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PILOTING SMALL RURAL SYSTEMS FOR FE, MN & TDS REMOVAL

D. R. Corkal[1], L. Braul[1a], D. Poon[2], W. Hicks[3], and G. Germin[3a]
1. Agriculture and Agri-Food Canada-Prairie Farm Rehabilitation Administration, Saskatoon, SK (1a: Regina, SK)
2. SAL Engineering Ltd. Saskatoon, SK
3. Indian and Northern Affairs Canada, Prince Albert, SK (3a: Regina, SK)

ABSTRACT

First Nations and agricultural producers often face difficult and similar challenges with their water supplies. Poor quality water must be treated by micro-systems in remote locations. This project investigated a variety of conventional and innovative micro-scale rural water treatment technologies to deal with high concentrations of iron (1.3 to 4.1 mg Fe/L), manganese (0.07 to 0.70 mg Mn/L) and total dissolved solids (620 to 1,720mg TDS/L). Full system design flow rates were set at a range of 3 to 10 Lpm, targeted to serve clusters of three to fifteen homes. A variety of treatment processes designed and supplied by a number of different vendors of small systems were piloted on two First Nations locations. At Mistawasis, successful Fe and Mn removal processes included combinations of biological filtration, cold lime softening, catalytic conversion with manganese greensand filters, and membranes. At Peepeekisis, various combinations of chlorine oxidation, ozonation, pressure filtration, ion exchange softening and biological slow sand filtration were effective for Fe and Mn removal. For reduction of high TDS, cold lime softening, or, membranes utilizing reverse osmosis or nanofiltration were effective. Advanced technologies can be down-scaled to deal with very low flow rates. Robust operation can be achieved with appropriate water treatment technologies. Experienced and trained operators are beneficial to ensure effective process operations. Rural remote micro-systems properly designed by vendors are able to deal with challenging water quality problems. The pilot challenges were useful in gaining better understanding of process limitations and improving the designs of the micro-systems.

INTRODUCTION

First Nations and agricultural producers often face difficult and similar challenges with their water supplies. Source water quality from wells, rivers or lakes is often poor. Water treatment systems must meet difficult treatment challenges and be sustainable for long-term operation. The remote location of rural water treatment plants often means expert support is not readily available. Conventional or advanced water treatment technologies must be manageable by the operator, and robust enough for the very low flow rates required by these micro-systems.

Most micro-systems are supplied directly from a vendor to the end-user. Vendors use a variety of design approaches, such as past experience, empirical calculations, process product performance literature, technical and engineering support from suppliers and consultants, etc. Indian and Northern Affairs Canada was interested in evaluating a variety of vendor-supplied designs at two First Nations locations, Mistawasis (near Leask, central Saskatchewan) and Peepeekisis (near Balcarres, southern Saskatchewan). The goal of the project was to gather information about the approaches and performance of vendor designs supplying water for clusters of homes (ranging from 3 to 15 homes). The knowledge gained from the pilot challenges was expected to be useful for determining future applications, potentially 130 community wells supplying water to 500 First Nations homes across Saskatchewan. Knowledge was also expected to be transferred to agricultural water users across Canada.

MATERIALS AND METHODS

Indian and Northern Affairs Canada (INAC) initiated the pilot project. A project management team was established to oversee the work, including personnel from INAC, Mistawasis and Peepeekisis First Nations, Health Canada, SAL Engineering Ltd. for contract management, and Agriculture and Agri-Food Canada's Prairie Farm Rehabilitation Administration for applied research and system evaluations.

Vendor Selection

Eighteen companies were invited to submit proposals to conduct "Small Water Treatment Plant Studies" at two First Nations sites in Saskatchewan during the period from Sept. 8 to Nov. 10, 2004. A broad suite of raw water quality characteristics was provided to the vendors, and the full plant flow rate was specified at 3 to 10 L/min. Vendors were required to complete detailed reports of their pilot challenges.

Five vendors submitted proposals, with costs to conduct each pilot ranging from $7,620 to $53,500 per location. The project management team selected 3 vendors for each site, conducting simultaneous equipment performance evaluations. The vendor pilot costs were $83,500 for Mistawasis and $89,500 for Peepeekisis, for a total of $173,000.

Vendor and Independent Water Treatment Process Evaluations

To prove out the technologies of future full plant designs, each vendor designed smaller pilot systems with flow rates ranging from 1 to 4 L/min. Well water was pumped into a trailer and processed through each vendor's treatment train. Processed water, waste water (filter backwashing, membrane concentrate) was disposed overland adjacent to the site.

Personnel access into each trailer was logged to ensure no issues occurred with equipment settings and to respect confidentiality issues. Vendors conducted their own on-site operation and maintenance on an as-needed basis. For most, this meant site visits once or twice per week. Vendors also kept their own records and conducted on-site water quality analyses using portable field kits. All of the vendors left the equipment operating continuously, usually to simulate daily demands. One vendor left equipment on at a constant rate throughout the entire challenge, and another, conducted a number of short duration experiments to test out a variety of processes and process sequences. After termination of the pilot challenges, each vendor submitted a detailed report documenting system performance and recommending future design options.

First Nations staff inspected the trailers daily, to ensure there were no equipment failures. Agriculture and Agri-Food Canada staff from Prairie Farm Rehabilitation Administration (PFRA) conducted independent water testing by gathering field testing data, and sampling water after each major treatment device. Systems were sampled generally once per week, or more frequently if additional experiments were being conducted. PFRA evaluated all vendor challenges, evaluated process performance laboratory water quality data and submitted detailed reports of process performance.

On-site and Analytical Water Quality Tests

On-site tests conducted by PFRA included: pH, turbidity, dissolved oxygen, conductivity, alkalinity, chlorine (oxidant and disinfection residual), and oxidation reduction potential. PFRA also collected water and completed particle size distribution analyses in Regina. A series of Biological Activity Reaction Tests (BART™) were undertaken for water sampled from most sample ports, to determine biological activity of the raw water as well as the processed water.

PFRA staff collected water after each treatment device for a more comprehensive suite of water analyses, completed by the Saskatchewan Research Council's analytical laboratory in Saskatoon. The suite included over 30 parameters: bicarbonate, calcium, carbonate, chloride, hydroxide, magnesium, pH, potassium, sodium, conductivity, sulfate, sum of ions, alkalinity, hardness, ammonia as nitrogen, nitrate, ortho-phosphate as P, dissolved organic carbon, aluminum arsenic, iron, manganese, phosphorus, Langlier Saturation Index, total dissolved solids, true color, *E. Coli*, fecal coliform, heterotrophic plate count, total coliform, tannin/lignin, and some other miscellaneous tests. The costs for water quality analyses were $25,000 for Mistawasis and $35,000 for Peepeekisis for a total of $60,000.

PILOT SYSTEM CHALLENGES

Raw Water Quality and Well Description

Each of the vendors designed water treatment processes primarily to deal with iron (Fe), manganese (Mn), and total dissolved solids (TDS); in addition, Peepeekisis systems were designed to remove arsenic (As), sodium (Na) and sulfate (SO_4). Selected raw water quality characteristics from Mistawasis and Peepeekisis wells are listed in Table 1:

Table 1 - Selected Raw Water Quality Characteristics – problem parameters in bold

Parameter	**Mistawasis** mg/L	**Peepeekisis** mg/L	**Guideline** G = Goal	**Comment**
Iron	**4.03**	**2.2**	0.3	Aesthetic, stains; foulant
Manganese	**0.08**	**0.82**	0.05	Aesthetic, stains, foulant
TDS	**620**	**1,700**	500	Aesthetic; scales; foulant
Hardness	**420**	**900**	G <200	Aesthetic, scales; foulant
Calcium	96	170	-	Fouls membranes
Chloride	23	30	250	Aesthetic
Magnesium	45	90	-	Fouls membranes
Ammonia, as N	2.0	2.6	G = low	Chlorine demand; N conversion
Nitrate	<0.04	<0.04	10	Health
Sodium	58	**230**	200	Aesthetic & Na-restricted diets
Sulfate	130	**800**	500	Aesthetic & Laxative
Arsenic	0.010	0.011**- 0.049**	0.025	Health
pH	7.2 – 7.6	7.2 – 7.6	6.5 -8.5	Aesthetic
Alkalinity	401	430	-	< 200 desirable
Dissolved oxygen	1.1 to 1.6	1.0 to 2.5	-	Aerobic
Turbidity, NTU T = 5 minutes T > 24 hour	 0.2 to 1.1 42 to 52	 0.8 to 38 12 to 84	<1.0	Desirable: <0.1 NTU
True Colour, TCU	7	7	15	Aesthetic
Diss. Org.Carbon; Tannin/lignin	**3.7 to 5.8;** 0.8	**4.7 to 5.5;** 0.6	G<2.0; G<0.1	THMs; impairs treatment;foulant Org. complexing/binds Fe, Mn
Total Coliform, Ct/100mL	<1	**< 1 to 101**	0	Disease-causing indicator
Bacteria, non-path.	**Fe, SO_4,HAB**	**Fe, SO_4,HAB**	G = Low	Impairs treatment; foulants

The **Mistawasis Island Lake Village Well** is located in a buried valley aquifer in LSD 14 of NE 29-48-06 W3M and has a ground elevation of 541 m (1775 ft). The well is a 152 mm (6 inch) diameter PVC casing, and was completed in 1997 to a depth of 69.5 m, drawing water from the lower 40 m zone of clean river-washed deposits of sand (predominantly silica) and fine gravel. Well maintenance and site work cost $11,000.

The **Peepeekisis Poitras Well** is located in LSD 16 of NE 35-21-11 W2M and has a ground elevation of about 625 m (2050 ft.). The well is a 125 mm (5”) nominal diameter PVC casing, about 10 to 20 years old, and was completed to a depth of 107 m, with well intake set at approximately 60.5 m (200’). Water is likely extracted from an aquifer of sands and silts formed by sediments of the Empress Group, a major drift aquifer. Preparatory site work, electrical supply, and well maintenance cost $20,400.

Mistawasis Vendor 1: Biological Filtration, GAC, Anti-scalant and RO

Vendor 1 utilized a gravity slow sand filter (SSF) and granular activated carbon (GAC) filter followed by ultraviolet disinfection and a storage tank to compensate for low flow rates processed by the SSF. This design relied on the SSF to remove iron (Fe), colour and turbidity. After re-pressurizing the water, an anti-scalant was injected as a sequestering agent to keep calcium, magnesium and other inorganic matter in solution to prevent membrane fouling. Finally, the water was processed with a reverse osmosis (RO) membrane to reduce total dissolved solids (TDS) and manganese (Mn). Soda ash was added to buffer aggressive water and chlorine disinfection was included to demonstrate a complete water treatment plant. Additional experiments were conducted using only the anti-scalant for RO pre-treatment for two weeks. Vendor 1 ran pilot challenges for a total duration of nine weeks.

Mistawasis Vendor 2: Chlorine Oxidation, Filtration, Softening and RO

Vendor 2 incorporated a standard oxidation-filtration design for Fe and Mn removal. A chlorine oxidant was used, ahead of a contact/settling tank for the precipitated metals. After settling, water was processed with multi-media depth filtration and carbon filtration. An ion exchange softener was incorporated to reduce membrane fouling hardness ions, ahead of an RO membrane, with chlorine disinfection as the last step. Vendor 2 operated this design for five weeks.

Mistawasis Vendor 3: Chlorine Oxidation, Inclined plate settling, Dissolved Air Flotation, Manganese Greensand Filtration, Softener, Cold Lime Softening, and Reverse Osmosis membrane filtration

Vendor 3 conducted a variety of short term pilot tests to verify numerous processes, including Fe and Mn oxidation using chlorine or potassium permanganate, coagulation with aluminum sulfate or cold lime for turbidity (with the lime also functioning as a softening process), inclined plate settling to remove precipitated matter, aeration using dissolved air flotation, catalytic conversion with four variations of manganese greensand (MnO_2) filters, and ion exchange softening to remove membrane foulants, and reverse osmosis membranes for TDS reduction. While this vendor initially proposed to be on site for 2 weeks, process testing was conducted intermittently over a period of about 7 weeks.

Peepeekisis Vendors

Vendors 1 and 2 essentially used the same designs at the Peepeekisis well as at Mistawasis. Both vendors adjusted their procedures slightly to ensure equipment robustness, and conducted some additional experiments to verify performance. A fourth challenge (for about 8 weeks) was conducted by Vendor 4.

Vendor 4's design was air injection with biological slow sand and re-circulating biological granular activated carbon filters as centralized pre-treatment for Fe, Mn and turbidity reduction. After chlorination for disinfecting distributed water, a household point-of-use reverse osmosis membrane (i.e. for a dedicated kitchen tap) was added to provide small quantities of water with acceptable TDS. Vendor 4 also investigated ozonation (instead of air injection) to improve manganese removal by the biological slow sand and carbon filtration processes.

RESULTS

Even though the pilot challenges were conducted for a relatively short duration, the quantity of data collected is too numerous to report in one publication. This paper focuses on the most main processes tested for the Mistawasis First Nation pilot challenges, with comments on the Peepeekisis results for comparative purposes.

Mistawasis Iron Removal

The longest-performing and most effective pre-treatment process for Fe removal was Vendor 1's aeration and slow sand filtration (Fig. 1a, Ports 1 to 3; operated for 9 weeks). The second most effective was Vendor 3's chlorine oxidation followed by cold lime softening, inclined plate settling (IPS) or dissolved air flotation (DAF), and manganese greensand filtration (Fig 1c, Ports 1 to 6, for tests I and II, 1 day). Both of these processes reduced Fe from 4.0 mg/L to 0.1 mg/L.

Vendor 2's Fe removal by conventional chlorine oxidation followed by settling and filtration was not successful (Fig. 1b Ports 1 to 3.5, 5 weeks). Fe breakthrough occurred past the settling tank, the multi-media depth filter, the carbon filter, and the softener.

All reverse osmosis membranes removed any residual Fe.

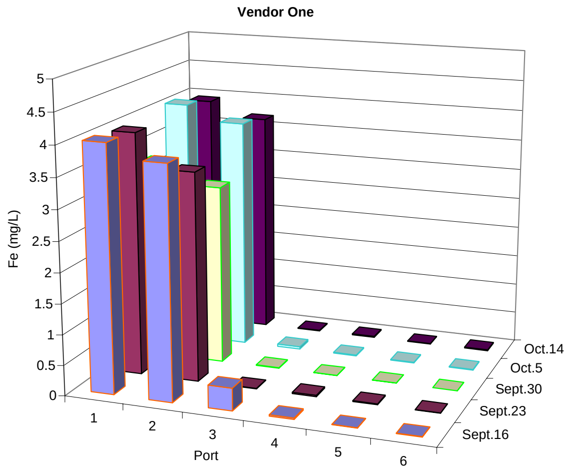
Mistawasis Manganese Removal

The most effective pre-treatment processes for manganese removal was Vendor 3's chlorine oxidation (as NaOCl) plus cold lime softening, IPS or DAF and manganese greensand filtration. Mn was reduced from 0.08 to <0.001 mg/L (Fig. 2c, Tests I and II, 1 day). Dissolved air floatation was more effective than the inclined plate settling tube. Manganese greensand (MnO_2) Filter No 2. performed better than MnO_2 Filter No. 1.

Vendor 2's and 3's softener alone (Fig. 2b Port 4 and Fig 2c, Tests I and II Port 7), and, Vendor 3's chlorine oxidation (as CaOCl) plus IPS or DAF, followed by the manganese greensand filtration (Fig, 2c Tests III and IV), reduced Mn from 0.08 to <0.008 mg/L.

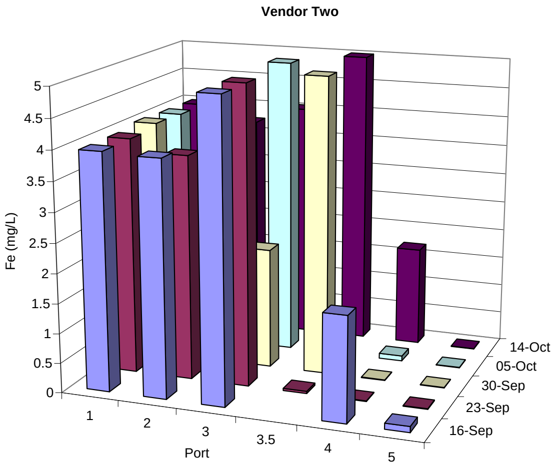
Vendor 2's chlorine oxidation (as NaOCl) plus depth filter and GAC filter (Fig 2b), and Vendor 1's aeration plus slow sand filtration (Fig 2a) were not effective for Mn removal.

All reverse osmosis membranes removed any residual Mn.



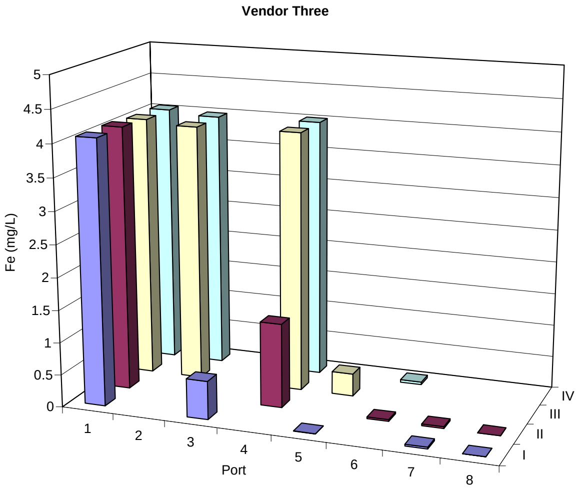
Port	
1	Raw
2	Aeration
3	Slow Sand Filter
4	Gravity GAC Filter
4.	
5	Storage
5	Anti-scalant
6	RO Product

Fig. 1a



Port	
1	Raw
2	Chlorine oxidant
3	Depth Filter
3.5	GAC Filter
4	Softener
5	RO Product

Fig. 1b

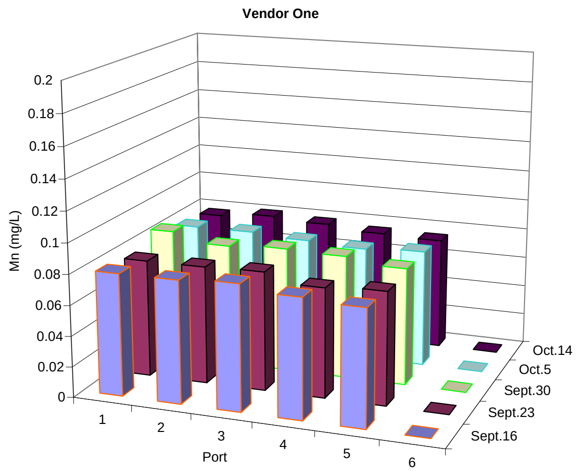


Port	
1	Raw
2	Chlorine (+lime for I&II)
3	Inclined Pipe Settler
4	Dissolved Air Flotation
5	MnO_2 Filter 1
6	MnO_2 Filter 2
7	Softener
8	RO Product

Fig. 1c

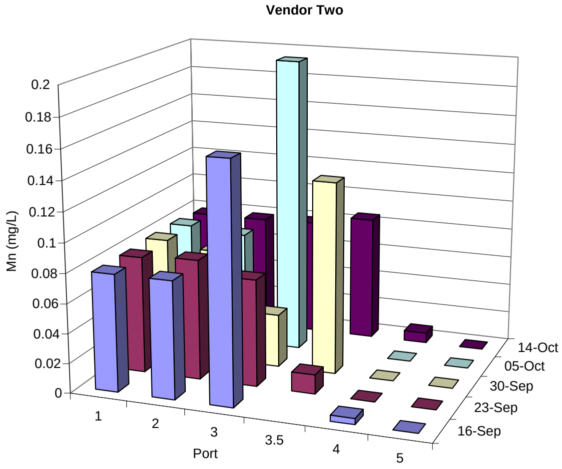
Tests I and II
7ppmNaOCl chlorine+20ppm$Ca(OH)_2$ lime;Oct, 4
Tests III+IV
40ppmCaOCl chlorine; Nov. 4, 2004

Figure 1 – Iron Removal, Mistawasis



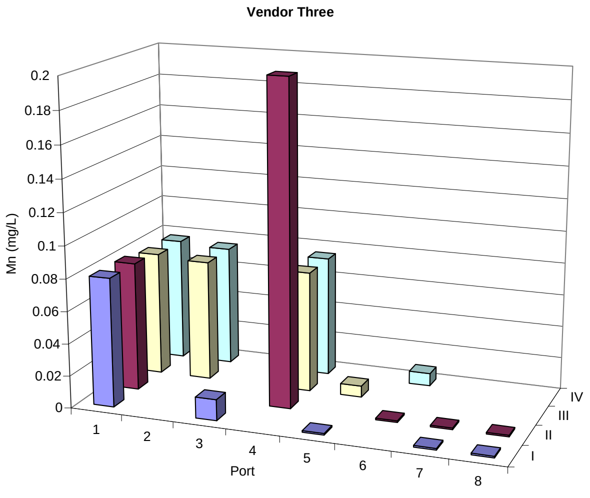
Port	
1	Raw
2	Aeration
3	Slow Sand Filter
4	Gravity GAC Filter
4.	
5	Storage
5	Anti-Scalant
6	RO Product

Fig. 2a



Port	
1	Raw
2	Chlorine
3	Depth Filter
3.5	GAC Filter
4	Softener
5	RO Product

Fig. 2b



Port	
1	Raw
2	Chlorine (+lime for I&II)
3	Inclined Pipe Settler
4	Dissolved Air Flotation
5	MnO_2 Filter 1
6	MnO_2 Filter 2
7	Softener
8	RO Product

Fig. 2c

Tests I and II
7ppmNaOCl chlorine+20ppm$Ca(OH)_2$ lime Oct, 4
Tests III+IV
40ppmCaOCl chlorine, Nov. 4, 2004

Figure 2 – Manganese Removal, Mistawasis

Mistawasis Total Dissolved Solids Removal

Only Vendor 3 was able to reduce the total dissolved solids using a pre-treatment filtration process. After chlorine oxidation, cold lime softening and manganese greensand filtration, Vendor 3 reduced TDS from 638 to 373 mg/L. This process was also effective for reduction of hardness from 437 to 135 mg/L, without increases of sodium concentrations as is caused by ion exchange softeners (Table 2 –Total Dissolved Solids and salts removal).

Table 2 - Total dissolved solids, hardness and sodium (successful results are bolded)

	Raw Water mg/L	**Goal mg/L**	**Vendor 1**		**Vendor 2**	**Vendor 3**	**Vendors 2 & 3**	**Vendors 1, 2 &3**
			Slow Sand Filter	**Post Antiscalant**	**Post Carbon Filter**	**Post chlorine, lime+MnO_2**	**Post Softener**	**Post ROs**
TDS	638	<500	648	623	641	**373**	710	**2**
Hardness	437	<200	424	424	415	**135**	**2**	**2**
Ca	96	-	96	96	94	**18**	**0.3**	**0.3**
Mg	48	0	45	45	44	**38**	**0.2**	**0.2**
Na	59	<200	58	57	72	**82**	270	**1.1**

The ion exchange softeners by Vendors 2 and 3 were effective for reducing hardness (calcium and magnesium) but exchanged the hardness ions for sodium. Sodium increased from 59 to 270 mg/L, a negative impact for people on sodium-restricted diets; in turn, TDS worsened and increased from 638 to 710 mg/L. In each case however, the softener was incorporated as a membrane pre-treatment process to reduce the risk of causing membrane fouling from hardness ions.

The RO membranes provided by all three vendors polished the water to remove virtually all total dissolved solids, hardness, arsenic, sodium and other parameters. Alkalinity was also reduced to under 4 mg/L and pH was reduced to 5.3, reducing the buffering nature of water and increasing the corrosivity of the distributed water The Langlier Index was about Negative 6.5. The vendors expected to adjust the pH of distributed water to cope with this problem.

Mistawasis Turbidity and Particle Size Reduction

Raw water turbidity within five minutes of sample collection ranged from 0.2 to 1.1 nephelometric turbidity units (NTU). When tested at an analytical laboratory 24 hours or more after sampling, turbidity was consistently about 50 NTU. Particle size analyses were also conducted more than 24 hours after the sample was collected. Figure 3a to c shows the total particle count for all particles in size range from 1 to 16 micrometers. The most consistent turbidity and particle size reduction occurred with aeration plus slow sand filtration (Fig 3a), and, with chlorine oxidation plus cold lime softening plus MnO_2 Filter 2 (Fig 3c, Test II). Polishing ion exchange softeners were also effective (Fig. 3b, Port 4, and Fig. 3c, Port 7). Turbidity was reduced from 50 to <0.5 NTU and Total Particle Count 1 to 16 µm was reduced from about 250,000 (and up to 440,000) to <600 particles.

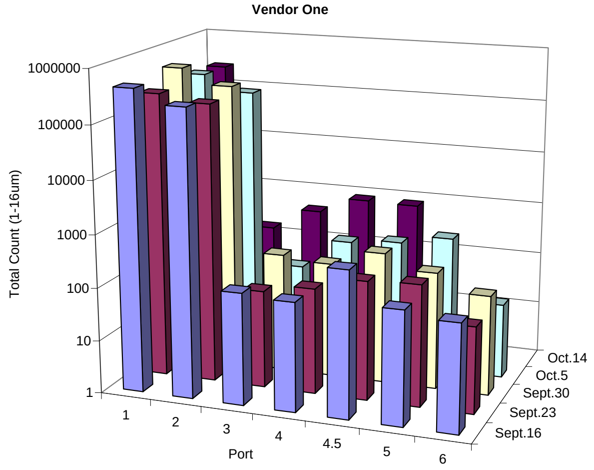


Fig. 3a

Port	
1	Raw
2	Aeration
3	Slow Sand Filter
4	Gravity GAC Filter
4.5	Storage
5	Anti-scalant
6	RO Product

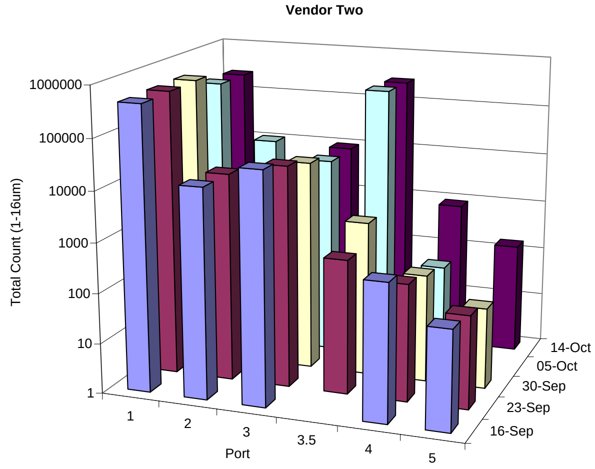


Fig. 3b

Port	
1	Raw
2	Chlorine
3	Depth Filter
3.5	GAC Filter
4	Softener
5	RO Product

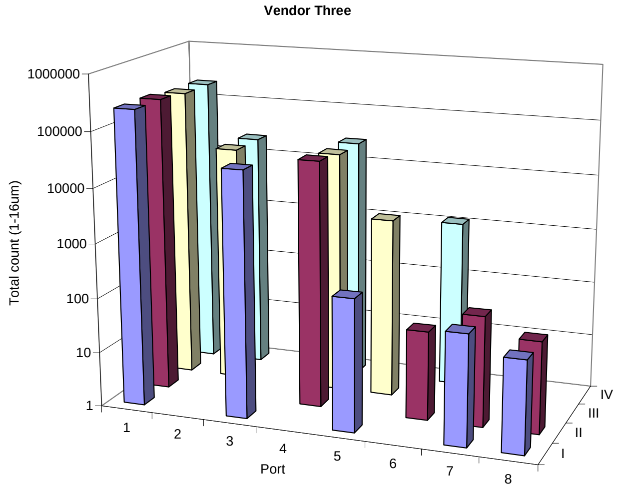


Fig. 3c

Port	
1	Raw
2	Chlorine (+lime for I&II)
3	Inclined Pipe Settler
4	Dissolved Air Flotation
5	MnO_2 Filter 1
6	MnO_2 Filter 2
7	Softener
8	RO Product

Tests I and II
7ppmNaOCl chlorine+20ppmCa$(OH)_2$ lime Oct, 4
Tests III+IV
40ppmCaOCl chlorine, Nov. 4, 2004

Figure 3 – Total Particle Count Reduction (1-16µm), Mistawasis

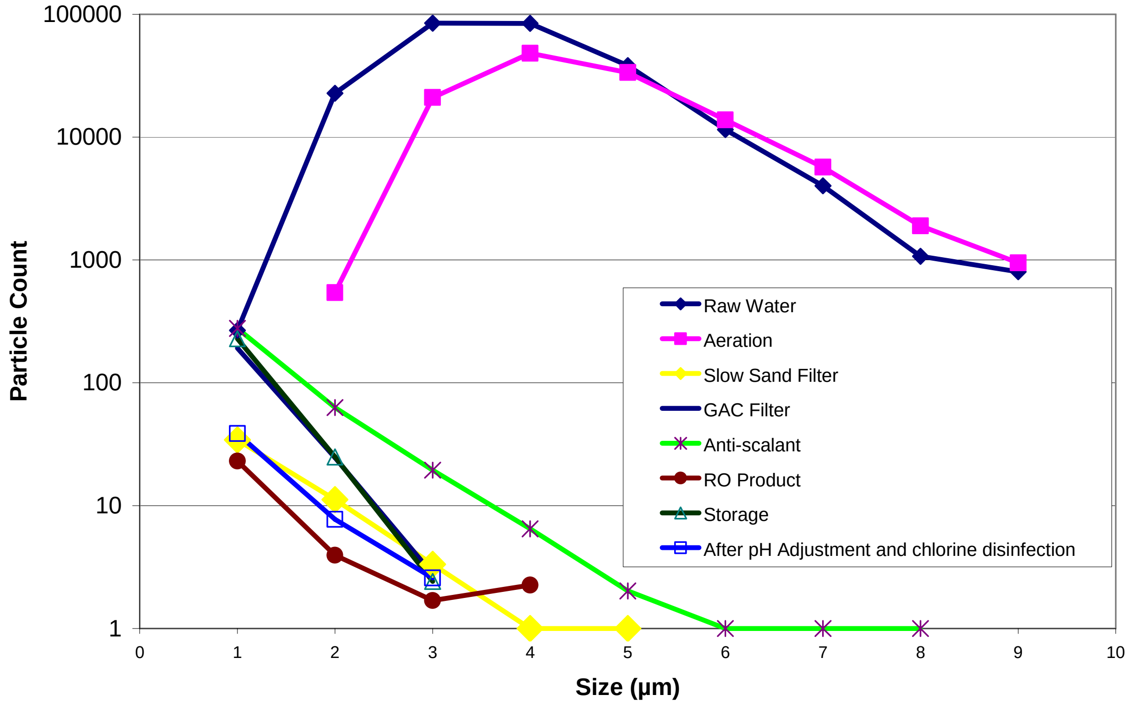


Fig. 4a - Vendor 1 Oct. 5

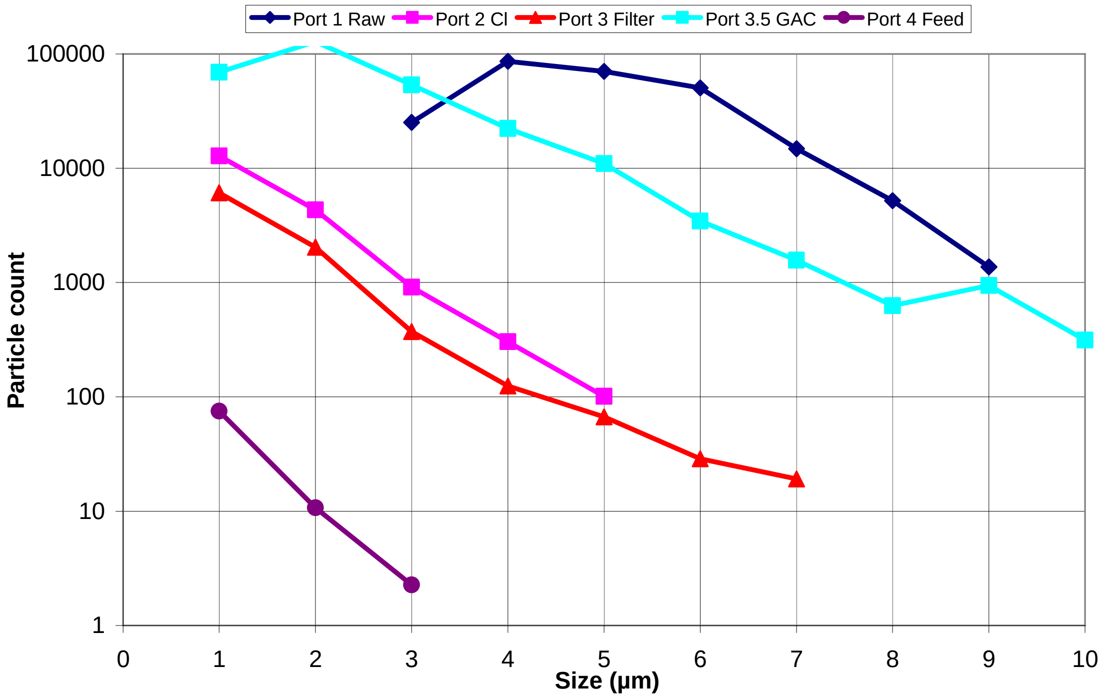


Fig. 4b - Vendor 2 Oct.5

Figure 4 – Particle Size Distribution Breakdown, Mistawasis

Particle Size Distribution Breakdown for October 5, 2004 is shown for Vendor 1 (Fig.4a) and Vendor 2 (Fig. 4b). The raw water particle count distribution ranged in size from 3 µm to 9 µm. For Vendor 1, the raw water had 85,000 particles of 3 µm and 84,000 particles of 4 µm size. For Vendor 2, the raw water had 86,000 particles of 4µm size and 70,000 particles of 5µm size. These counts were measured after 24 hours of sampling, and indicate a colloidal particle distribution.

Figure 4a shows that aeration treatment created marginally larger-sized particles: the distribution curve after aeration had a reduced total particle count and a shift to the right (i.e. larger particles). After the slow sand filter, the total particle size count was significantly lower: under 60 particles ranging from 1 µm to 6 µm in size. The anti-scalant caused a marginal increase in total particle count and a wider distribution range.

Figure 4b shows that chlorine oxidation was not able to form larger particles for settling and filtration. Immediately after chorine oxidation, the total particle count was reduced and distributed over a range of 1 µm to 5 µm. Further reductions occurred after the Depth Filter (Port 3). However, after the GAC Filter (Port 3.5), a large breakthrough of small particles was measured: about 290,000 particles in total were counted, ranging from 1 µm to 10 µm in size. Of these, about 285,000 were under 5µm and about 200,000 particles were under 2µm in size. Significant particle reduction was measured after the softener (Port 4 Feed), with total particle count at about 100, ranging from 1µm to 3 µm.

Peepeekisis results

The Peepeekisis results are not reported in detail. However, several highlights are noted:

- Vendor 1's slow sand filtration process was effective in reducing Fe.
- Vendor 2's chlorine oxidation/filtration/softening processes were effective in reducing Fe, Mn, turbidity and particle count (in contrast to Mistawasis water)
- Vendor 4's biological sand and carbon filter was effective for Fe, turbidity and particle count reduction but not for Mn reduction. Ozonation pre-treatment was required for Mn reduction.
- All vendors achieved successful reduction in TDS and associated minerals with reverse osmosis polishing membranes. (Vendor 1 also relied on RO membranes to reduce Mn concentrations).

Biological Activity Reaction Tests BART™ and Dissolved Organic Carbon (DOC)

The raw and treated ground water samples for Mistawasis and Peepeekisis pilot challenges were tested for BARTs and DOC. BART testing revealed the following non-pathogenic bacteria in the raw water and/or throughout the treatment processes:

- Iron-related bacteria (IRB) – high aggressivity for Mistawasis, primarily anaerobic
- Slime-forming bacteria (SLYM) – high aggressivity for Mistawasis
- Sulfate-reducing bacteria (SRB) – low to medium aggressivity for Mistawasis
- Heterotrophic Aerobic Bacteria (HAB) medium aggressivity for Mistawasis

Dissolved organic carbon for both of these relatively deep wells ranged from 4 to 5 mg/L, and was reduced only by the reverse osmosis and nanofiltration membranes.

DISCUSSION

The raw water quality problems at Mistawasis and Peepeekisis First Nations are very common problems in Saskatchewan. Over 99% of raw water wells exceed either an aesthetic or health-related water quality guideline. A survey of wells identified health parameters exceeded guidelines for selected parameters as follows: 33% of wells for total coliforms, 14% for nitrate, 8% for arsenic, and 11% for selenium (Sketchell and Shaheen, 2001). In this survey; aesthetic guidelines for selected parameters were exceeded as follows: 45% of wells for iron, 71% of wells for manganese, 88% of wells for a hardness of 200 mg/L, and an estimated 90% of wells for TDS above 500 mg/L. Most of these problems are likely due to the natural characteristics of Saskatchewan's highly mineralized ground water aquifers. These problems are confronted by First Nations populations and all citizens reliant on private water wells, such as agricultural producers, acreage and cottage owners, and the rural population in general.

Vendor 1's slow sand filter was very robust in achieving consistent removal of iron, but experienced a relatively short run length prior to plugging and backwashing maintenance. Modifications were made to improve the settling prior to filtration. During a typical run length, the actual filter flow rate was about 83 Lph, or 35% of the rated capacity of 240 Lph. The rated filtration rate was not achievable and a full plant design of 10 Lpm would therefore require a larger surface area than originally anticipated.

Vendor 2's chlorine oxidation, settling, filtration and softening was not effective for Fe and Mn removal. In theory, the oxidant should create particles large enough for settling and trapping by the subsequent depth filter and polishing by the carbon filter. The breakthrough of Fe and Mn particles may be due to a variety of potential causes:

- water withdrawal from sampling ports may have increased flow rates excessively, riling up the trapped particles, and causing breakthrough (although breakthrough continued to occur even when water was sampled at slower withdrawal rates)
- the chlorine oxidant dose may not have been optimal (e.g. too low or too high, possibly causing variable particle oxidation formation and effectiveness)
- the effective diameter of filter media (0.65mm) may have been unable to trap the large quantities of colloidal iron (generally ranging from 2 µm to 6 µm).
- filter flow rate, oxidant contact time and pH adjustments may have been required
- other unknown factors

By inference from the data (Fe, Mn, turbidity, particle size distribution, colour), the bulk of the oxidized particles were largely Fe particles (with some Mn), particularly after oxidation with aeration and/or chlorine. As previously noted, the chlorine oxidation formed colloidal particles in the size range of 2 to 6 µm. This would be very difficult for removal by pressure filters, which are generally designed to removal particles larger than 10µm in size. Vendor 2's pressure filter had a pilot filtration rate of about 3.4 m/hr or higher, with an effective grain size of 0.65 mm. dia. The gravity filters of Vendors 1 and 3 used an effective grain size of 0.3 mm dia. or less, and achieved better removal of Fe, turbidity and colloidal particles. The typical 7 day filter run for the slow sand filter had an estimated average filtration rate of about 0.3 to 1.0 m/hr. The slow sand filter required manual scarification of the surface layer to recover filter productivity after plugging reduced the flow rate an excessive amount. While effective for Fe and particle removal, slow sand filtration requires a larger filtration surface area, and therefore a larger floor space for the water treatment plant building.

Chlorine oxidation in combination with cold lime softening was successful in achieving reductions of Fe, turbidity and total particle counts (Vendor 3 Tests I and II). The success of this option was likely due to the lime functioning as a coagulant, causing the colloidal iron to form larger clumps of particles (in essence, a floc). The floc (larger clumps of Fe particles) would settle, and be filtered, more readily. Even so, the subsequent filters required proper design. The gravity manganese greensand (MnO_2) filters performed better when the bed depth was greater (900 vs. 750 mm) and the media grain size was smaller (effective grain size diameter of 3 mm vs 5 mm).

For Mn removal, it was apparent that aeration and/or chlorine oxidation were not effective oxidants. Ion exchange filtration with softeners (exchanging Na for Ca, Mg, Mn, and other ions) was generally effective for Mn reduction. Catalytic conversion with MnO_2 filters was also generally effective with properly-designed media grain size and depth, contact time and high pH levels.

Mn removal was clearly enhanced at higher pH levels (this is also supported in the scientific literature). The incorporation of cold lime softening raised the pH to about 10 and would have improved Mn removal by the MnO_2 filters. Furthermore, an additional benefit of the cold lime softening was the reduction of TDS and hardness to 370 mg/L and 135 mg/L respectively. The net effect of adding cold lime softening allowed chlorine oxidation and MnO_2 filtration, to be highly successful in reducing the combined problems of Fe, Mn, TDS, and hardness, without any need for membrane polishing treatment.

Membrane filtration using reverse osmosis or nanofiltration membranes was successful for residual removal of Fe, Mn, TDS and other water parameters. The concerns with membranes are long-term performance and wastewater disposal. If pre-treatment is not adequate, membranes will foul, and require frequent cleaning and replacement. In addition, membranes will only process a percentage of water - about 20 to 50% of the membrane feedwater must be wasted as a membrane concentrate. The disposal of membrane concentrate must be done safely to ensure the environment is not impacted. Membrane concentrate disposal facilities (e.g. evaporation ponds) are sometimes required to trap the salts, and can significantly impact water treatment costs.

The biological BART tests and the DOC concentrations indicate that the raw water may be problematic to treat. The raw water contained iron bacteria, slime-forming bacteria, sulfate reducing bacteria and heterotrophic aerobic bacteria, and had DOC concentrations of about 4 to 5 mg/L. These natural characteristics will impair treatment processes such as oxidation, filtration and disinfection. DOC concentrations above 2 mg/L are recognized as a problem for Fe and Mn removal, as organic binding of the minerals with the DOC may impair and reduce process effectiveness and performance. Furthermore, DOC will react with chlorine to form disinfection by-products such as trihalomethanes.

CONCLUSIONS AND RECOMMENDATIONS

Each of the vendor designs to deal with the common problems of iron, manganese, and TDS were distinct and quite elaborate for such small systems. The vendors were posed with difficult challenges at both Mistawasis and Peepeekisis. Initially, the Mistawasis water was deemed to be "easy" to treat, but very soon into each challenge, problems were encountered with the colloidal nature of the oxidized Fe.

Principle conclusions from this project include:

1. Aeration with biological slow sand filtration was a simple, robust and consistent technology for Fe removal. Mn and TDS removal required membrane polishing treatment. Slow sand filter flow rates were 35% of rated capacity for Mistawasis.
2. Chlorine oxidation required the addition of cold lime softening in front of properly-designed manganese greensand filters, for effective Fe removal. The lime formed a floc for more effective removal of colloidal Fe. The lime also raised the pH to 10 for effective Mn removal by the manganese greensand filters.
3. Dissolved air flotation after the chlorine oxidation and lime softening, was more effective than inclined plate settling and lime softening.
4. Manganese greensand filters required an effective grain size of 0.3 mm dia. and a bed depth of at least 900 mm for Fe and Mn removal.
5. Pressure filters (with effective grain size of 0.55-0.65 mm dia.) and ion exchange softeners were not able to prevent Fe breakthrough when used in combination with chlorine oxidation at Mistawasis; in contrast, these filters were effective at Peepeekisis.
6. At Peepeekisis, air injected biological slow sand filters and re-circulating biological carbon filters were effective for removal of Fe. However, to remove Mn, these biological filters required ozonation pre-treatment instead of aeration.
7. Reverse osmosis and nanofiltration membranes were effective as a polishing treatment to reduce TDS and other minerals. However, pre-treatment must be adequate to prevent fouling. The product water also requires pH adjustment to prevent the distribution of corrosive water. Furthermore; the membrane concentrate water must be managed and properly disposed to prevent environmental contamination problems from occurring.

Designing micro-systems is particularly challenging because of the very low flow rates. Not all treatment technologies are suitable for down-scaling. The participating vendors were creative when designing their systems to suit micro-applications. Biological filtration with aeration and biological sand and carbon filtration are particularly suited to micro-systems. Pressure filtration systems are also suitable but may have limitations depending on the water characteristics. Reducing pressure filter flow rates and filter media effective grain size may be beneficial for different types of source water. One vendor was successful in down-scaling dissolved air floatation and cold lime softening to a lower threshold level of 10 L/min. This approach may have potential applications for water that is marginally high in TDS (likely up to 1000mg/L) because it can simplify the design, and eliminate the need for polishing treatment by membranes (and associated environmental concerns with membrane concentrate disposal).

After the pilot tests, the vendors' cost estimates for full-plant design were similar. For Mistawasis, the capital cost of a 10 Lpm water treatment plant was estimated to be about \$83,000; serving 15 houses, this is about \$5,500 per household, or a unit cost of about \$4.00/m^3 of treated water. For Peepeekisis, a 3 Lpm water treatment plant was estimated at about \$50,000; serving 4 houses, this totals about \$12,500 per household at a unit cost of about \$11.00/m^3 of treated water. These costs are more expensive than centralized water treatment plants which serve a much larger population base.

A variety of benefits resulted from these micro-system pilot challenges. Theses pilots provided:

- an increased understanding of treatment process effectiveness for two water types,
- a better understanding of capital and operational costs for micro-systems,
- an increased capacity of vendors to deal with problematic water supplies,
- potential for improved vendor design approaches for a variety of technologies (for both small and large-scale systems), and,
- increased possibilities for micro-system applications at other sites for First Nations and rural agri-food sector sites.

The knowledge learned from this project will be transferable to other systems of similar scale. Some of the knowledge will also be beneficial for larger-scale systems. There continues to be a need for applied research projects investigating solutions to the water treatment needs of small rural water treatment systems, such as those required by First Nations and the agri-food sector.

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