Green sand filtration

Filtration is sometimes used in combination with oxidation, where dissolved metals are converted to an insoluble complex when exposed to an oxidizing agent such as chlorine (Cl_2) or potassium permanganate ($KMnO_4$). For instance, ferrous iron is oxidized to ferric iron, which readily forms the insoluble iron hydroxide complex ($Fe(OH)_3$; reduced manganese (Mn^{2+}) is oxidized to (Mn^{4+}), which forms insoluble (MnO_2). These insoluble oxides can then be removed by precipitation in a settling tank, or be filtered out.

Green sand filtration is used to oxidize, precipitate and filter out iron and manganese. It is often used to prevent iron fouling of downstream units. Such a filter needs to be periodically backwashed to remove all filtered particles (insoluble oxides). If operated on a batch mode, the greensand filter also needs to be periodically regenerated with potassium permanganate ($KMnO_4$). If it is operated on a continuous mode, the green sand filter does not need to be stopped and regenerated, as regeneration is done continuously.

2.3 Ion exchange

In the ion exchange process, hardness cations (mainly Ca^{2+} and Mg^{2+}) in the water are replaced by Na^+ fixed to resin beads, as shown in Figure 2. This "water softening" reduces deposits and scaling that result from water with high level of hardness. Eventually, the ion exchanger's capacity is exhausted and a concentrated solution of salt is used to regenerate the resin.

Ion Exchange is often used upstream of a membrane systems such as reverse osmosis, in order to prevent fouling that could be caused by scaling if hardness cations were not removed.

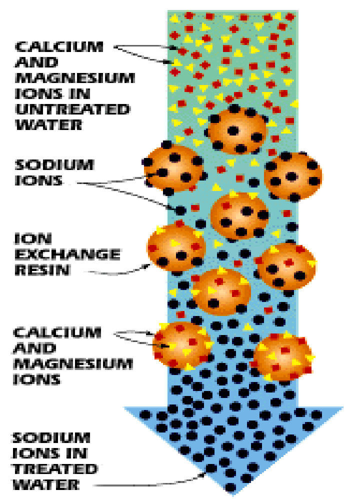

Figure 2: Ion exchange principle. Adapted from classwater (2014)

2.4 Capacitive deionization

Capacitive deionization (CDI) is an electrostatic water treatment process making use of the ability of electrodes to pull salts out of solution by using electricity at low voltage. Porous electrodes are used, which act as capacitors and temporarily hold ions to remove them from water (Figure 3). It operates on an intermittent basis, where the potential difference (voltage) is sequentially applied and inverted. In the first part of a cycle, potential difference is applied between the two electrodes (e.g. 75% of the entire cycle period) – the negative electrode then attracts positively charged ions (e.g. calcium, magnesium, sodium) and the positive electrode attracts negatively charged ions (e.g. chloride, sulfate, nitrate), and purified filtrate leaves the unit. The electrodes eventually become saturated with ions. Water circulation is then stopped and the electrical charge is reversed or reduced to zero. Water circulation resumes for a limited period of time (e.g. 25% of the entire cycle period), and a brine containing the ions is expelled from the unit.

When compared to traditional water treatment options, capacitive deionization has the potential to be simpler, have less maintenance needs, have a lower environmental footprint, and lower capitalization and operational costs (Zhang et al., 2012). Being relatively new, a common concern is however that this technology requires ground-proofing.

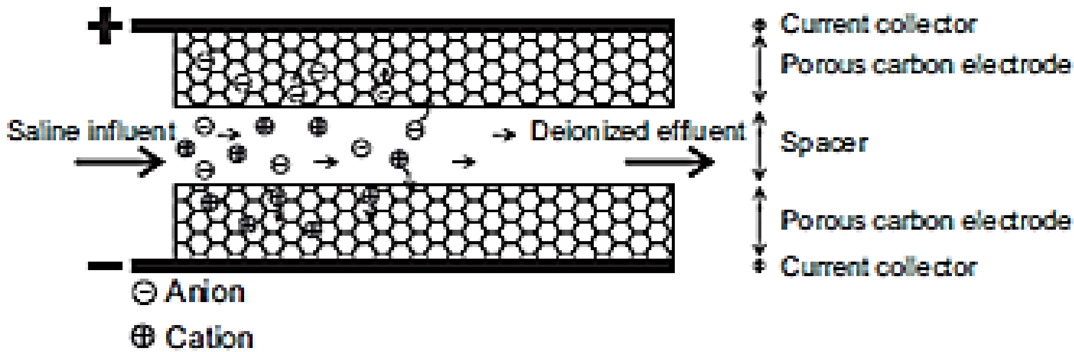

Figure 3: Capacitive Deionization principle.
Adapted from nmnuclear (2014)

3 MATERIALS AND METHODS

3.1 Time frame

The experiment was conducted between June 1, 2014 and July 25, 2014 at the Yukon College, Whitehorse (Yukon, Canada).

3.2 Experimental units

Three different water treatment train options (Figure 4) were compared at lab scale. The first option (A) involved a treatment train of greensand filtration, ion exchange, and reverse osmosis. This ''classic'' treatment method was proposed by an external consultant, but serious doubts were objected to this “classic” treatment method, given the remote context of the base camp and the heavy load of chemicals that would be needed to operate such a treatment train. The second treatment train (B) involved capacitive deionization. This “novel” water treatment method, proposed by the YRC, had proven efficient, but needed ground-proofing. . If proven, the capacitive deionization option could further reduce Northern Cross’ environmental footprint, and reduce capital and operational needs. A third treatment train (C) was proposed by another consultant: it involved a particular type of sand filtration – using nextsand^{TM} material-, and reverse osmosis. This “improved” method stemed from conventional methods, but used a particularly efficient sand material.

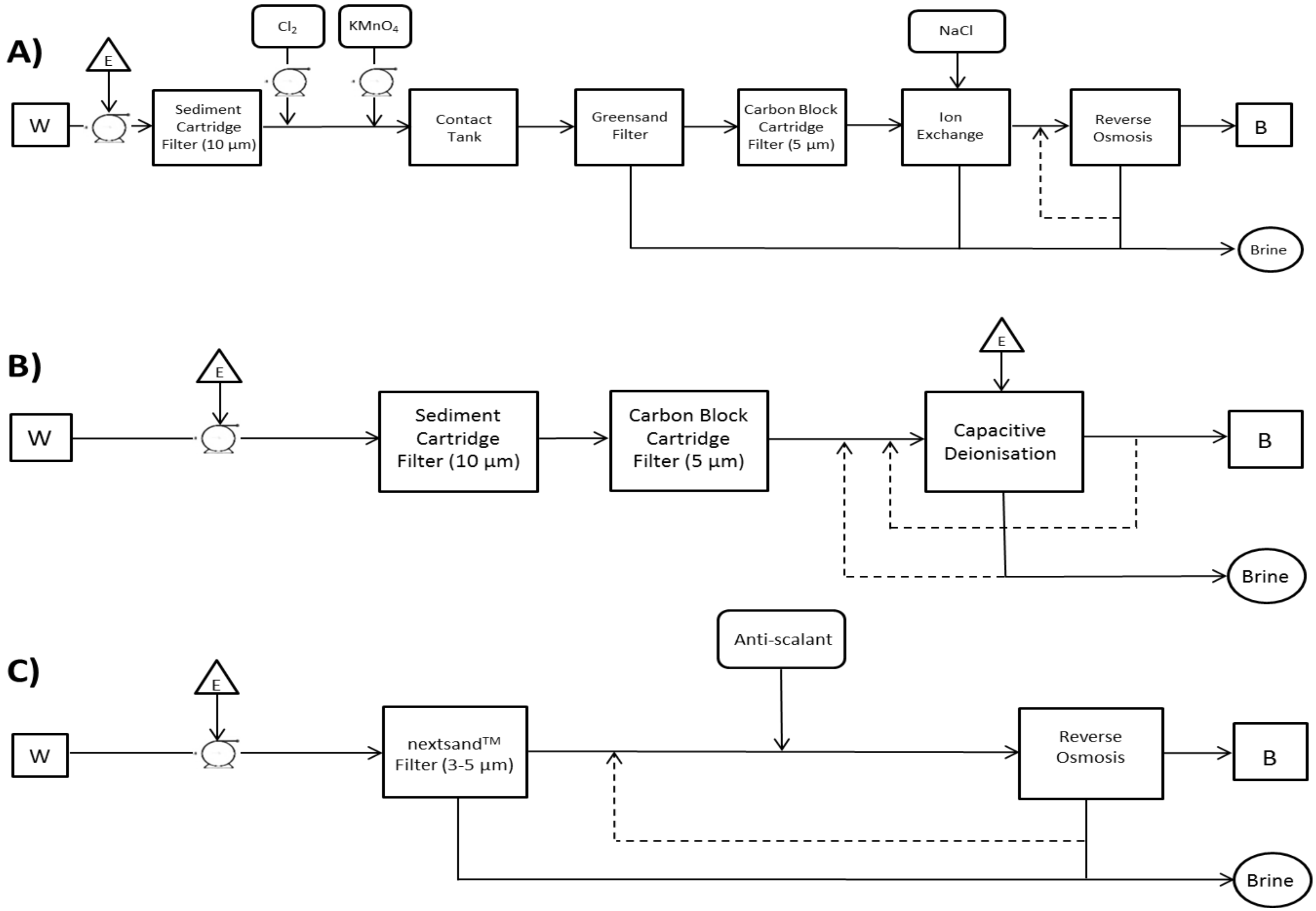

Figure 4: Layout of the three treatment trains that were compared in this study.

3.3 Water quality targets

Design of the treatment processes and operation of the treatment units was done with the intention that the end-stage water would meet drinking water criteria included in the ''Guidelines for Canadian Drinking Water Quality'' (Health Canada, 2012), unless specified otherwise (Table 1).

Table 1: Drinking water quality criteria used in this study.

Type of test	Parameter		Units	Criteria
Physical Tests	Colour, True		CU	<15
	Hardness, Total (as $CaCO_3$)	Soft	mg/L	< 17.1 (< 1.0 gpg) [1]
		Slightly hard	mg/L	17.1 - 60 (1.0 - 3.5 gpg) [1]
		Moderately hard	mg/L	60 - 120 (3.5 - 7.0 gpg) [1]
		Hard	mg/L	120 - 180 (7.0 - 10.5 gpg) [1]
		Very hard	mg/L	> 180 (> 10.5 gpg) [1]
	pH		pH	6.5 - 8.5
	Total Dissolved Solids		mg/L	<500
	Turbidity		NTU	<1.0
Anions and Nutrients	Alkalinity, Total (as $CaCO_3$)		mg/L	500 [1]
	Chloride (Cl)		mg/L	500 [1]
	Sulfate (SO4)		mg/L	500 [1] and 250 [2]
Total Metals	Aluminum (Al)-Total		mg/L	0.2
	Arsenic (As)-Total		mg/L	0.01
	Barium (Ba)-Total		mg/L	1.0
	Cadmium (Cd)-Total		mg/L	0.005
	Chromium (Cr)-Total		mg/L	0.05
	Copper (Cu)-Total		mg/L	<1.0
	Iron (Fe)-Total		mg/L	<0.3
	Lead (Pb)-Total		mg/L	0.01
	Manganese (Mn)-Total		mg/L	<0.05
	Mercury (Hg)-Total		mg/L	0.001
	Selenium (Se)-Total		mg/L	0.01
	Sodium (Na)-Total		mg/L	<200
	Uranium (U)-Total		mg/L	0.02
	Zinc (Zn)-Total		mg/L	<5.0

[1] Source : Commercial standards (Petwa, 2014).

[2] Source : European Union Drinking Water Directives (EU, 1998) and World Health Organization Guidelines for Drinking-water Quality (WHO, 2011).

3.4 Water quality evaluation

Quality of the raw groundwater was evaluated by an accredited external lab (ALS, Whitehorse, Yukon) prior to the study. Evolution of water quality through the individual treatment processes was evaluated in-house. To do so, samples were drawn from the purified stream of each water treatment process, and water quality parameters were measured using methods presented in Table 2. Quality of the end-stage water was evaluated by an accredited external lab (ALS, Whitehorse, Yukon).

Table 2: Test methods used in-house for the study of water quality parameters

Parameter (units)	Test method	Applicable range
TDS (mg/L)	Oakton, TDS Testr 11	0-2 000 mg/L and 0-10.00 g/L
Turbidity (ntu)	Hach, 2100P Portable Turbidimeter	0-1 000
pH	Hanna, Combo pH/ORP/Temp Tester, HI 98121	-2.00-16.00
Total Alkalinity (mg/L as $CaCO_3$)	Hach, Alkalinity Test Kit, Model AL-AP, gpg (cat.24443-00)	0.4-8 gpg and 1-20 gpg
Total Hardness (mg/L as $CaCO_3$)	Hach, Digital Titrator Kit (cat.22709-00), Method 8213 using EDTA	10-4 000
Total Chlorine (mg/L)	Hach, 5- in-1 test trips, Aqua Check (cat.27552-50)	0-10
Free Chlorine (mg/L)	Hach, 5- in-1 test trips, Aqua Check (cat.27552-50)	0-10
Manganese (mg/L)	Hach DR/890 colorimeter, Method 8149 DR 800, PAN Method	0-0.700
Iron (mg/L)	Hach DR/890 colorimeter, Method 10249 or 8008 DR 800	

A number of indexes were calculated too: Silt density index (SDI), Langelier saturation index (LSI), Stiff and Davis stability index (S&DSI). SDI is a specialized test used to predict the fouling potential of feedwater for Reverse Osmosis systems. Low SDI values allow RO's to operate at higher efficiencies. The Langelier saturation index and the Stiff & Davis stability index are a measure of the saturation of $CaCO_3$ in water and are used to predict the scale formation potential. The LSI is better at representing brackish water (TDS < 10 000 mg/L) and the S&DSI better at representing saltwater (TDS > 10 000 mg/L).

3.5 Quality of the raw groundwater

The quality of the raw groundwater available at Northern Cross' base camp (Eagle Plains, Yukon, Canada) is presented in Table 3 (Appendix A). Those results were obtained from the analysis by ALS Laboratory (Whitehorse, Yukon) of one sample taken from the well water on Sept. 24, 2013, and another sample taken on March 19, 2014. An average value for the two samples was calculated - whenever the laboratory reported a concentration that was under the detection limit, the concentration was assumed to be half the detection limit.

The raw groundwater was considered brackish, with a TDS content of 13 600 mg/L. It was also very hard, at 3 950 mg/L as $CaCO_3$, or 235 gpg. Alkalinity stood at 1 300 mg/L as $CaCO_3$, much higher than the criterion of 500 mg/L as $CaCO_3$ that is used in the water treatment business (Table 1, p. 10). The raw water's iron and manganese content was much higher than the Canadian drinking water guidelines (0.3 mg/L and 0.05 mg/L, respectively; Health Canada, 2012), at 5.5 and 1.2 mg/L, respectively. The drinking water criteria for some metals were also exceeded, more specifically for Cadmium, Lead and Manganese.

Consequentially, the total permanent hardness (accounting for Ca and Mg) was also very high, at 4 480 mg/L as $CaCO_3$. In the same way, the total equivalent hardness (accounting for Fe and Mn) was very high, at 241.7 mg/L as $CaCO_3$. The LSI and S&DSI were negative (-0.64 and -1.25), which indicated corrosivity potential, and a scale dissolving tendency for Ca (no scale formation potential for Ca).

3.6 Scale and Flow rate

In this experiment, house-hold scale units were used. They were operated within recommended operational range, if not otherwise specified. Full scale units should be operated using the same loading rates, and all other parameters would have to be adjusted taking into account the capacity of the units.

At full scale, Northern Cross camp's water treatment system should be able to produce 16 000 LPD of drinking water. This is equivalent to 16 m^3/day, 666.67 LPH, or 0.67m^3/hour. As the camp is operating intermittently, the water treatment system might often have to be shut down and restarted.

In this experiment, each treatment train received 50 L of raw groundwater, and the flow rates were adjusted to fit the treatment unit's operating capacity.

3.7 Theoretical quality of the water rejects

The water rejects were assumed to contain all that was present in the raw groundwater and that did not make it to the end-stage water. Whenever possible, the contribution of secondary wastes (i.e. load brought by the use of any chemical inputs) was also taken into account in the calculation of the quality of the water rejects. Retention of any load by cartridge filtration or any other matrix was not taken into account. R_C

Equation 3-1 describes the calculation that was made, using the water quality results obtained from ALS and water volumes calculated from daily drinking water needs (16 000 L) and recovery rates.

$$Rc = \frac{Rl}{Rv} \qquad \text{Equation 3-1}$$

$$Rc = \frac{Gl + Sl}{Rv}$$

$$Rc = \frac{(Gc \times Gv) - (Ec \times Ev) + Sl}{Rv}$$

where

c = concentration
v = volume

l = load
R = Rejects
G = Groundwater
S = Secondary wastes
E = End-stage water

3.8 Energy usage

The amount of energy that would be necessary to invest in order to produce 16 000 L of drinking water was calculated for each treatment train.

Where necessary, the pump power requirements were calculated. The pump power requirements were calculated using Equation 3-2, taking into account the maximum differential head, with a pump efficiency of 60% :

$P_h = q\ \rho\ g\ h\ /\ \eta\ (3.6\ 10^6)$ Equation 3-2

where
P_h = power (kW)
q = flow capacity (m^3/h)
ρ = density of fluid (1000 kg/m^3)
g = gravity (9.81 m/s^2)
h = differential head (m)
η = pump efficiency (0.6)

The energy usage (kWh) was calculated by multiplying the power requirement by the time period (h) it would take, at the service flow rate, to treat the water volume that was necessary to produce 16 000 of drinking water (Equation 3-4).

$E = P \times \mathrm{t}$ Equation 3-3

3.9 Operation of the treatment units

The treatment units were operated following standards and real-life conditions, unless otherwise specified.

3.9.1 Treatment train A

Sediment cartridge Filter

Raw water was first passed in a sediment cartridge filter (10 µm) in order to remove all coarse particles, which could otherwise damage downstream units. Two Excelpure™ PL10B-10 pleated cartridges (polypropylene, 10 in long) were put in series in a 20 in Big Blue housing (4.5 in diameter). It was operated at 13 LPM (31.22 GPM/ft^2), which is higher than the recommended 3-5 GPM/ft^2 (Alaska DEC, 1993).

Oxidation

Chlorine (Cl_2) and Potassium permanganate (K_2MnO_4) were injected to initiate oxidation of dissolved Fe and Mg before water hit the greensand filter. The green sand filter could then remove any remaining dissolved or solid forms of iron and manganese – it could thus be said to operate on a ''continuous regeneration'' basis. Injection of the oxydants was done using two Grundfos Alldos (Bjerringbro, Denmark) dosing pumps, model ''Dosing Digital Internal (DDI) 209 (0.4-10)''. The feed water flow rate was set at 13 LPM (4.35 GPM/ft^2), which is slightly higher than the recommended operation rate of 3-4 GPM/ft^2 (Alaska DEC, 1993). A total volume of 50 L was treated.

A contact time of 1.5 min was allowed for the oxidants to operate before water hit the green sand filter, by letting the water rest in a fiberglass reinforced plastic (FRP) tank (9 in X 48 in) before being pumped to the green sand filter.

Cl_2 was injected first, so that a majority of Fe was precipitated by Cl_2. With Fe concentration in the raw water at 5.5 mg/L, the Cl_2 demand was 5.5 mg/L (*Equation 3-4*; slideshow, 2010; Inversand, 2014).

$$\begin{aligned} Cl_2 \text{ demand} &= [Fe] \\ &= 5.5 \text{ mg/L} \end{aligned} \qquad \text{Equation 3-4}$$

With a total treated volume of 50 L, the total Cl_2 demand was 275 mg. At a service flow rate of 13 LPM, the timely Cl_2 demand was 4290 mg/h. Cl_2 was supplied by using a 12% solution, with volumetric mass of 1.08 g/mL (Advance 12A, Advance Chemicals Ltd.). The injection pump was thus adjusted to 0.03306 LPH. At 7.5, the pH did not need to be corrected (Inversand, 2014). As the residual in the green sand filter filtrate was > 0.5 mg/L (it was 2.0 mg/L), the chlorine dose did not need to be augmented due to any presence of reducing compounds such as nitrite, ammonia, hydrogen sulfide or organic matter (Rader, 2014).

$KMnO_4$ was injected 10 seconds after Cl_2 (minimum 10-20 seconds, Inversand, 2014) to oxidize Mn and any remaining Fe, using sufficiently long piping. With Mg concentration in the raw water at 1.2 mg/L, the $KMnO_4$ demand was 3.5 mg/L (Equation 3-5; slideshow, 2010; Inversand, 2014).

$$\begin{aligned} KMnO_4 \text{ demand} &= 0.2 * [Fe] + 2 * [Mg] \\ &= 0.2 * 5.5 \text{ mg/L} + 2 * 1.2 \text{ mg/L} \\ &= 3.5 \text{ mg/L} \end{aligned} \qquad \text{Equation 3-5}$$

With a total treated volume of 50 L, the total $KMnO_4$ demand was 175 mg. At a service flow rate of 13 LPM, the timely $KMnO_4$ demand was 2730 mg/h. $KMnO_4$ was supplied by using a 4% solution (38.4 g/L of Pro™ Pot Perm®) with a volumetric mass of 1.204 g/mL. The injection pump was thus adjusted to

0.071 LPH. At 7.5, the pH did not need to be corrected (Inversand, 2014). As a ''just pink'' color was observed in the influent leading to the green sand filter, a slight excess of $KMnO_4$ was assumed to be carried onto the green sand filter, which would maintain it in a continuously regenerated condition. As no fair pink color developed in the filtrate, the $KMnO_4$ dosage did not need to be reduced.

Green Sand Filter

The green sand filter was contained in a 12 in X 52 in FRP tank. It was constituted of 2 ft^3 of glauconite media (height: 30.5in; surface area: 0.79 ft^2; Petwa, 2009). The filter also comprised a gravel underbed and the media was capped with anthracite, leaving a sufficient freeboard for bed expansion. The tank was a Model 1252-2.0GA, sold by Petwa Ltd. (Calgary, AB, Canada). The control valve was a GE Autotrol Logix™ Controller, Model 268/742, manufactured by Pentair USA and sold by Petwa Ltd. The valve was operated on 5-cycle mode (298), so as to provide for filtering (and not ion exchange). The greensand filter was operated on continuous regeneration mode. It was fed with a service flow rate of 13 LPM (3.43 GPM), which fits within recommended parameters by Inversand (2014) of 6-15 LPM for a 0.79 ft^2 filter (2.5 GPM/ft^2), and is close enough to recommended standard by Petwa (2009) of 15.14 LPM (4 GPM for a 12 in X 52 in tank with 2ft^3 of media).

The filter did not need to be backwashed during the experimentation. However, a backwash would need to be initiated when the loss of head through the greensand filter attains 8-10 psi (Inversand, 2014). This should happen when the run length is attained, which depends on the contaminant loading, the service flow rate and the capacity of the media. At iron and manganese concentration of 5.5 mg/L and 1.2 mg/L, respectively, the contaminant loading was 7.9 mg/L, or 0.46 GPG (Equation 3-6; Inversand, 2014). With a media capacity estimated at 400 grains/ft^3 when both iron and manganese are present (Clack, 2001), the run length would be 504.85 min (8.4 h), which corresponds to treating 6 563 L at a service flow rate of 13 LPM (Equation 3-7; Inversand, 2014).

$$\begin{aligned}\text{Contaminant loading} &= ([Fe] + 2*[Mn]) * 1\text{ GPG} / 17.1\text{ mg/L} \\ &= (5.5\text{ mg/L} + 2 * 1.2\text{ mg/L}) * 1\text{ GPG} / 17.1\text{ mg/L} \\ &= 7.9\text{ mg/L} * 1\text{ GPG} / 17.1\text{ mg/L} \\ &= 0.46\text{ GPG}\end{aligned} \quad \text{Equation 3-6}$$

$$\begin{aligned}\text{Run length} &= \text{Capacity of media} * \text{Bed volume} / (\text{Contaminant loading} * \text{Service flow rate}) \\ &= 400\text{ grains/ft}^3 * 2\text{ft}^3 / (0.46\text{ GPG} * 3.43\text{ GPM}) \\ &= 504.85\text{ min}\end{aligned} \quad \text{Equation 3-7}$$

The backwash rate should be set at 35 LPM during 15 min as per standards (Rader, 2014; Clack 2001). A rinse step should follow for 5 minutes (Pentair, 2008) at the service flow rate of 13 LPM. Thus, a total of 590 L of brine would be produced every time the run length is attained. The recovery rate would thus be 93%.

Prior to the experiment, the green sand media was fully regenerated by soaking in a 3 % solution of $KMn0_4$ (4 $oz_{\text{by weight}}$/ft^3 of media) and let to ''marinate'' overnight (Inversand, 2014). A backwash was first initiated, then the $KMn0_4$ solution was drawn and let to sit. The following morning, another backwash was performed, and the filter was thoroughly rinsed with water until no trace of permanganate remained - it was rinsed for 20 min until there was no pink color, and then rinsed for another 28 min running clear (standard minimum: 10 min).

Carbon Cartridge Filter

Water was passed through a 5 µm granular activated carbon filter in order to remove chlorine, which could otherwise damage the ion exchange resin. A Watts^{M} GAC-BB20 cartridge was used in a 20 in Big Blue housing (4.5 in diameter).

Ion Exchange

The ion exchange softener was contained in a 12 in X 48 in FRP tank. It was constituted of 2 ft^3 of synthetic zeolite resin (height: 30.5 in; surface area: 0.79 ft^2). The filter also comprised a gravel underbed, and sufficient freeboard was left for bed expansion. The control valve was a Waterite™ Custom Control Fusion^2 (F2CC), with an *Intelogic Ultra*® Controller.

The ion exchange softener was operated on a ''top to bottom, with pressure'' mode (most classic). It was fed with a service flow rate of 20 LPM, or 5.28 GPM as per standards (6-12 GPM/ft^2; GE Water, 2014). The control valve was set on ''Demand Initiated Regeneration (DIR)''.

During the experimentation, the ion exchanger did not need to be backwashed and regenerated, but a regeneration cycle was performed prior to the experimentation. To regenerate the resin, Windsor® System saver II salt pellets were used. The brine was brewed by mixing 50 kg of salt pellets in 15 L of water. With total hardness assumed to be equal to the raw groundwater (235 gpg) and with a capacity (Equation 3-8) estimated at 10 000 grains/ft^3 (Yukon WWOP, 2014), regeneration would be needed after 16.11 min of operation, or 322.14 L (Equation 3-9).

$$\begin{aligned} \text{Capacity} &= \text{Volume of media} * \text{Softener capacity} \\ &= 2\ ft^3 * 10\,000\ \text{grains}/ft^3 \\ &= 20\,000\ \text{grains} \end{aligned} \qquad \text{Equation 3-8}$$

$$\begin{aligned} \text{Volume of water between regenerations} &= \text{Capacity / Hardness} \\ &= 20\,000\ \text{grains} / 235\ \text{gpg} \\ &= 85.10\ \text{gallons} \\ &= 322.14\ \text{L} \\ &= 16.11\ \text{min} \end{aligned} \qquad \text{Equation 3-9}$$

The backwash rate was set at 15 LPM during 10 min as per standards (GE Water, 2014). Brine was then let to enter the unit and flow down through the resin bed at a slow rate of 2 LPM, for sufficiently long to allow for approximately one resin bed volume of brine to be introduced in the unit (60L) (GE Water, 2014). A slow rinse followed, sufficient to allow for approximately one resin bed volume of water (60L) to pass through the unit. (GE Water, 2014). Regeneration was completed by a fast rinse step, at a flow rate of 5 LPM for 10 min (GE Water, 2014). Thus, a total of 320 L of brine would be produced every time the run length is attained. The recovery rate would thus be 50 %.

It is estimated that 1.880 g of sodium were used per liter of filtrate (Skipton, 2008).

Reverse Osmosis

The reverse osmosis unit was a Waterite Vectapure™ system. The replacement membrane was a 1.8 inch diameter CSM RE1812-80 (TFC) membrane, with the following specifications: max output: 303 LPD, max feed flow rate: 2 880 GPD, max operating pressure: 125 psi; max chlorine concentration: < 0.1 mg/L; max SDI (15 min): 5.0; salt reject: 98.0%; permeate flow: 303 LPD @ 60 psi, 77°F (25°C), 15% recovery rate (Lenntech, 2014).

It was operated to produce 66 GPD (0.174 LPM), at a theoretical recovery rate of 15%, so was fed with a pressure of 60 psi, which produced a service flow rate of 440 GPD (0.31 GPM, or 1.16 LPM). In order to enhance the recovery rate, the concentrate was recirculated 9 times by mixing it to the feed water; this treatment process' recovery rate was thus 77%.

Prior to the experimentation, the unit was sanitized with chlorine as per standards (Lenntech, 2014).

3.9.2 Treatment train B

Treatment train B produced drinking water from a capacitive deionization (CDI) technology. Pre-treatment consisted in cartridge sediment removal and carbon block filtration.

Sediment cartridge Filter

Raw water was first passed in a sediment cartridge filter (10 µm) in order to remove all coarse particles, which could otherwise damage the downstream CDI unit. Two Excelpure™ PL10B-10 pleated cartridges (polypropylene) were put in series in a 20 in Big Blue housing (4.5 in diameter).

Capacitive Deionisation treatment

The CDI unit that was used was a MiniEWP® model from Aquaewp™ (Sacramento, Texas). It was operated at 0.225 LPM (max: 0.40 LPM; min: 0.15 LPM, Atlas, R., 2014., pers. comm.), using a pressure pump delivering 35-45 psi. Voltage was set at 1.33 V, as per standards (Atlas, R., 2014. pers. comm.).

The filtrate was recirculated until the TDS drinking water standard (≤ 500 ppm; Health Canada, 2012) was attained. In order to improve water recovery, brine that was less concentrated then the original water was set aside to be purified in a further cycle, and only the brine that was more concentrated then the original was disposed of.

Prior to the experiment, the unit was cleaned with citric acid to remove any organic deposit that could have lied on the electrodes. A 600 g/L solution was recirculated for 20 min with the power-supply shut off and the unit was rinsed with water for 1 h as per standard procedures (Robert Atlas, 2014, pers. comm.).

Operational parameters were kept constant at 35 psi (which brought a flow rate of 225 mL/min) and 1.33 V.

Brine that had a lower TDS value than the original feed water (i.e. low brine) was kept aside to be re-treated in another cycle.

3.9.3 Treatment train C

Line C) option produced water from a reverse osmosis system. The pre-treatment need consisted in a sand filter and anti-scalant dosing.

Sand filter (Multi-media filter, or high rate open gravity filter)

The sand filter was used to remove silt, sediment and turbidity. A high performance type of sand was used: nextsand™ (<5 µm nominal). This sand is a rare natural mineral (clinoptilolite zeolite) that is highly processed and graded. The filter was constituted of a 10 in X 54 in FRP tank, filled with 33'' of nextsand™ (1.5 ft^3). The underbed consisted in 3-4 in (1 lb) of pea gravel; a 50% freeboard was left. The control valve was a Canature™ (Regina, SK Canada) Electronic Meter of the 165 series (dual electronic and manual functions). The system was operated at a service flow rate of 8.61 LPM (loading rate of 4.17 GPM/ft^2), in order to give a good filtrate and require less frequent back wash (Bert Albisser, 2014, pers. comm.); the manufacturer recommends a loading rate of 16-20 GPM/ft^2, and 12 GPM/ft^2 when optimizing for removal of silt, SDI and ultrafine particulates (Next, 2010).

The filter did not need to be backwashed during the experimentation. However, a backwash would need to be initiated when the loss of head through the nextsand™ filter attains 15 psi (Bert Albisser, 2014 comm. pers.). The volume-wise run length was estimated to be equal to that of the greensand filter: 7 800 L (15 hours of operation).

The backwash rate should be set at 6.85 LPM (3.32 GPM/ ft^2 of media) for 10 min (Bert Albisser, 2014 comm. pers.); the manufacturer recommends a backwash loading rate of 13-22 GPM/ft^2 of media (Next, 2010) . A rinse step should follow for 5 minutes at the service flow rate of 8.61 LPM. Thus, a total of 111.55 L of brine would be produced every time the run length is attained. The recovery rate would thus be 98%.

Prior to the experiment, the next sand filter was built and rinsed following recommended procedures (Next, 2004).

Anti-scalant dosing

An anti-scalant was used to prevent early obturation of the reverse osmosis membrane due to precipitation of sparingly soluble salts (e.g. Ca and Mg).

As no values were available for the nextsand™ filtrate , anti-scalant dosing was calculated by the manufacturer based on raw groundwater quality (Genesys, 2014a, Appendix D). Following the raw groundwater quality, the dosing rate needs were calculated as 8.11 mg/L for scale control and 323.84 mg/L for iron control, making up for a total dosage of 331.95 mg/L.

It was estimated that all iron would be removed by the nextsand™ filter, and that all scale forming ions would remain. The anti-sclant dose need was thus assumed to be 8.11 mg/L. Injection of anti-scalant was done using two Grundfos Alldos (Bjerringbro, Denmark) dosing pumps, model ''Dosing Digital Internal (DDI) 209 (0.4-10)''. It was introduced on the line leading to the reverse osmosis.

Considering that the volumetric mass af anti-scalant was 1.33 g/mL, the dosing pump was set at 0.00609 mL/L. Considering that the flow rate to the reverse osmosis was 1.16 LPM, the injection pump was thus adjusted to 0.00042 LPH.

Reverse Osmosis

The reverse osmosis unit was a Waterite Vectapure™ system, operated and prepared as for line A), with a recovery rate of 77%.

4 RESULTS AND ANALYSIS

4.1 Treatment train A

4.1.1 Practicality

All processes used in treatment train A) are well-known technologies and proven reliable. The units are easy to obtain from any consultant, and it is possible to find operators that are trained to maintain and operate them.

Although known, these technologies are relatively finicky – they require constant adjustment by experienced operators, especially when it comes to dosing Cl_2 and $KMnO_4$. In the advent that the treatment plant would be frequently shut down and turned back on to accommodate fluctuating number of camp users, this would compound the situation.

The green sand filter and the ion exchanger require a lot of adjustments inherent to the operation of any filter, among which: flow rate during operation, flow rate during back-wash, duration of back-wash, when to start a back-wash, and based on what type of information (pressure-drop-based, volume-based or time-based). Sufficient pressure and flowrate are required for backwashing any filter, otherwise a ‘’cake’’ could accumulate and compromise the filter.

Operation of a green sand filter requires the adjustment of other parameters, such as: dosage of oxydants (i.e. Cl_2 and $KMnO_4$), concentration of those oxydants’ solutions, length of time between dosing of the oxydants, contact time (residence time) for the oxydants, etc. As oxydant dosage must be exact, bench scale tests are required.

An ion exchange has the same parameter-adjustment complications inherent to all filters, and has parameter-adjustment issues of its own, among which: rate of brine draw during regeneration, duration of brine draw, duration of rinse, etc.

A reverse osmosis system is relatively simple to operate, but as the ion content of the filtrate coming out of a reverse osmosis system usually is too low to be readily used for drinking, it needs to be adjusted by careful and tightly monitored addition of untreated water.

4.1.2 Quality of the end-stage water

The evolution of water quality throughout treatment train A is presented in Figure 5.

Cartridge filtration diminished the total dissolved salt (TDS) content, but the greensand filter introduced some more. Ion exchange reduced TDS again, and it established at 780 mg/L at the outlet of the end-stage process - the reverse osmosis system. This TDS value is slightly higher than the Canadian drinking water quality guideline (< 500 mg/L; Health Canada, 2012). By nature, Ion exchange softening increases TDS, and especially Na. If not completely taken care of by the reverse osmosis step, this could become an issue for end-users on low-sodium diet. In this experiment, Na was abated down to 210 mg/L in the end-stage water, which again is slightly higher than Canadian drinking water quality guideline (< 200 mg/L; Health Canada, 2012). The difficulty to remove sodium is not surprising, given the huge quantity of salt used for ion exchange.

Turbidity diminished successively throughout the treatment train, establishing at 0.25 ntu in the end-stage water, which meets the Canadian drinking water guideline (< 0.1 ntu; Health Canada, 2012). Alkalinity followed the same trend, establishing at 173 mg/L as $CaCO_3$, although there is no water quality guideline for this parameter. Hardness clearly diminished in the same fashion but the end-stage stage water was still considered moderately hard (59.91-119.82 mg/L; Petwa, 2014), at 60.5 mg/L as $CaCO_3$. This was still well above the *soft* threshold (< 17.2 mg/L as $CaCO_3$; Petwa, 2014).

Although not monitored, the oxidation and green sand filter steps would likely have removed Fe and Mg. They were further diminished by reverse osmosis. Final values were 0.009 and 0.01 mg/L, respectively, which meets the Canadian drinking water guidelines (<0.05 and <0.3, respectively; Health Canada, 2012).

Health Canada (2012) does not have a quality guideline for sulfate content in drinking water. However, the World Heatlh Organization (2011) recommends it should not be higher than 500 mg/L, and the European Union (1998) suggests a maximum of 250 mg/L in water intended for human consumption. At 362 mg/L, then end-stage water would not meet EU's sulfate guideline. Sulfate can give a bitter or medicinal taste to water if it exceeds 250 mg/l, which may make the water unpleasant to drink (Lenntech, 2014b). Over 500 mg/L, it may have a slight laxative effect, especially when combined with calcium and magnesium. Also, high sulfate levels may be corrosive for plumbing, particularly copper piping. In areas with high sulfate levels, it is common to use corrosion resistant plumbing materials, such as plastic pipe.

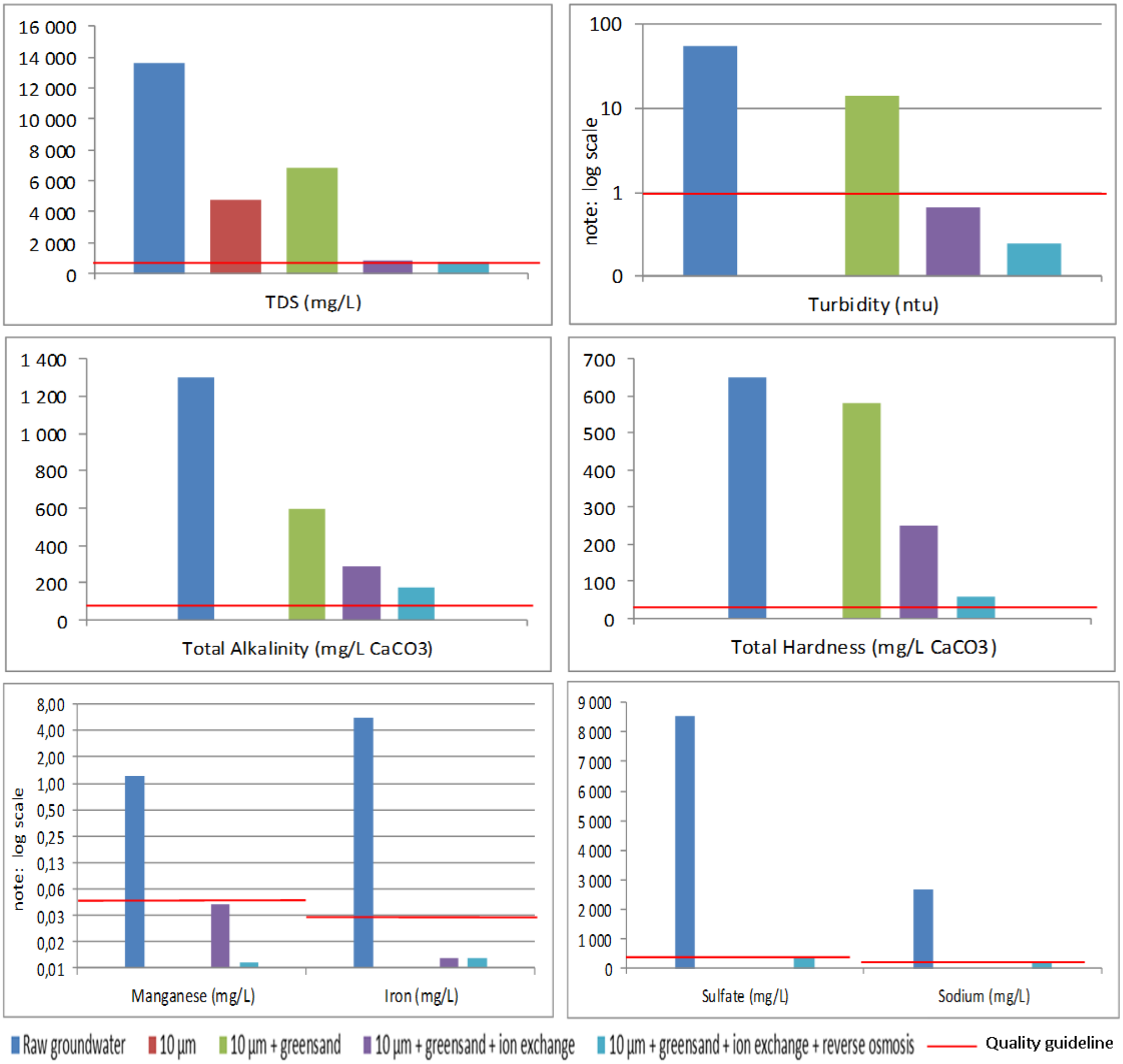

Figure 5: Water quality at the outlet of the different steps of treatment line A.

In this experiment, the end-stage water did not meet all quality guidelines. However, it is evident that operation of the treatment units could be adjusted which would guarantee quality of the end-stage water.

An issue that was not considered could stem from the addition of Cl_2 as oxidant before green sand filtration: formation of Tri-halomethane (THM). These compounds are potential carcinogen and are formed when chlorine is added to water containing organics. The presence of organic compounds in the raw groundwater was not evaluated, nor the presence of THMs. However, it is suspected that it could be non-negligible, given that suspended particles that looked like biofilms were observed in the raw groundwater.

4.1.3 Recovery rate

In the 10 µm cartridge filter, the recovery rate was 100%. In the green sand filter, the recovery rate was 93%, as some water would be used for backwash and rinse of the system. In the 5 µm cartridge filter, the recovery rate was 100%. In the ion exchanger, the recovery rate was 50%, as some of the feed water would be used for backwash, regeneration and rinse of the system. The filtrate production of the ion exchanger would thus be .. LPD. The recovery rate at the reverse osmosis was 15% per pass; as the brine was recirculated 9 times, the total recovery rate for the reverse osmosis process was 77%. Hence, the global recovery of water for treatment train A was fairly low, at 36%.

Considering that drinking water production at the base camp should be 16 000 LPD, the raw groundwater should be fed to the head of this treatment train at a rate of 44 444 LPD, and brine would be produced at a rate of 28 444 LPD (

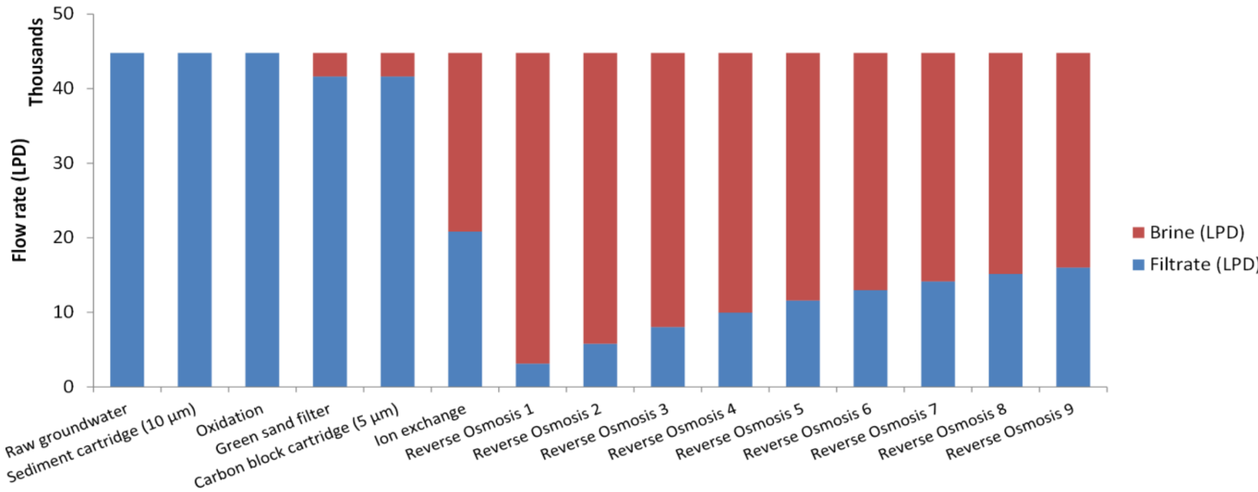

Figure *6*). The green sand filter would produce 43 111 LPD of filtrate, and reject 1 333 LPD of brine. The ion exchanger would produce 21 555.5 LPD of filtrate and reject 21 555.5 LPD of brine. The reverse osmosis system would produce 16 598 LPD of filtrate and reject 4 958 LPD of brine.

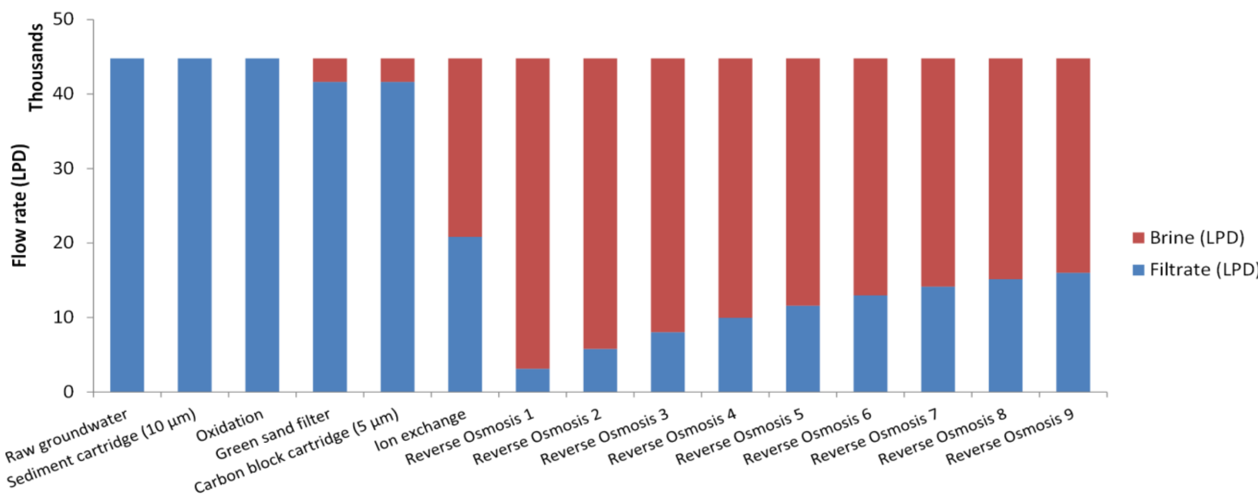

Figure 6: Water recovery observed with treatment train A, which consisted in 1 Sediment cartridge stage, 1 Green sand stage, 1 Carbon block cartridge stage, 1 Ion exchange stage, and 9 Reverse Osmosis stages.

4.1.4 Input requirements

Oxydation and green sand filtration
The chlorine solution (12% by weight; Advance 12A, Advance Chemicals Ltd.) was dosed at 0.03306 LPH, and the service flow rate was 13 LPM (780 LPH). Thus, the chlorine solution was dosed at 0.0424 mL/L. Considering that the total volume of water that would be treated daily at the base camp by the green sand filter would be 44 444 L, this makes up for a total usage of 1.88 L of chlorine solution per day.

The $KMnO_4$ solution (4% solution; 38.4 g/L of Pro™ Pot Perm®) was dosed at 0.071 LPH, and the service flow rate was 13 LPM (780 LPH). Thus, the $KMnO_4$ solution was dosed at 0.0911 mL/L. Considering that the solution was brewed using 38.4 g/L of powder $KMnO_4$, the powder was dosed at 3.46 µg/L. Considering that the total volume of water that would be treated daily at the base camp by the green sand filter would be 44 444 L, this makes up for a total of 153.78 mg of $KMnO_4$ powder per day.

Ion exchange
It is estimated that 1.88 g of sodium were used per liter of filtrate (Skipton, 2008). Considering that sodium accounts for 39% of salt pellets' weight, salt pellet usage would be 4.82 g per liter of filtrate. Considering that the daily production of ion exchange filtrate at the base camp would be 21 555.5 LPD, this makes up for a usage of 104 kg of salt pellets per day. This salt requirement may be prohibitive for operation of a treatment plant in Northern Yukon.

Reverse osmosis
A main disadvantage associated with reverse osmosis is the cost and maintenance of the membranes used. A reverse osmosis membrane can easily be fouled if the quality of the feed water is not appropriate.

4.1.5 Theoretical quality of the water rejects

The theoretical quality of the brine that would be produced by treatment train A is presented in Table 5 (

Appendix *C*). This theoretical brine quality was calculated by subtracting the filtrate quality from the raw groundwater quality, and adding up the secondary wastes. These secondary wastes came from the input of chlorine, potassium permanganate and salt throughout the treatment processes.

It was estimated that salt would boost up the Na and Cl concentrations by 1 405.37 mg/L and 2 198.15 mg/L, respectively. This estimate was calculated by taking into account the daily salt usage (104 kg/day), the daily brine production (28 444 LPD), and the relative molecular weight of Na and Cl (39% and 61%, respectively). In the same way, $KMnO_4$ would boost up the K and Mn concentrations, but in a minor fashion (both boosted up by 0.001 mg/L, respectively). The $KMnO_4$ usage was 153.78 mg/day and the relative molecular weight of K and Mn was 24.74% and 34.76%, respectively. Chlorine used as an oxidizing agent would further boost up the Cl concentration by 9.88 mg/L. The daily chlorine usage was 1.88 L/day of a 12% solution, whereas Cl volumetric weight is 1.2 g/mL.

Hence, sodium would reach as high as 5 459.12 mg/L, chloride as high as 2 223.17 mg/L, and sulfate 13 108.88 mg/L. Calcium would reach 484.89 mg/L and Fe and Mg 8.72 and 1 324.12 mg/L, respectively. Uranium could overpass the maximum allowable concentration for drinking water (0.02 mg/L; Health Canada), reaching 0.03 mg/L.

Management of such concentrated brine might be challenging, which would be compounded by the high rate of production.

4.1.6 Energy usage

Pump for sediment cartridge filtration(10 µm)

The differential head through the cartridge filter (10 µm) was estimated at 2 PSI (3.52 m). As the service flow rate was 13 LPM (0.78 m^3/h), the pump power requirement for the cartridge filter was 0.012 kW. As it would take 57 h to treat 44 444 L of raw groundwater, the energy usage for the cartridge filter pump would be <u>0.68 kWh</u> to produce 16 000 L of drinking water.

Pump for green sand filter

As the service flow rate was 13 LPM (0.78 m^3/h) and the maximum differential head was 8 PSI (5.63 m), the pump power requirement for the green sand filter was 0.02 kW. As it would take 57 h to treat 44 444 L of water, the energy usage for the green sand filter pump would be <u>1.14 kWh</u> to produce 16 000 L of drinking water.

Pump for carbon block cartridge (5 µm)

The differential head through the carbon block cartridge filter (5 µm) was estimated at 4 PSI (2.81 m). As the service flow rate was 20 LPM (1.2 m^3/h), the pump power requirement for the carbon block cartridge filter was 0.01531 kW. As it would take 36 h to treat 43 111 L of water, the energy usage for the carbon block filter pump would be <u>0.55 kWh</u> to produce 16 000 L of drinking water.

Pump for ion exchange

The differential head through the ion exchange was estimated at 5 PSI (3.52 m). As the service flow rate was 20 LPM (1.2 m^3/h), the pump power requirement for the ion exchanger was 0.01918 kW. As it would take 36 h to treat 43 111 L of water, the energy usage for the ion exchange pump would be <u>0.69 kWh</u> to produce 16 000 L of drinking water.

Pump for reverse osmosis

As the service flow rate was 1.16 LPM (0.07 m^3/h) and the differential head was 60 PSI (42.19 m), the pump power requirement for the reverse osmosis was 0.013 kW. As the brine would be recycled 9 times, a total of 105 865 L of water would be treated by the reverse osmosis system to produce 16 000 L of drinking water, which would take 1 534 h. Thus, the energy usage for the reverse osmosis pump would be <u>20.46 kWh</u> to produce 16 000 L of drinking water.

Total

Treatment train A would require a total of 23.52 kWh to produce 16 000 L of drinking water.

4.1.7 Possible improvements

Reducing the green sand's service flow rate might enhance the Fe and Mg removal efficiency, given the very high concentrations of those metals.

A deposition tank could be used upstream of the green sand filter in order to collect Fe and Mg precipitates, which would alleviate the solid burden onto the green sand filter.

A resin with higher capacity then synthetic zeolite could be used in the ion exchanger, such as polystyrene gel resin, in order to reduce salt pellet needs.

4.2 Treatment train B

4.2.1 Practicality

The technologies involved in treatment train B are simple to operate with only two stages, especially in comparison with green sand filtration and ion exchange that were used in treatment train A.

4.2.2 Quality of the end-stage water

The pre-treatment cartridge filtration step (5 µm) brought the TDS content down to 6 000 mg/L TDS, starting from 13 6000 mg/L TDS in the raw groundwater.

In this experiment, the filtrate was cycled as many times as necessary to bring the TDS content under the water quality guideline (< 500 mg/L; Health Canada, 2014). As a result, the end-stage water met the Canadian water quality guidelines (Health Canada, 2012) for all parameters except selenium (Table 4, Appendix B). The case of selenium is rather surprising and could be an indication that the CDI electrodes used in this experiment had a lower affinity for Se than for other ions that were present in the brackish groundwater.

TDS content was tracked with every cycle of CDI treatment, and an empirical model of TDS reduction efficiency was built (Figure 7). According to this model, the TDS reduction efficiency diminished logarithmically with higher salt content in the feed water. For instance, the efficiency reached 40% when the original TDS content was 500 mg/L, but it was 4% when the original content was 6 000 mg/L, such as groundwater pre-treated by cartridge filtration (5 µm).

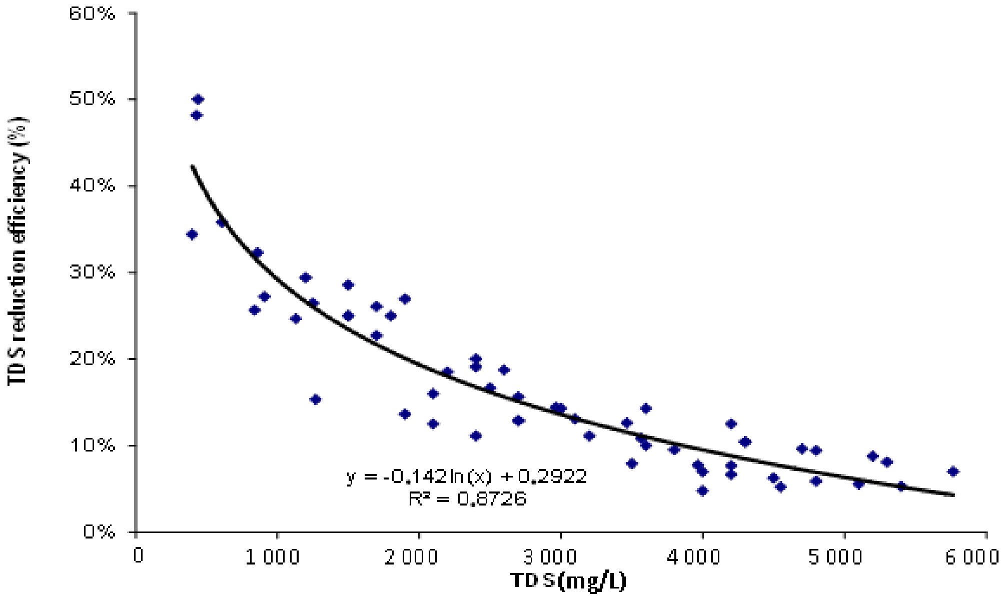

Figure 7: TDS reduction efficiency (%) of the pilot-scale capacitive deionization unit when treating cartridge-filtrated brackish groundwater.

The CDI unit at hand had a higher TDS reduction efficiency when treating a simple NaCl solution as compared to when treating the brackish groundwater used in this experiment (results not shown here); this might indicate that the electrodes have a better affinity for Na and Cl ions than for other ions present in the brackish groundwater.

In any given run, removal efficiency of Fe and Mg was much higher than TDS (results not shown here), indicating that the electrodes might have a preference for those metals over other ions that were present in the brackish groundwater.

It is interesting to note that TDS removal was not influenced by the feed water concentration – it was comprised most of the time between 200 mg/L and 600 mg/L, but no consistent pattern could be detected (Figure 8).

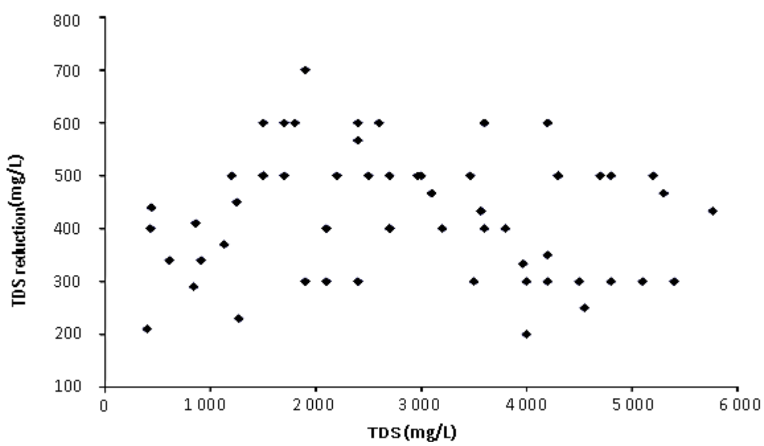

Figure 8: TDS reduction in relation to the feed water TDS content.

This CDI unit was most efficient when the water had a TDS content in the range of 2 000 mg/L – 4 000 mg/L. When the TDS content was higher than 4,000 mg/L, the efficiency was lower (< 10%) than it would have been with other treatment processes (e.g. green sand filtration). When the TDS content was lower than 2 000 mg/L, the recovery rate was lower (75%) than it would have been with other treatment processes (e.g. reverse osmosis).

4.2.3 Recovery rate

In the 10 µm cartridge filter, the recovery rate was 100%. In the 5 µm cartridge filter, the recovery rate was 100%.

Following the model, 18 CDI production run were necessary to bring the TDS content from 6 000 mg/L the drinking water criteria (< 500 mg/L TDS; Health Canada, 2012). With a 25% loss to brine production in each run, and starting with 50 L, the final filtrate volume was 0.28 L, making up for a recovery rate of 0.56%.

Brines that have a lower TDS content than the original feed water (i.e. < 6 000 mg/L TDS) can be recirculated as many times as necessary in an attempt to enhance water recovery. The cumulative volume of brines that had a lower TDS content than the original feed water was 9.27 L and it had a global TDS content of 4 500 mg/L. When recirculating those lower brines, the final recovery rate could be boosted up to 1.34%, with the recuperation of 0.29 L that fit the TDS criterion (< 500 mg/L TDS; Health Canada, 2012). It necessitated 13 run to produce those 0.29 L of water that fit the criterion.

Considering that drinking water production at the base camp should be 16 000 LPD, the raw groundwater should be fed to the head of this treatment train at a rate of 1 194 030 LPD, and brine would be produced at a rate of 1 684 412 LPD (Figure 9). Hence, when applying the Mini-EWP technology to treat water that is as highly concentrated as that of the pre-treated brackish groundwater studied in this experiment (6 000 mg/L), the recovery rate is deceptively low.

The cartridge filters would produce 1 194 030 LPD of filtrate. The 18 production run would treat a total of 4 749 194 LPD which would produce 6 732 LPD of filtrate and reject 1 187 298 LPD of brine. The 13 recovery run would treat a total of 685 296 LPD, which would produce 11 620 LPD of filtrate and reject 1 182 410 LPD of brine. The global volume of water that would be treated by the CDI unit would be 7 507 438 LPD, which would produce 18 352 LPD of filtrate and reject 1 684 412 LPD of brine.

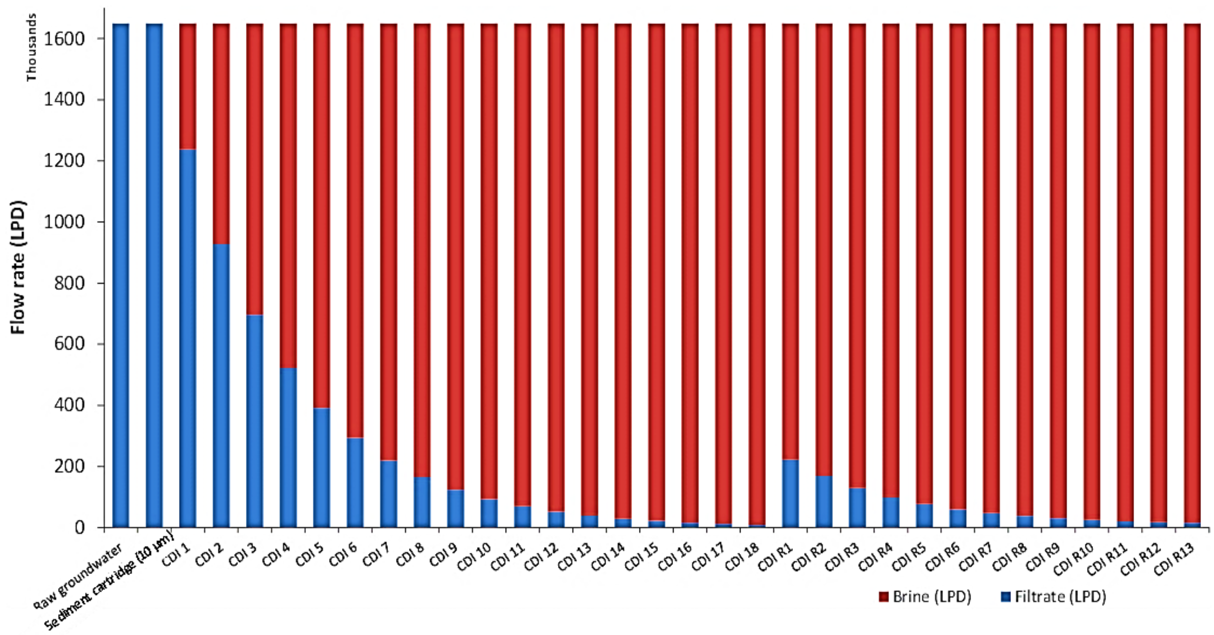

Figure 9: Water recovery observed with treatment train B, which consisted in 1 Sediment cartridge stage, 18 Capacitive deionization production stages (CDI), and 13 Capacitive deionization (CDI) recovery stages (CDI R).

4.2.4 Input requirements

Cartridge filters

Cartridge filters should be replaced when attaining the maximum allowable head loss.

CDI

The input requirements for the capacitive deionization process are null, as no chemical or regenerant of any kind is needed to operate capacitive deionization.

4.2.5 Theoretical quality of the water rejects

The brine that was produced by treatment train B) did not contain any extra solutes other than what was contained in the raw groundwater, i.e. no extra Cl_2, $KMnO_4$ or NaCl.

The theoretical quality of this brine as calculated by subtracting the filtrate content from the raw water content is presented in Table 5 (Appendix C). Because the recovery rate was very low (1.34%), the brine would actually be only slightly more concentrated then the raw groundwater. For instance, the TDS content would be 13 800 mg/L, whilst it was 13 600 mg/L in the raw groundwater. Fe and Mn would be boosted to 5.66 and 1.22, up from 5.59 mg/L and 1.20 mg/L in the raw groundwater, respectively.

The theoretical quality of brine that would be produced by a CDI system that would have a 75% recovery rate (e.g. EWP *Prestige*) was also calculated (Table 5, Appendix C). It was assumed that the filtrate quality would be the same as in this experiment. Unmistakably, this brine would be much more concentrated, but would still not contain any extra solutes other than what was contained in the raw groundwater. In such a case, the TDS would be boosted up to 53 257 mg/L. One thing to consider would be the Uranium content, which would be boosted up to 0.08 mg/L, well above the guideline for Canadian drinking water quality (0.02 mg/L; Health Canada, 2012).

4.2.6 Energy usage

Pump for sediment cartridge filter 10 µm
The differential head through the sediment cartridge filter (10 µm) was estimated at 2 PSI (3.52 m). As the service flow rate was 0.225 LPM (0.0135 m^3/h), the pump power requirement for the sediment cartridge filter would be 0.00022 kW. As it would take 8 847 h to treat 1 194 030 L of water, the energy usage for the cartridge filter pump would be 1.95 kWh to produce 16 000 L of drinking water.

Pump for carbon block cartridge filter (5 µm)
The differential head through the carbon block cartridge filter (5 µm) was estimated at 4 PSI (2.81 m). As the service flow rate was 0.225 LPM (0.0135 m^3/h), the pump power requirement for the carbon block cartridge filter was 0.00017 kW. As it would take 8 847 h to treat 1 194 030 L of water, the energy usage for the carbon block filter pump would be 1.50 kWh to produce 16 000 L of drinking water.

Pump for capacitive deionization
The differential head through the CDI unit was estimated at 2 PSI (3.52 m). At a service flow rate of 0.225 LPM (0.0135 m^3/h), the pump power requirement for the CDI unit would be 0.00022 kW. As it would take 556 106 h to treat 7 507 438 L of water, the energy usage for the CDI unit pump would be 122 kWh to produce 16 000 L of drinking water.

Capacitive deionization unit
The power requirement (kW) for the CDI unit was estimated by multiplying the voltage at which the unit was operated (1.33 V) by the maximum current draw (5 amp; EWP, 2014b).

$$
\begin{aligned}
P &= V * amp \\
&= 1.33\ V * 5\ amp \\
&= 0.00665\ kW
\end{aligned}
$$

As it would take 556 106 h to treat 7 507 438 L of water, the energy usage for the CDI unit would be 3 699 kWh to produce 16 000 L of drinking water.

Total
Taking into account our calculations using pump power requirements and estimates for the CDI unit (EWP-Mini), treatment train B would require a total of 3 824 kWh to produce 16 000 L of drinking water.

4.2.7 Possible improvements

Recovery rate
In the case of CDI, scaling up from lab scale to full scale would drastically improve water recovery, with no compromise one end-stage water quality. One such full scale CDI technology is the ''*Prestige*'' units, manufactured and commercialized by EWP (San Antonio, Texas USA; EWP, 2014a). The electrodes that are utilized in a *Prestige* unit are 11 times bigger than those utilized in the lab-scale unit that was used in this experiment (Atlas, R., 2014, personal communication).

A pilot-test system built and operated by EWP (Atlas, R., 2014, comm. pers.) and making use of 6 Prestige units (4 production stages and 2 recovery stages) and treating brackish water with TDS contents of 10 000 mg/L and 20 000 mg/L down to drinking water standards, at a production rate of 8 000 LPD, had a final recovery rate of 75%. A gross estimate for such a system is 60 000$. In such a case, producing 16 000 LPD of drinking water would require the treatment of 21 333 LPD, and brine would be produced at a rate of 5 333 LPD.

EWP (Atlas, R., 2014, comm. pers.) asserts that a water treatment train making use of 5 *Prestige* units (4 production stages and 1 recovery stage) and treating heavily concentrated water, such as the base camp's raw groundwater, to drinking water standards could have a final recovery rate of 85% (Figure 12, p. 34). In such a case, producing 16 000 LPD of drinking water would require the treatment of 18 824 LPD, and brine would be produced at a rate of 2 824 LPD.

Furthermore, EWP (Atlas, R., 2014, comm. pers.) asserts that a water treatment train making use of 9 *Prestige* units (6 production stages and 3 recovery stages) and treating brackish water of 7 200 mg/L TDS down to 100 mg/L TDS at a production rate of 16 000 LPD could have a final recovery rate of 98%. A gross estimate for such a system is 85 339$. In such a case, producing 16 000 LPD of drinking water would require the treatment of 16 327 LPD, and brine would be produced at a rate of 327 LPD. The brine quality would be 300 000 mg/L TDS.

Other CDI unit manufacturers have similar claims.

TDS reduction efficiency

According to EWP (EWP, 2014a), the efficiency of one *Prestige* unit in reducing the TDS content depends on the quality of the feed water (TDS content), and follows the model depicted in Figure 10. For instance, when the feed water has a TDS content of 7 200 mg/L, the TDS reduction efficiency is 24%.

Other CDI unit manufacturers have similar claims.

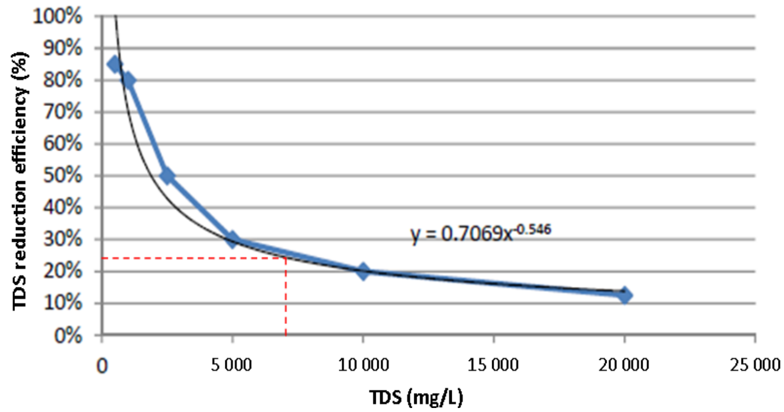

Figure 10: TDS reduction efficiency of one *Prestige* full-scale unit. The dashed lines represent the efficiency (24%) at a feed water content of 7 200 mg/L TDS.
(adapted from EWP, 2014a)

Energy usage

According to EWP (EWP, 2014a), the power usage for operation of one *Prestige* unit depends on the quality of the feed water (TDS content), and follows the model illustrated in Figure 11. For instance, the first stage of a treatment train treating brackish water of 7 200 mg/L TDS would require 0.50 kWh to treat 1 m^3 (1 000 L). Treating 16 327 L of this water would require 8.23 kWh.

Other CDI unit manufacturers have similar claims.

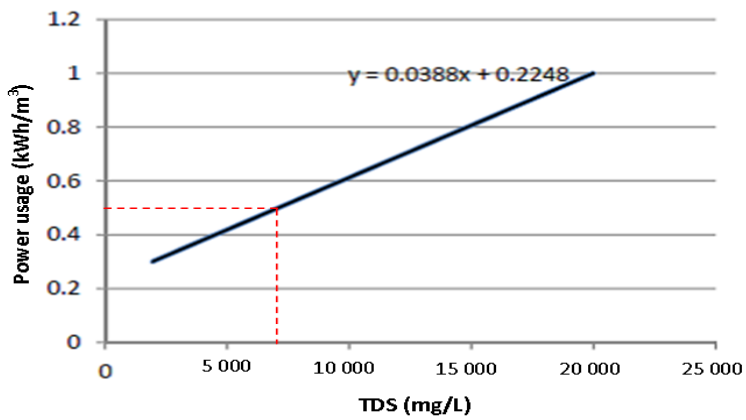

Figure 11: Power usage of one *Prestige* full-scale unit. The The dashed lines represent the power usage (0.50 kWh/m^3) at a feed water content of 7 200 mg/L TDS.
(adapted from EWP, 2014a)

With the last CDI system presented (6 production stages and 3 recovery stages), starting with feed water that has a TDS content of 7 200 mg/L, and assuming that the TDS reduction efficiency follows the model presented in Figure 10 and that the power usage follows the model presented in Figure 11, the energy usage of the CDI system would be <u>31.6 kWh</u> to produce 16 000 LPD of drinking water.

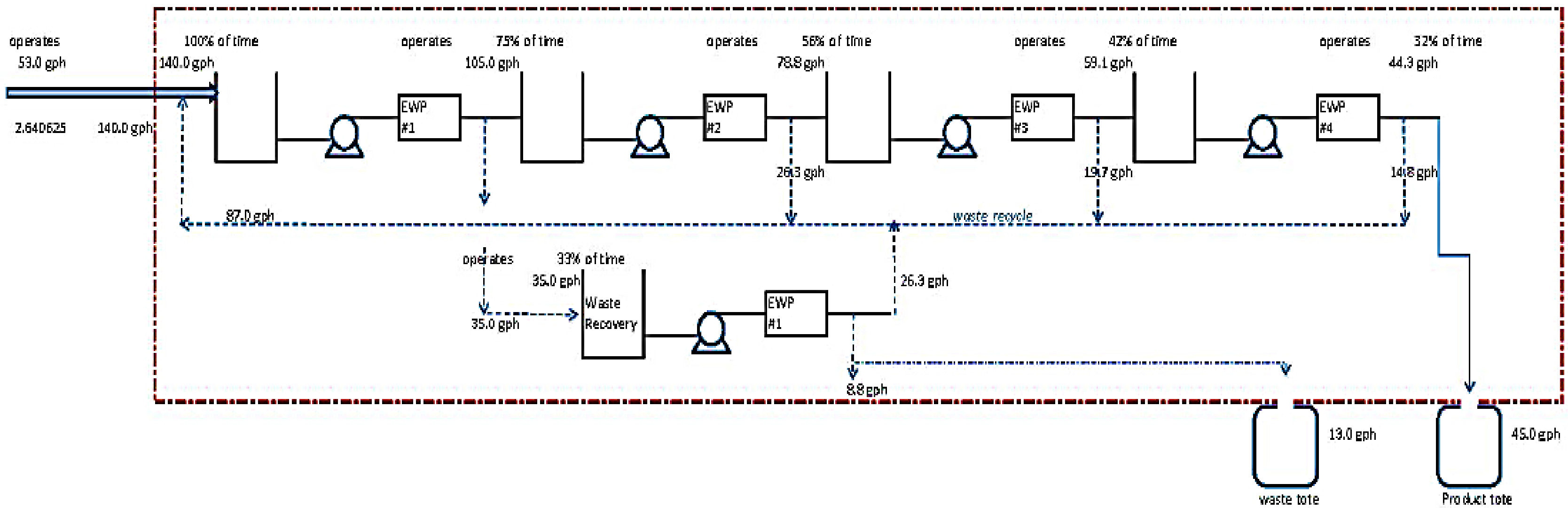

Figure 12: Illustration of a potential layout for a full-scale capacitive deionization water treatment train based on EWP's full scale *Prestige* units, making use of a series of 5 *Prestige* units (4 production stages and 1 recovery stage).
(adapted from Atlas, B., 2014. pers. comm.)

4.3 Treatment train C

4.3.1 Practicality

A nextsand^{TM} filter is easy to operate and does not require specific training. Overall, this treatment train is certainly more practical than the treatment train A) but might be more complex than treatment train B), with addition of anti-scalant to prevent clogging of the reverse osmosis unit. Noteworthy, reverse osmsosis need re-addition of un-treated water to compensate for low-content filtrate.

4.3.2 Quality of the end-stage water

The quality of the filtrate coming out of the nextsand^{TM} filter is presented in Table 4 (Appendix B). It was assumed that reverse osmosis could easily produce a filtrate that met the Canadian drinking water quality guidelines (Health Canada, 2012), and a detailed evaluation of water quality coming out of the nextsand^{TM} filter was needed to calculate anti-scalant dosage.

The TDS content of water coming out of the nextsand^{TM} filter was slightly lower (11 600 mg/L TDS) than the raw groundwater (13 600 mg/L TDS). Iron and manganese also diminished, to 1.52 mg/L and 0.949, respectively. However, the content of several other components augmented, such as nitrate, aluminum, calcium, copper, uranium and zinc. As a matter of fact, the filtrate coming out of the nextsand^{TM} filter did not meet the Canadian drinking water quality guidelines (Health Canada, 2012) for many parametes, but it was not expected to.

The quality of the filtrate that would be produced from the raw groundwater if reverse osmosis was to be used as a stand-alone treatment (i.e. without nextsand^{TM} filtration or other) was simulated using the ROSA model (Canature, 2014, Appendix E). According to this computer simulation, TDS would be brought down to 257.53 mg/L, and all simulated parameters would meet Canadian water quality guidelines (Health Canada, 2012). However, the membrane would rapidly be fouled and need frequent replacement.

If anti-scalant was used (e.g. Genesys LF) to enhance the service life of the membrane, the required dosage would not meet the maximum allowed dosage to fit NSF/ANSI standard 60 for drinking water (NSF, 2014). For instance, it was estimated that 8.1 mg/L of Genesys LF anti-scalant would be required to efficiently control scaling (Genesys, 2014a), while maximum dosage rate is 5 mg/L, with typical dosage rates at 2-4 mg/L (Genesys, 2014b).

4.3.3 Recovery rate

In the nextsand^{TM} filter, the recovery rate was 98%, as some water would be used for backwash and rinse of the system. The recovery rate of one reverse osmosis pass was 15%; as the brine was recirculated 9 times, the total recovery rate for the reverse osmosis process was 77%. Hence, the global recovery of water for treatment train C) was good, at 74%.

Considering that drinking water production at the base camp should be 16 000 LPD, the raw groundwater should be fed to the head of this treatment train at a rate of 21 248 LPD, and brine would be produced at a rate of 5 248 LPD (*Figure 13*). The nextsand™ filter would produce 20 823 LPD of filtrate and reject 425 LPD of brine. The reverse osmosis system would produce 16 034 LPD of filtrate and reject 4 789 LPD of brine.

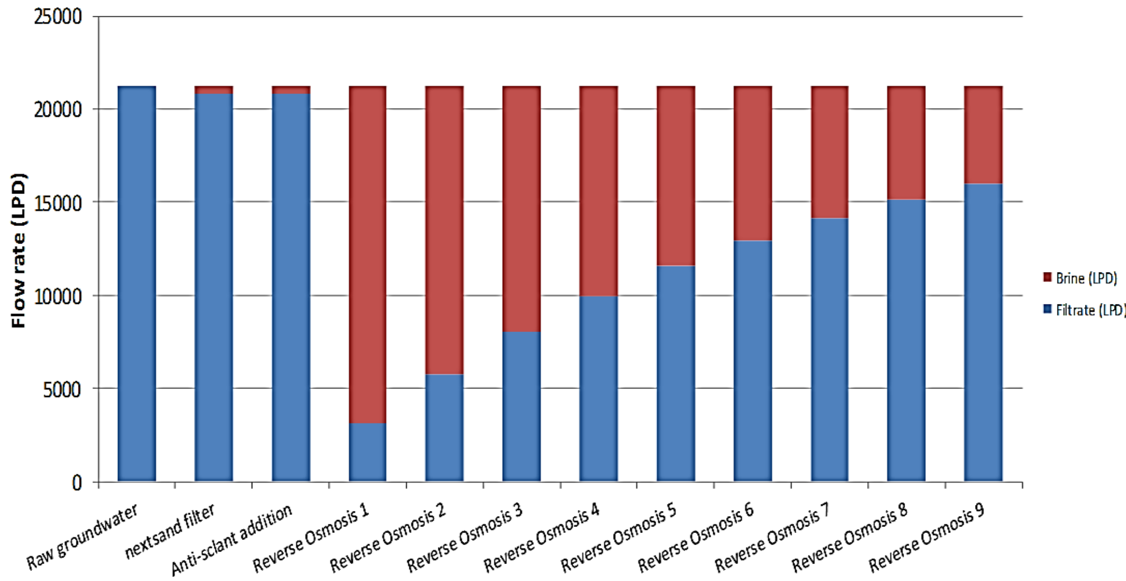

Figure 13: Water recovery observed with treatment train C, which consisted in 1 *nextsand™* stage, and 9 Reverse osmosis stages.

4.3.4 Input requirements

nextsand™

The advantage of using nextsand™, is that water can be purified using less chemicals than a typical conventional drinking water treatment system (e.g. ion exchange, combined or not with green sand filtration).

Anti-scalant

The anti-scalant was dosed at 8.11 mg/L, based on estimates described in Materials and Methods. This is higher than maximum dosage to meet NSF/ANSI standard 60's EPA criteria (5 mg/L), with typical dosage at 2-4 mg/L (Genesys, 2014b).

Considering that the flow rate making it to the reverse osmosis would be 42 514.3 LPD, this makes up for a total need of 344.8 g of anti-scalant per day. With a volumetric mass of 1.33 g/mL, this makes up for a total of 259.25 mL of anti-scalant per day.

Reverse osmosis

A main advantage of using reverse osmosis is that ion removal is performed without adding extra sodium ions, as used in ion exchangers. However, membranes have to be replaced relatively frequently, and they are expensive.

4.3.5 Theoretical quality of the water rejects

Because the quality of the end-stage water of treatment train C was not evaluated, it was impossible to calculate a theoretical brine quality. However, it can be said with certitude that this brine would contain much less secondary waste than the brine produced by treatment train A, but slightly more secondary waste than what was produced by treatment train B, because anti-scalant was used. As the recovery rate (74%) was very similar to what would be produced by a full-scale CDI technology (75%), it can be estimated that the brine concentration would be similar to that presented in Table 5 (Appendix C) for such full-scale technology, with a minor adjustment for the presence of anti-scalant.

The quality of the brine that would be produced from the raw groundwater if reverse osmosis was to be used as a stand-alone treatment (i.e. without nextsand™ filtration or other) was simulated using the ROSA model (Canature, 2014, Appendix E). According to this computer simulation, the TDS content of the brine would be as high as 25 708.54 mg/L.

4.3.6 Energy usage

Pump for nextsand™ filter

As the service flow rate was 8.61 LPM (0.5166 m^3/h) and the maximum differential head was 15 PSI (10.55 m), the pump power requirement for the nextsand™ filter was 0.02475 kW. As it would take 41.13 h to treat 21 248 L of water, the energy usage for the nextsand™ filter pump would be <u>1.02 kWh</u> to produce 16 000 L of drinking water.

Pump for reverse osmosis

As the service flow rate was 1.16 LPM (0.07 m^3/h) and the differential head was 60 PSI (42.19 m), the pump power requirement for the reverse osmosis was 0.013 kW. As the brine would be recycled 9 times, a total of 106 667 of water would be treated by the reverse osmosis system to produce 16 000 L of drinking water, which would take 1 533 h. Thus, the energy usage for the reverse osmosis pump would be <u>20.44 kWh</u> to produce 16 000 L of drinking water.

According to the ROSA simulation, the reverse osmosis process would require 1.36 kWh/kL (Canature, 2014; Appendix E). As the reverse osmosis system would treat 20 823 L of water, the reverse osmosis process would require 28.3 kWh to produce 16 000 L of drinking water. This value is of the same order of magnitude with our calculation using pump power requirement.

Total

Taking into account our calculations using pump power requirement, treatment train C would require a total of 21.46 kWh to produce 16 000 L of drinking water.

4.3.7 Possible improvements

An oxidation (Cl_2 and/or $KMnO_4$) step could be added upstream from the nextsand™, in order to precipitate Fe and Mg and enhance the removal capacity of the nextsand™ filter, much like in the case of a green sand filter. A deposition tank could also be added to collect the precipitates before the nextsand™.

In order to provide continuous treatment when allowing for backwash, a duplex of nextsand™ filters would be used. Two filters of 110 Gal each (220 Gal total) are suggested (Bert Albisser, pers. comment).

The anti-scalant could be dosed before the cartridge filter, instead of after like was done in this experiment.

An alternative to the Genesys anti-scalant is Avista™ Vitec® 7000 calcium sulfate antiscalant/dispersant. It should be injected neat at a dosage of 30 mg/L was recommended (Bert Albisser, 2014, comm. pers.). Typical dosage of Vitec® 7000 is 2-5 mg/L. Still, this dosage would not meet NSF/ANSI 60 standards for use in reverse osmosis system producing drinking water, as the maximum dosage in this case is 7 mg/l.

A static mixer could be used to provide homogeneous blend downstream the point of injection.

Alternatively, the anti-scalant dosage could be reduced to fit the NSF/ANSI standards (5 mg/L in the case of Genesys LF), and the reverse osmosis membrane would be replaced frequently as it gets fouled. However, the cost of membrane replacement is high and should be taken into consideration.

5 DISCUSSION

5.1 Summary of the results and analysis

The three treatment trains under scrutiny in this experiment had their share of advantages and shortcomings, and their relative merit can be expressed as in Figure 14.

In treatment train A, the ion exchange step had the disadvantage of requiring prohibitive quantities of inputs. Ion exchange would also produce brine that would be difficult to manage both in terms of quality and in terms of volume. In treatment train B, the lab-scale capacitive deionization unit used in this experiment had the disadvantage of a low water recovery rate and high energy usage. In treatment train C, the reverse osmosis step had the disadvantage of requiring an anti-scalant dosage that would not meet NSF/ANSI standard 60.

On the other hand, cartridge filtration proved to be the cheapest, simplest and most efficient way to remove coarser solutes; it also has a very high recovery rate and does not require any input. Similarly, nextsand^{TM} proved very efficient at removing high concentrations of Fe and Mn. Finally, reverse osmosis has shown very cost-effective at polishing pre-treated water down to drinking water standards.

Also, given the information gathered from commercial suppliers (EWP, 2014a; Atlas, R., 2014., pers. comm.), it is deemed possible to overcome the low water recovery rate and high energy usage of capacitive deionization when using a full-scale unit.

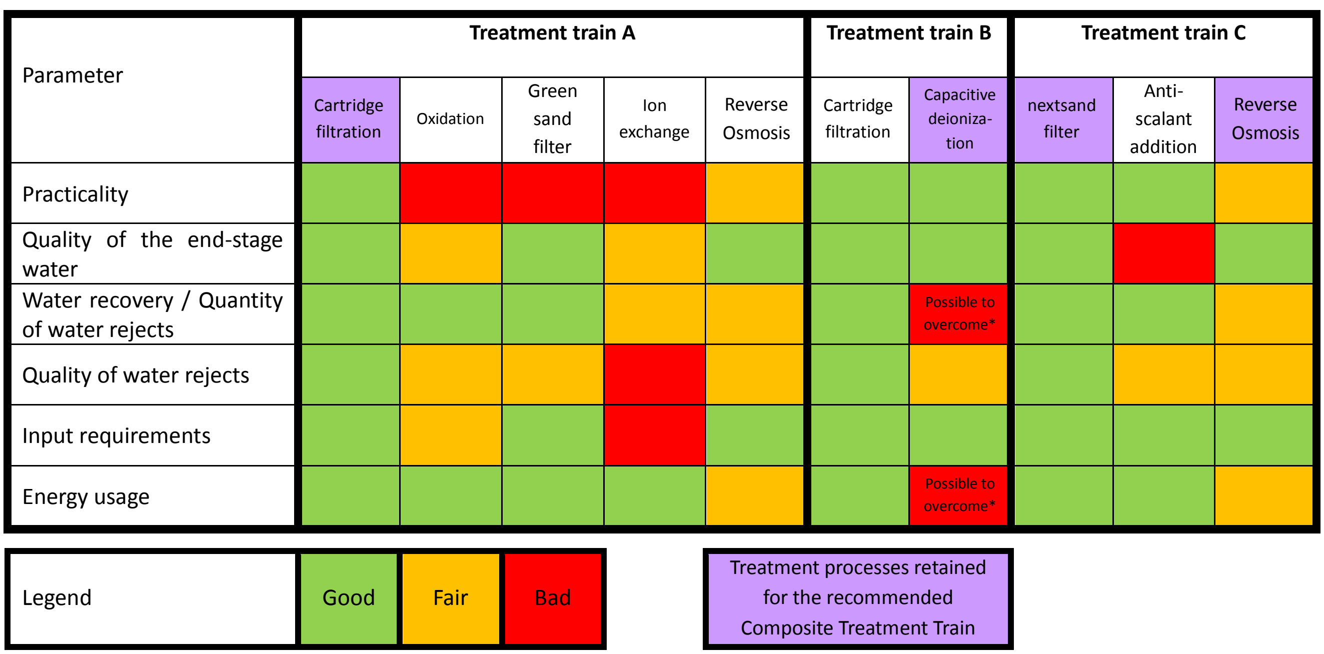

Figure 14: Relative merit of the individual treatment processes used in the three treatment trains (A, B, and C), when compared to one another in the context of this study. The treatment processes that were retained for the recommended composite treatment train (D) are highlighted in purple.

*The relatively *bad* merit of capacitive deionization in terms of *Water recovery/Quantity of water rejects* and in terms of *Energy usage* is deemed possible to overcome when using a full-scale unit (EWP, 2014a; Atlas, R., 2014., pers. comm.).

5.2 Recommendations for the treatment train

Rather than one of the particular treatment trains studied in this experiment, our recommendation goes towards using a treatment train involving a mix of the technologies that were studied during this experiment, as depicted in Figure 15. This composite treatment train capitalizes on the benefits demonstrated by the treatment processes in this experiment.

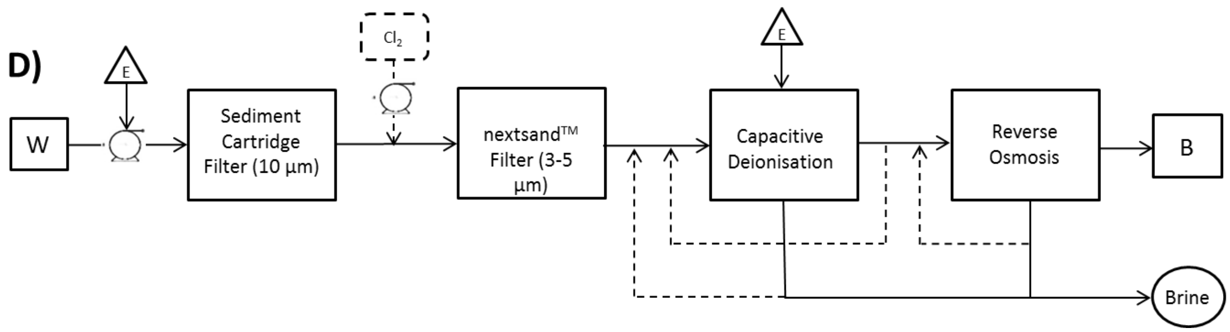

Figure 15: Recommended composite treatment train for provision of drinking water from brackish groundwater available at Northern Cross' base camp in Eagle Plains (Yukon, Canada).

With this recommended composite treatment train, raw groundwater would first pass in a 10 µm cartridge filter, in order to remove any coarse particle; this should bring the TDS content from 13 600 mg/L down to 6 000 mg/L. Water would then be routed to a nextsand™ filter, in order to further reduce TDS content. Next, the CDI system should be designed to and operated to bring the TDS content down to 2 000 mg/L. The last treatment step would involve Reverse Osmosis, which should bring the TDS content < 500 mg/L; final output quality should be adjusted using untreated water.

Optionally, chlorine could be injected upstream the nextsand™ filter, in order to initiate oxidation of Fe and Mn. This would enhance the quality of the water coming out of the nextsand™ filter; however, chlorine injection requires close monitoring and implies handling of hazardous products. Capacitive deionization would follow, using a properly scaled system. Also, non-soluble forms of Fe and Mn (Ferric and Manganic oxides) could be precipitated in a settling tank and be evacuated directly from there, which would diminish the amount of solids going to the nextsand™ filter, and enhance thereof the service run of the nextsand™ filter.

5.3 Suggestions for the management of the brine

With any water treatment technology, brine is always produced. Such a liquid would potentially be difficult to dispose of. Here are a few options on how to manage this brine:

- Recycling the brine somewhere in the industrial operations
- Hauling the brine back to an existing wastewater treatment plant down south
- Treating the brine on-site. Possible on-site treatment technologies, including passive treatment technologies, could be investigated.
- Injecting the brine in a class III disposal wells.

The Yukon research Centre has a strong expertise in investigating water management solutions for the Yukon mining industry. Mine-impacted water potentially share characteristics with brine that would be rejected by the production of drinking water at Northern Cross' base camp in Eagle Plains. The Yukon Research Centre would be open to investigating on-site brine treatment possibilities.

5.4 Contacts

Dimensioning and implementation of the recommended composite treatment train should be performed by private water specialists. Here is some contact information:

General:

- Bert Albisser
Aquatec
Whitehorse, Yukon Canada
tel 867- 668-5544

Capacitive deionization:

- Robert Atlas
Aqua EWP
San Antonio, Texas, USA
www.aquaewp.com
tel 210-737-8000
cell 210-771-4353
- Gene Shelp
ENPAR
Guelph, Ontario, Canada
www. enpar-tech.com
tel 519 836 6155 ext: 222
cell 519 546 6423

6 CONCLUSION

Northern Cross Yukon Ltd. is currently looking for a treatment system for producing drinking water from groundwater that is available at its base camp in Eagle Plains, Yukon (Canada). The groundwater is considered brackish, with a TDS content of 13 600 mg/L. The end-stage water should meet the Canadian drinking water quality standards (Health Canada, 2012). The drinking water daily production should be 16 000 LPD.

Three Treatment train options were examined by the Yukon Research Centre. Treatment train A was a ''classic'' option, making use of a green sand filter, an ion exchanger, and reverse osmosis. Treatment train B consisted in a ''novel'' approach, with Capacitive Deionization as the main treatment process. Treatment train C was an ''improved'' model, building on the use of a new type of sand filter (nextsand™), along with reverse osmosis with anti-scalant. The three treatment trains were evaluated along their practicality, quality of the end-stage water, recovery rate, input requirements, quality of water rejects, and energy usages.

All three Treatment trains had their shortcomings. In particular, Treatment train A called for heavy usage of inputs, which would render practicality and operation costs prohibitive. Treatment train B had a deceptively low recovery rate. Treatment train C needed an anti-scalant dosage that did not meet the NSF/ANSI 60 standards for drinking water.

Therefore, it is recommended to capitalize on treatment processes gleaned throughout all those studied in this experiment. The proposed composite treatment train implies nextsand™ filtration, capacitive deionization, and reverse osmosis, with an oxidation option upstream the nextsand™ filter.

No matter what water treatment option is elected, the production of drinking water from a brackish groundwater source will necessarily involve the production of brine. The quantity and quality of the brine that would be produced by the different treatment trains was presented. Different brine management options were offered, and further investigation would be necessary to appraise these.

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APPENDIX A

Table 3: Quality of the raw groundwater at Northern Cross' base camp, and comparison to the drinking water quality criteria used in this study (Table 1, p. **Error! Bookmark not defined.**).

Type of test	Parameter	Units	Raw groundwater quality			Exceedance of criteria
			24 Sep 2013	19 March 2014	Representa-tive value	
Physical Tests	Conductivity	uS/cm	13 800		13 800	
	Hardness (as $CaCO_3$)	mg/L	3 820	4 080	3 950	X
	pH	pH	7.4	7.9	7.7	
	Total Dissolved Solids	mg/L	14 500	12 700	13 600	X
Anions and Nutrients	Alkalinity, Bicarbonate (as CaCO3)	mg/L		1 290	1 290	
	Alkalinity, Carbonate (as CaCO3)	mg/L		<20	10	
	Alkalinity, Hydroxide (as CaCO3)	mg/L		<20	10	
	Alkalinity, Total (as CaCO3)	mg/L	1 360	1 290	1 325	X
	Ammonia, Total (as N)	mg/L		7.26	7.26	
	Chloride (Cl)	mg/L	<25	<25	12.5	
	Fluoride (F)	mg/L	<1.0	<1.0	0.5	
	Nitrate (as N)	mg/L	<0.25	<0.25	0.125	
	Nitrite (as N)	mg/L	<0.050	<0.050	0.025	
	Phosphorus (P)-Total	mg/L		0.004	0004	
	Sulfate (SO4)	meq/L	8 790	8 250	8 520	X
	Anion Sum	meq/L		197	197	
	Cation Sum	%		194	194	
	Cation - Anion Balance			-0.9	-0.9	
Total Metals	Aluminum (Al)-Total	mg/L	<0.03	<0.03	0.02	
	Antimony (Sb)-Total	mg/L	<0.001	<0.001	0.001	
	Arsenic (As)-Total	mg/L	0.009	<0.001	0.009	
	Barium (Ba)-Total	mg/L	0.003	<0.050	0.003	
	Beryllium (Be)-Total	mg/L		<0.025	0.0125	
	Bismuth (Bi)-Total	mg/L		<1.0	0.5	
	Boron (B)-Total	mg/L	0.4	<0.5	0.4	
	Cadmium (Cd)-Total	mg/L	<0.0001	<0.0005	0.0001	X
	Calcium (Ca)-Total	mg/L	324	304	314	
	Chromium (Cr)-Total	mg/L	<0.0010	<0.0050	0.0005	
	Cobalt (Co)-Total	mg/L		0.002	0.002	
	Copper (Cu)-Total	mg/L	0.016	<0.005	0.016	
	Iron (Fe)-Total	mg/L	5.4	5.8	5.6	X
	Lead (Pb)-Total	mg/L	<0.0005	0.0013	0.0013	X
	Lithium (Li)-Total	mg/L		0.190	0.190	
	Magnesium (Mg)-Total	mg/L	894	807	851	
	Manganese (Mn)-Total	mg/L	1.18	1.22	1.20	X
	Mercury (Hg)-Total	mg/L		<0.0002	0.0001	
	Molybdenum (Mo)-Total	mg/L		0.005	0.005	
	Nickel (Ni)-Total	mg/L		0.005	0.005	
	Phosphorus (P)-Total	mg/L		<1.5	0.75	
	Potassium (K)-Total	mg/L	14	12	13	
	Selenium (Se)-Total	mg/L	<0.0010	<0.0100	0.001	
	Silicon (Si)-Total	mg/L		3.6	3.6	
	Silicon (as SiO2)-Total	mg/L		7.68	7.68	
	Silver (Ag)-Total	mg/L		<0.0001	0.0001	
	Sodium (Na)-Total	mg/L	2 780	2 560	2 670	X
	Strontium (Sr)-Total	mg/L		0.86	0.86	
	Thallium (Tl)-Total	mg/L		<0.0010	0.001	
	Tin (Sn)-Total	mg/L		<0.15	0.08	
	Titanium (Ti)-Total	mg/L		<0.05	0.03	
	Uranium (U)-Total	mg/L	0.0198	0.0196	0.0197	
	Vanadium (V)-Total	mg/L		<0.15	0.075	
	Zinc (Zn)-Total	mg/L	<0.030	<0.025	0.013	
Indexes	Total permanent hardness (as $CaCO_3$)	mg/L			4 480	
	Total equivalent hardness (as $CaCO_3$)	mg/L			241.7	
	Langelier Saturation Index				-0.64	
	Stiff and Davis Stability Index				-1.25	

APPENDIX B

Table 4: Quality of the filtrate coming out of the Reverse Osmosis (RO) process of Treatment train A (end-stage filtrate), quality of the filtrate coming out of the Capacitive Deionization (CDI) process of Treatment train B (end-stage filtrate), and quality of the filtrate coming out of the nextsand™ process of Treatment train C, along with a comparison to the drinking water quality criteria used in this study (Table 1, p. **Error! Bookmark not defined.**).

Note that nextsand™ is not the end-stage filtrate of treatment train C.

Type of test	Parameter	Units	Treatment train A, RO		Treatment train B, CDI		Treatment train C, nextsand™	
			Water quality	Exceed-ance of criteria	Water quality	Exceed-ance of criteria	Water quality	Exceed-ance of criteria
Physi-cal Tests	Hardness (as CaCO3)	mg/L	60.5	X	9.5		4 550	X
	Total Dissolved Solids	mg/L			381		11 600	X
Anions and Nutrients	Alkalinity, Total (as CaCO3)	mg/L	173		10.9		1 180	X
	Ammonia, Total (as N)	mg/L			0.54		0.23	
	Chloride (Cl)	mg/L	7.7		<0.5		<25	
	Nitrate (as N)	mg/L	0.34		<0.02		1.10	
	Nitrite (as N)	mg/L	0.073		<0.005		<0.250	
	Phosphorus (P)-Total	mg/L	<0.010		<0.001		<0.050	
	Sulfate (SO4)	mg/L	362	X	243		7 660	X
Total Metals	Aluminum (Al)-Total	mg/L	<0.01		0.01		4.03	X
	Antimony (Sb)-Total	mg/L	0.001		0.001		<0.001	
	Arsenic (As)-Total	mg/L	0.002		0.002		0.002	
	Barium (Ba)-Total	mg/L	<0.020		<0.020		0.814	
	Beryllium (Be)-Total	mg/L	<0.005		<0.005		<0.015	
	Boron (B)-Total	mg/L	<0.10		<0.10		0.33	
	Cadmium (Cd)-Total	mg/L	<0.0001		<0.0001		0.0009	
	Calcium (Ca)-Total	mg/L	10.2		0.8		533	
	Chromium (Cr)-Total	mg/L	<0.001		0.005		<0.005	
	Cobalt (Co)-Total	mg/L	<0.0005		<0.0005		0.0026	
	Copper (Cu)-Total	mg/L	0.007		0.087		0.109	
	Iron (Fe)-Total	mg/L	<0.030		0.040		1.52	X
	Lead (Pb)-Total	mg/L	<0.001		0.005		0.008	
	Lithium (Li)-Total	mg/L	<0.05		<0.05		0.20	
	Magnesium (Mg)-Total	mg/L	8.5		1.8		781	
	Manganese (Mn)-Total	mg/L	<0.01		<0.01		0.95	X
	Molybdenum (Mo)-Total	mg/L	0.002		0.001		0.006	
	Nickel (Ni)-Total	mg/L	<0.005		<0.005		0.009	
	Selenium (Se)-Total	mg/L	<0.001		0.065	X	<0.010	
	Silicon (Si)-Total	mg/L	5.7		7.6		14.8	
	Silver (Ag)-Total	mg/L	<0.0001		0.0002		0.0001	
	Sodium (Na)-Total	mg/L	210	X	111		1 780	X
	Thallium (Tl)-Total	mg/L	<0.0002		<0.0002		0.0011	
	Titanium (Ti)-Total	mg/L	<0.05		<0.05		0.12	
	Uranium (U)-Total	mg/L	0.005		0.001		0.025	X
	Vanadium (V)-Total	mg/L	<0.03		<0.03		<0.09	
	Zinc (Zn)-Total	mg/L	0.007		0.017		0.078	

APPENDIX C

Table 5: Theoretical quality of the water rejects that would be produced by Treatment Train A, Treatment Train B if using a small scale unit (e.g. EWP-Mini, with 1.34% recovery rate), and Treatment Train B if using a full scale unit (e.g. EWP *Prestige*, with 75% recovery rate). Note that the theoretical quality of the water rejects that would be produced by Treatment train C was estimated to be similar to what would be produced by Treatment train B if using a full scale unit.

Type of test	Parameter	Units	Water quality		
			Treatment train A	Treatment train B with a recovery rate of 1.34%	Treatment train B with a recovery rate of 75%
Physical Tests	Total Dissolved Solids	mg/L		13 780	53 257
Anions and Nutrients	Ammonia, Total (as N)	mg/L		7.35	27.41
	Chloride (Cl)	mg/L	2 223	13	49
	Fluoride (F)	mg/L			
	Nitrate (as N)	mg/L	0.00	0.13	0.47
	Nitrite (as N)	mg/L	0.00	0.03	0.09
	Phosphorus (P)-Total	mg/L	0.00	0.00	0.01
	Sulfate (SO4)	mg/L	13 109	8 632	3 3351
Total Metals	Arsenic (As)-Total	mg/L	0.013	0.009	0.031
	Beryllium (Be)-Total	mg/L	0.02	0.01	0.04
	Boron (B)-Total	mg/L	0.61	0.42	1.49
	Cadmium (Cd)-Total	mg/L	0.000	0.000	0.000
	Calcium (Ca)-Total	mg/L	485	318	1 254
	Cobalt (Co)-Total	mg/L	0.003	0.002	0.007
	Copper (Cu)-Total	mg/L	0.02	0.02	-0.20
	Iron (Fe)-Total	mg/L	8.7	5.7	22.2
	Lead (Pb)-Total	mg/L	0.002	0.001	-0.010
	Lithium (Li)-Total	mg/L	0.27	0.19	0.69
	Magnesium (Mg)-Total	mg/L	1 324	862	3 397
	Manganese (Mn)-Total	mg/L	1.9	1.2	4.8
	Molybdenum (Mo)-Total	mg/L	0.007	0.005	0.017
	Nickel (Ni)-Total	mg/L	0.007	0.005	0.013
	Potassium (K)-Total	mg/L	0.001		
	Selenium (Se)-Total	mg/L	0.001	0.000	-0.194
	Silicon (Si)-Total	mg/L	2.4	3.5	-8.3
	Sodium (Na)-Total	mg/L	5 459	2 705	10 347
	Thallium (Tl)-Total	mg/L	0.001	0.001	0.002
	Titanium (Ti)-Total	mg/L	0.03	0.03	0.03
	Uranium (U)-Total	mg/L	0.03	0.02	0.08
	Vanadium (V)-Total	mg/L	0.11	0.08	0.26
	Zinc (Zn)-Total	mg/L	0.02	0.01	0.00

APPENDIX D

MM4 Report (Genesys, 2014a)

User & Plant Details

Project Name /	yukon college
Reference	
Contact Name	
Company	
Date	
Report Author	
Contact Number	
Email Address	

Water and Membrane Details

Water Type	Brackish Water
Membrane Manufacturer	Brackish Water
Membrane Type	Polyamide
Average Salt Passage	0.5 %

Recommended Product: GENESYS LF

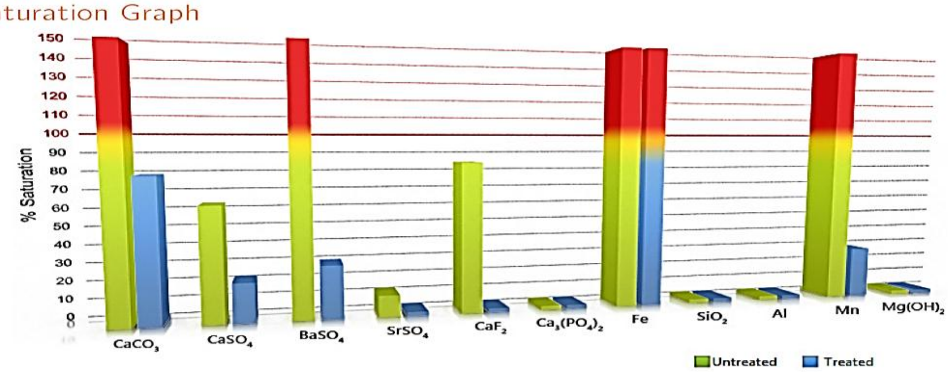
Dosing Data

For Scale Control - Feed	8.11 mg/l
For Iron Control - Feed	323.84 mg/l
Total Dosage	331.95 mg/l
Dose In Concentrate	390.53 mg/l
Set Dosing Pump To	1.89 ml/hr
Daily Requirement	0.05 l/day

Acid Dosing

Acid dosing is not required.

Saturation Graph



Scaling Indices

	$CaCO_3$	$CaSO_4$	$BaSO_4$	$SrSO_4$	CaF_2	$Ca_3(PO_4)_2$	$Fe(OH)_3$	SiO_2	$Al(OH)_3$	$Mn(OH)_2$	$Mg(OH)_2$
Conc. Untreated	149.34	60.90	1389.66	12.41	84.27	0.00	5913.12	0.00	2.99	417.48	0.06
Conc. Treat.	77.25	21.75	27.79	1.24	0.60	0.00	394.21	0.00	1.94	27.83	0.00

Water Analysis Data

Component	Feed Water mg/l	Concentrate mg/l
Ca^{2+}	304.00	355.86
Mg^{2+}	807.00	944.66
Na^{+}	2560.00	2996.71
K^{+}	12.00	14.05
Ba^{2+}	0.05	0.06
Sr^{2+}	0.86	1.01
Fe^{3+}	5.76	6.74
Al^{3+}	0.03	0.04
Mn^{2+}	1.22	1.43
SO_4^{2-}	8250.00	9657.35
Cl^{-}	25.00	29.26
F^{-}	1.00	1.17
HCO_3^{-}	1316.88	1541.53
CO_3^{2-}	6.79	7.95
CO_2	36.26	36.26
NO_3^{-}	0.25	0.29
SiO_2	0.00	0.00
PO_4^{3-}	0.00	0.00

Operation Details

Permeate Flow	0.3 USgal/hr
Recovery Rate	15.0 %
Feed Flow	2.0 USgal/hr
Concentration Factor	1.18
Concentrate Flow	1.7 USgal/hr
pH Raw Water	7.5
pH Feed Water	7.5
Operating Pressure	125.0 PSI
Operating Temperature	20.0 °C
Operating Time	24.0 hr/day

Water Indices

Index	Feed Water	Concentrate
pH	7.50	7.47
TDS	13277.17	15542.10
Ionic Strength (I)	0.32	0.38
LSI	1.37	1.48
Alkalinity ppm $CaCO_3$	1091.41	1277.61

Scaling Indices Feed

Scalant Type	Feed Water Untreated (%)	Feed Water Treated (%)
$CaCO_3$	145.77	75.40
$CaSO_4$	48.71	17.39
$BaSO_4$	1171.61	23.43
$SrSO_4$	10.64	1.06
CaF_2	52.54	0.38
$Ca_3(PO_4)_2$	0.00	0.00
$Fe(OH)_3$	5118.11	341.21
SiO_2	0.00	0.00
$Al(OH)_3$	2.54	1.65
$Mn(OH)_2$	361.35	24.09
$Mg(OH)_2$	0.06	0.00

Scaling Indices Concentrate

Scalant Type	Concentrate Untreated (%)	Concentrate Treated (%)
$CaCO_3$	149.34	77.25
$CaSO_4$	60.90	21.75
$BaSO_4$	1389.66	27.79
$SrSO_4$	12.41	1.24
CaF_2	84.27	0.60
$Ca_3(PO_4)_2$	0.00	0.00
$Fe(OH)_3$	5913.12	394.21
SiO_2	0.00	0.00
$Al(OH)_3$	2.99	1.94
$Mn(OH)_2$	417.48	27.83
$Mg(OH)_2$	0.06	0.00

APPENDIX E

ROSA report (Canature, 2014)

Reverse Osmosis System Analysis for FILMTEC™ Membranes — ROSA 9.1 ConfigDB u399339_282

Project: 4-4-14 aquatech eagle lake — Case: 3

Dave Pitman, Canature NA — 4/4/2014

Project Information:

Case-specific:

System Details

Feed Flow to Stage 1	10.00 gpm	Pass 1 Permeate Flow	3.00 gpm	Osmotic Pressure:	
Raw Water Flow to System	6.00 gpm	Pass 1 Recovery	50.00 %	Feed	61.49 psig
Feed Pressure	170.79 psig	Feed Temperature	4.0 C	Concentrate	117.16 psig
Flow Factor	0.85	Feed TDS	12978.16 mg/l	Average	89.32 psig
Chem. Dose (100% H2SO4)	0.00	Number of Elements	9	Average NDP	58.38 psig
Total Active Area	783.00 ft²	Average Pass 1 Flux	5.52 gfd	Power	0.93 kW
Water Classification: Well Water SDI < 3				Specific Energy	5.16 kWh/kgal

Stage	Element	#PV	#Ele	Feed Flow (gpm)	Feed Press (psig)	Recirc Flow (gpm)	Conc Flow (gpm)	Conc Press (psig)	Perm Flow (gpm)	Avg Flux (gfd)	Perm Press (psig)	Boost Press (psig)	Perm TDS (mg/l)
1	XLE-4040	2	3	10.00	165.79	4.00	7.67	159.59	2.33	6.43	0.00	0.00	210.18
2	XLE-4040	1	3	7.67	154.59	0.00	7.00	141.76	0.67	3.69	0.00	0.00	422.51

Pass Streams (mg/l as Ion)								
Name	Feed	Adjusted Feed		Concentrate		Permeate		
		Initial	After Recycles	Stage 1	Stage 2	Stage 1	Stage 2	Total
NH4+ + NH3	7.19	7.26	9.88	12.76	13.87	0.71	1.23	0.83
K	12.00	12.00	16.62	21.55	23.54	0.39	0.80	0.49
Na	2560.00	2560.01	3561.28	4628.49	5061.13	49.93	101.19	61.36
Mg	807.00	807.00	1125.94	1465.58	1604.04	8.47	16.69	10.30
Ca	304.00	304.00	424.17	552.13	604.29	3.15	6.25	3.84
Sr	0.86	0.86	1.20	1.56	1.71	0.01	0.02	0.01
Ba	0.05	0.05	0.07	0.09	0.10	0.00	0.00	0.00
CO3	0.29	0.29	0.48	0.71	0.80	0.00	0.01	0.00
HCO3	12.90	12.90	17.02	21.44	23.05	2.03	3.93	2.45
NO3	0.25	0.25	0.35	0.46	0.50	0.00	0.00	0.00
Cl	25.00	25.00	34.65	44.94	49.08	0.78	1.58	0.96
F	1.00	1.00	1.38	1.79	1.96	0.04	0.07	0.04
SO4	9247.51	9247.51	12880.65	16751.52	18324.53	144.74	290.80	177.31
SiO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Boron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.15	0.15	0.19	0.25	0.28	0.15	0.17	0.15
TDS	12978.07	12978.16	18073.71	23502.96	25708.54	210.18	422.51	257.53
pH	7.94	7.94	7.90	7.84	7.83	7.45	7.65	7.51

Design Warnings

-None-

Solubility Warnings

CaSO4 (% Saturation) > 100%
BaSO4 (% Saturation) > 100%
CaF2 (% Saturation) > 100%
Antiscalants may be required. Consult your antiscalant manufacturer for dosing and maximum allowable system recovery.

Stage Details

Stage 1 Element	Recovery	Perm Flow (gpm)	Perm TDS (mg/l)	Feed Flow (gpm)	Feed TDS (mg/l)	Feed Press (psig)
1	0.09	0.45	163.98	5.00	18073.71	165.79
2	0.09	0.39	210.79	4.55	19855.10	163.46
3	0.08	0.33	273.59	4.16	21683.48	161.41
Stage 2 Element	**Recovery**	**Perm Flow (gpm)**	**Perm TDS (mg/l)**	**Feed Flow (gpm)**	**Feed TDS (mg/l)**	**Feed Press (psig)**
1	0.03	0.27	346.18	7.67	23502.96	154.59
2	0.03	0.22	426.27	7.40	24332.59	150.13
3	0.03	0.18	529.01	7.18	25069.42	145.86

Scaling Calculations

	Raw Water	Adjusted Feed	Concentrate
pH	7.94	7.94	7.83
Langelier Saturation Index	-0.64	-0.64	-0.21
Stiff & Davis Stability Index	-1.25	-1.25	-1.08
Ionic Strength (Molal)	0.34	0.34	0.67
TDS (mg/l)	12978.07	12978.16	25708.54
HCO3	12.90	12.90	23.05
CO2	0.15	0.15	0.28
CO3	0.29	0.29	0.80
CaSO4 (% Saturation)	94.60	94.60	208.64
BaSO4 (% Saturation)	1132.54	1132.54	2384.27
SrSO4 (% Saturation)	10.34	10.34	22.97
CaF2 (% Saturation)	40.41	40.41	307.97
SiO2 (% Saturation)	0.00	0.00	0.00
Mg(OH)2 (% Saturation)	0.21	0.21	0.25

To balance: 0.01 mg/l Na added to feed.