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Pilot Testing Project Report

Reduction of Arsenic in a Small Drinking Water System

Walkerton Clean Water Centre

May 21, 2020

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Executive Summary

Background

A village located in Southwestern Ontario has a population of less than 500 people and uses groundwater wells as its raw water source. The system consisted of two drilled wells; however, one was abandoned in 2012 due to high arsenic levels (> 25 µg/L) while the remaining has arsenic levels often higher than 10 µg/L. The water is being dosed with an iron sequestration chemical (sodium silicate) to bind soluble iron followed by chlorination for primary and secondary disinfection before it is pumped into the distribution system.

Arsenic levels in the well vary from 8.6 to 12.4 µg/L, with an average concentration of 10.6 µg/L during the 2018 sampling period. The current maximum acceptable concentration (MAC) for arsenic in Ontario is 10 µg/L (MOECC, 2018). The groundwater also contains iron levels of approximately 0.7 mg/L based on the available raw water quality data. As per Ontario's aesthetic objective (AO), iron should be ≤ 0.3 mg/L (MOECC, 2006).

Objective

The objectives of pilot testing were:

1) To reduce arsenic to less than 5 µg/L in the finished water
2) To reduce iron to less than 0.3 mg/L in the finished water

Approach

Jar Testing was conducted on-site to find optimum doses of chlorine and ferric chloride to oxidize and reduce the arsenic concentration. Based on jar testing results, pilot test experiments were planned on-site. Pilot tests were performed to assess a variety of cartridge filters and contact times to find the optimal set up for reducing arsenic with the optimal dosing found through jar testing.

Key Findings

Through both jar and pilot testing, it was determined that:

- Chlorine dosed at 4 mg/L was able to reduce the arsenic concentration to 2.4 µg/L and iron to 0.04 mg/L. was comparable to the chlorine dose of 4.2-4.3 mg/L that was in use by the Village.
- Jar Test 2 showed that filtered arsenic levels responded positively to the dose of ferric chloride. When 5 mg/L of ferric chloride was added, filtered arsenic concentrations were dramatically reduced to 0.25 µg/L. All filtered iron levels were less than 0.02 mg/L.
- When on-site pilot testing was conducted with a contact tank followed by 50-5 µm depth filter, a 1 and 0.35 µm nominal pleated cartridge filters, the average arsenic concentration was ≤ 3.7 µg/L. Most of the cartridge filter effluents measured less than 0.02 mg/L of iron.
- When the contact tank was removed with the same cartridge filter setup (Experiment 4 & 5), the arsenic level was reduced to 3.5 µg/L in treated water. There was no significant change in treatment performance with or without the contact tank with regards to the finished arsenic and iron concentration.
- When a coarser set of filters (75-25 µm depth filter, 5 and 1 µm pleated cartridge filters) was used, arsenic levels were reduced to 5.6 µg/L. This level is less than the Ontario Standard but is higher than the objective set for pilot testing. Iron was reduced to 0.05 mg/L.

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1. Introduction

A village located in Southwestern Ontario has a population of less than 500 people. The village uses groundwater as a raw water source. Their system consists of two drilled wells; Well 1 and Well 2. Well 1 was abandoned in 2012 due to high arsenic levels (> 25 µg/L) while the remaining has arsenic levels often higher than 10 µg/L. The system involves dosing an iron sequestration chemical (sodium silicate) to bind soluble iron followed by chlorination for primary and secondary disinfection before water is pumped into the distribution system.

As arsenic is a known carcinogen, it is regulated in the Province of Ontario to a maximum allowable concentration (MAC) of 10 µg/L. Arsenic levels in Well 2 vary from 8.6 to 12.4 µg/L, with an average concentration of 10.6 µg/L based on the 2018 sampling period. The current MAC for arsenic was introduced on January 1st, 2018, and was reduced from the previous value of 25 µg/L (MOECC, 2018). As a result, Well 2 may or may not remain in compliance as arsenic vary throughout the year.

The groundwater supply also contains iron levels of approximately 0.7 mg/L based on the available raw water quality data. Iron is commonly present in groundwater as a result of mineral deposits and chemically reducing underground conditions. As per Ontario's aesthetic objective (AO), iron concentrations should be equal to or less than 0.3 mg/L (MOECC, 2006). Excessive levels of iron may impart colour to water and fixtures, impart bitter tastes, and promote the growth of iron bacteria in pipes.

Ion exchange systems are a common technology implemented for the removal of arsenic from drinking water. This method of treatment was not selected for this project because ion exchange systems produce a liquid waste that requires disposal. The village does not have a sewer system for the disposal of generated waste and the costs associated with the implementation of this technology would be quite significant. The liquid waste would need to be properly handled, treated, and stored, all while following proper environmental policies and procedures for effective implementation (MOECC, 2011).

Another treatment strategy for the removal of arsenic from drinking water involves chlorination followed by filtration. A report published by the Water Research Foundation demonstrated that this approach can be both effective and economical for the reduction of arsenic concentrations to less than 10 µg/L. This process is enhanced by the iron available in the water which is being oxidized like arsenic to a form that can be filtered out (Chowdhury et al., 2002).

Adsorptive media contained in cartridges have also shown to be an effective method for arsenic reduction. In this method, cartridge (micro) filters fouled by arsenic and iron are easy to dispose of due to their reduced volume and solid hazardous waste containment in comparison to liquid waste disposal methods for technologies that require backwashing. However, the adsorptive media technology may have higher capital and operating costs than that of oxidation followed by filtration. The objective of this pilot testing project was to explore treatment options that can be considered by the village based on their site-specific requirements. Specific water quality objectives were:

1. To reduce the arsenic concentration to less than 5 µg/L in the finished water.
2. To reduce the iron concentration to less than 0.3 mg/L in the finished water.

2. Materials and Method

2.1 Jar Testing Conditions

Two jar tests were conducted on-site:

- Jar Test 1 was conducted to find an optimum dose of chlorine to oxidize arsenic.

- Jar Test 2 was conducted, using the optimum chlorine dose from Jar Test 1, to find an optimum dose of ferric chloride to reduce arsenic.

Jar testing conditions are described in Table 1 and Table 2 below.

Table 1. Jar Test 1 Conditions

	Jar Conditions					
Jar	1	2	3	4	5	6
Chlorine Dose (mg/L)	1	2	3	4	5	6
Stage 1:	Rapid Mixing: 100 RPM for 1 minute					
Stage 2:	Flocculation: 20 RPM for 15 minutes					
Stage 3:	Settling: 0 RPM for 30 minutes					
Stage 4:	Blank: 0 RPM for 0 minutes					

Table 2. Jar Test 2 Conditions

	Jar Conditions					
Jar	1	2	3	4	5	6
Chlorine Dose (mg/L)	4					
Ferric Chloride Dose (mg/L)	0	0.25	0.50	0.75	1.0	5.0
Stage 1:	Rapid Mixing: 100 RPM for 1 minute					
Stage 2:	Flocculation: 20 RPM for 15 minutes					
Stage 3:	Settling: 0 RPM for 30 minutes					
Stage 4:	Blank: 0 RPM for 0 minutes					

Note: The chlorine dose (mg/L) was determined during Jar Test 1.

2.2 Pilot Plant Design

Based on the jar test results, pilot testing was designed and planned to be conducted on-site. The pilot plant set-up is presented in Figure 1.

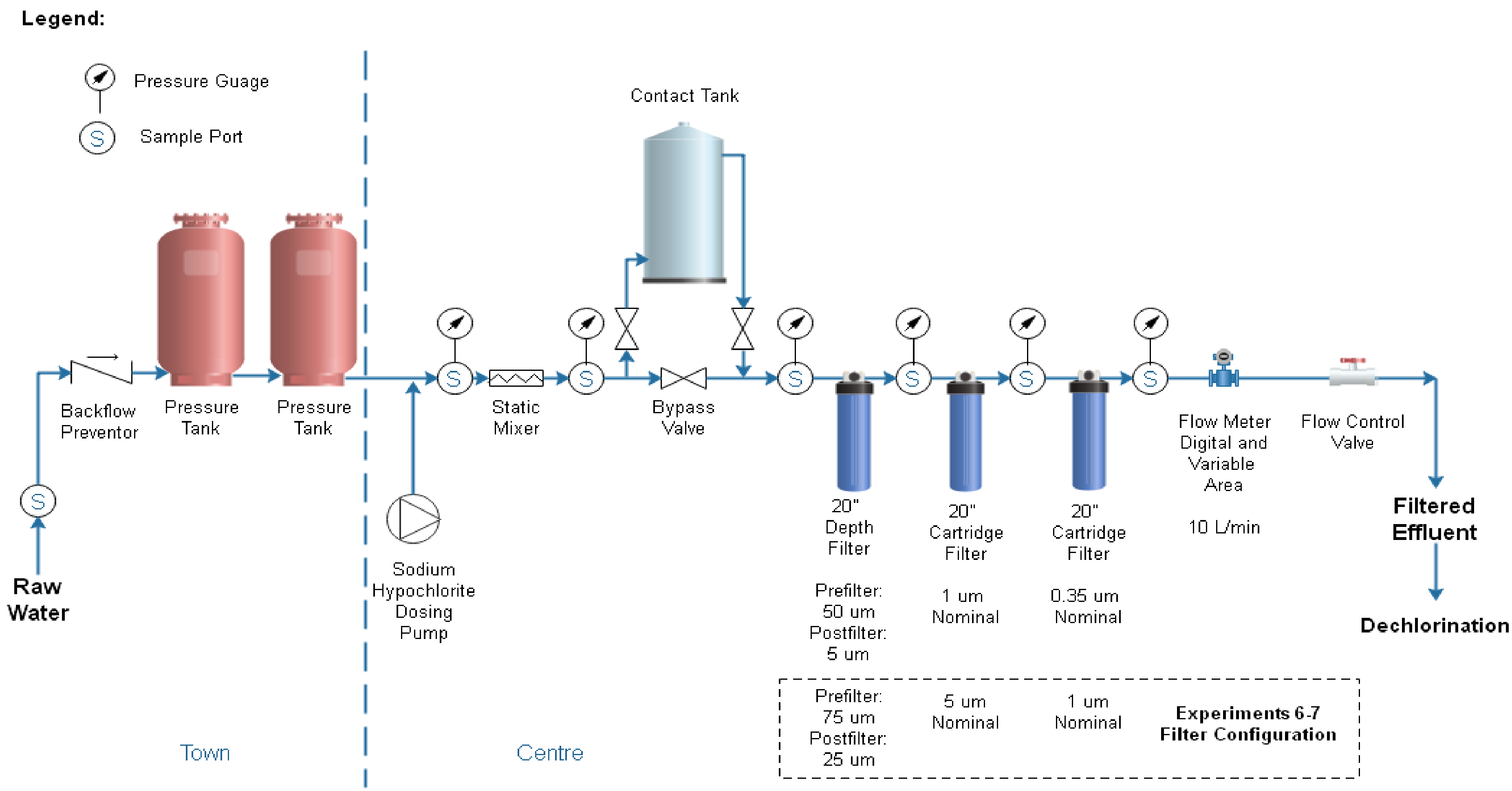

Figure 1. Schematic of Pilot Installation

The pilot set-up was installed, commissioned, and checked for leaks. Different flow tests were conducted to ensure the drinking water system could support the pilot operation in terms of providing constant and uninterrupted flow. It was determined that the drinking water system could support a maximum flow rate of 10 L/min.

Experiments 1-3 were conducted using a contact tank followed by a series of cartridge filters in decreasing pore size including a 50-5 µm depth cartridge filter, and 1 µm and 0.35 µm pleated nominal cartridge filters . Experiments 4 and 5 were conducted similarly but bypassed the contact tank to verify if the tank was required to achieve the same results. Experiments 6 and 7 were conducted using a series of larger pore sized filters to see if they would still be effective including a 75-25 µm depth cartridge filter and 5 µm and 1 µm pleated nominal cartridge filters without the contact tank. Table 3 summarizes these details below.

Table 3. Pilot Set-Up for Experiments

Experiments	Treatment units in Sequence
Experiments 1-3	• Contact tank in use • 50-5 µm depth cartridge filter • 1 µm pleated nominal cartridge filter • 0.35 µm pleated nominal cartridge filter
Experiments 4-5	• Contact tank bypassed • 50-5 µm depth cartridge filter • 1 µm pleated nominal cartridge filter • 0.35 µm pleated nominal cartridge filter
Experiments 6-7	• Contact tank bypassed • 75-25 µm depth cartridge filter • 5 µm pleated nominal cartridge filter • 1 µm pleated nominal cartridge filter

2.3 Water Quality Analysis

Grab samples were collected from each jar after the sedimentation stage and analyzed. Arsenic and iron analyses were conducted on both filtered and unfiltered samples. Samples were sent to an external accredited laboratory for analysis to obtain insight about oxidized, non-oxidized and total arsenic concentrations. Analysis for general water quality parameters such as turbidity, free chlorine and iron were conducted on-site and at the Walkerton Clean Water Centre laboratory.

During pilot testing, parameters such as turbidity, pH, alkalinity, colour (true and apparent), UV absorbance at 254 nm, dissolved organic carbon (DOC), chlorine, iron, and fluoride were analyzed in-house. Samples for arsenic were sent to the external lab for analysis. A summary of water quality parameters tested is summarized in Table 4.

Table 4. Methods of Water Quality Analysis

Parameter	Preparation	Method	Range
In-House Analysis			
Turbidity	N/A	USEPA Method 180.1	0 – 1000 NTU
Chlorine (free and total)	N/A	USEPA DPD Method	0.02 – 2.00 mg/L
Iron (total/dissolved)	Dissolved - 0.45 µm filtered	Hach Method 8008	0 – 3.00 mg/L
pH	N/A	Hach Method 8156	0 – 14
True/Apparent colour (unfiltered)	True colour – 0.45 µm filtered	Hach Method 8025 Platinum-Cobalt Standard Method	5 – 500 Pt-Co
UV_{254} absorbance	0.45 µm filtered	Real Tech UV_{254} Method	0 – 2 Abs/cm
Dissolved organic carbon	0.45 µm filtered	Standard Method 5310C UV/persulfate oxidation with conductometric detection	4 ppb to 50 ppm
Alkalinity	N/A	Hach Method 8203 Phenolphthalein and Total Alkalinity	10 – 4000 mg/L $CaCO_3$
Fluoride	N/A	Hach Method 8323 Direct Measurement	0.1 – 10.0 mg/L

Parameter	Preparation	Method	Detection Limit
Analyzed at a Licensed Laboratory			
Arsenic (total/dissolved)	Dissolved - 0.45 µm filtered	Standard Method 3030 /USEPA 200.8	Method Detection Limit: 0.00010 mg/L

3. Results and Discussions

3.1 Jar Test 1

Jar Test 1 was conducted on-site on March 28, 2019. The optimum chlorine dose required to oxidize the arsenic was determined from the results obtained from the accredited lab, along with the results from the general water quality analysis. The optimum chlorine dose determined was then used for Jar Test 2 and the on-site pilot experiments.

3.1.1 Arsenic

Figure 2 shows the various levels of arsenic observed during Jar Test 1. Total and dissolved arsenic levels of the raw water were 10.9 and 10.3 µg/L, respectively. Most of the arsenic was found to be in dissolved form, which is defined here as smaller than 0.45 µm particle size, and was determined through use of filtering with a 0.45 µm membrane filter paper (APHA et al, 2012). Chlorine dosages ranging from 2 to 7 mg/L were tested. Total arsenic levels in the treated water were 10.3 to 10.8 µg/L in all jars. Although chlorine oxidizes arsenic, the total arsenic concentration does not change. However, when the samples were filtered, dissolved arsenic levels were dramatically lowered to 2.05 – 2.63 µg/L, which was lower than the target objective of 5 µg/L. These results indicate that a process using oxidation by chlorine followed by filtration may be effective on a larger scale. The optimized chlorine dose was determined to be 4 mg/L because filtered arsenic was at its lowest relative level. This was achievable for the system, as they were already dosing approximately 4.2 - 4.3 mg/L of chlorine to meet their primary and secondary disinfection targets.

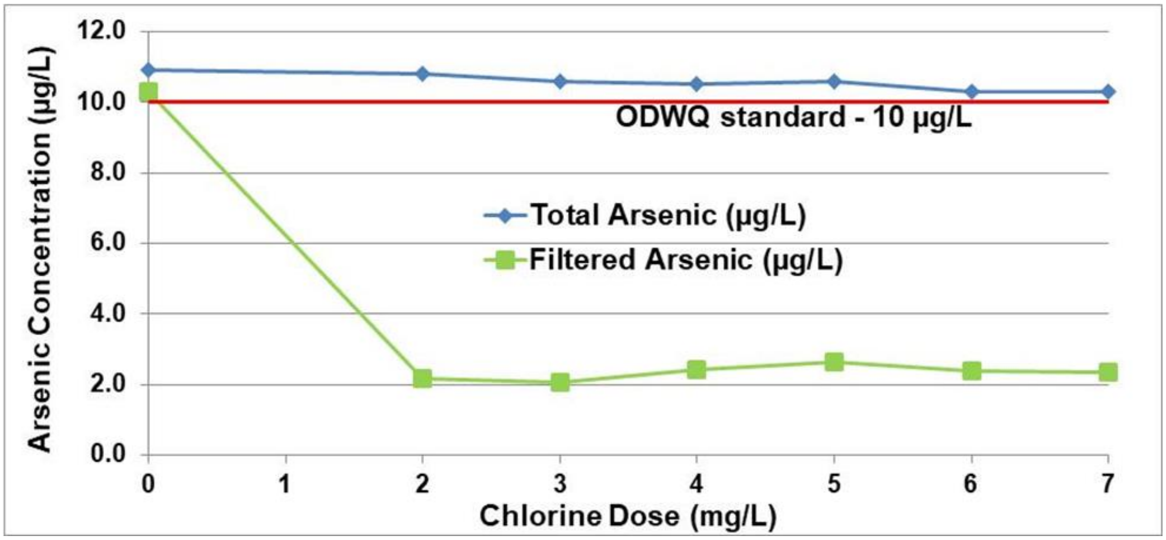

Figure 2. Arsenic Levels During Jar Test 1

3.1.2 Iron

The total iron level measured in the raw water was 0.76 mg/L. Most of the iron was in dissolved form, which was measured at 0.56 mg/L after the sample had been filtered. Total iron levels were 0.66 - 0.75 mg/L after adding chlorine which was similar to the total raw water iron level; however, when the samples were filtered, the iron level dropped significantly to 0.03 - 0.04 mg/L, which is lower than the 0.30 mg/L AO (MOECC, 2006). This result shows that most of the iron was converted to a non-soluble form by chlorine oxidation allowing its removal by filtration.

3.2 Jar Test 2

Jar Test 2 was conducted to confirm if the addition of ferric chloride to the chlorinated water would enhance the reduction of arsenic.

3.2.1 Arsenic

Figure 2 presents the total and dissolved arsenic levels as increasing amounts of ferric chloride are dosed following chlorination.

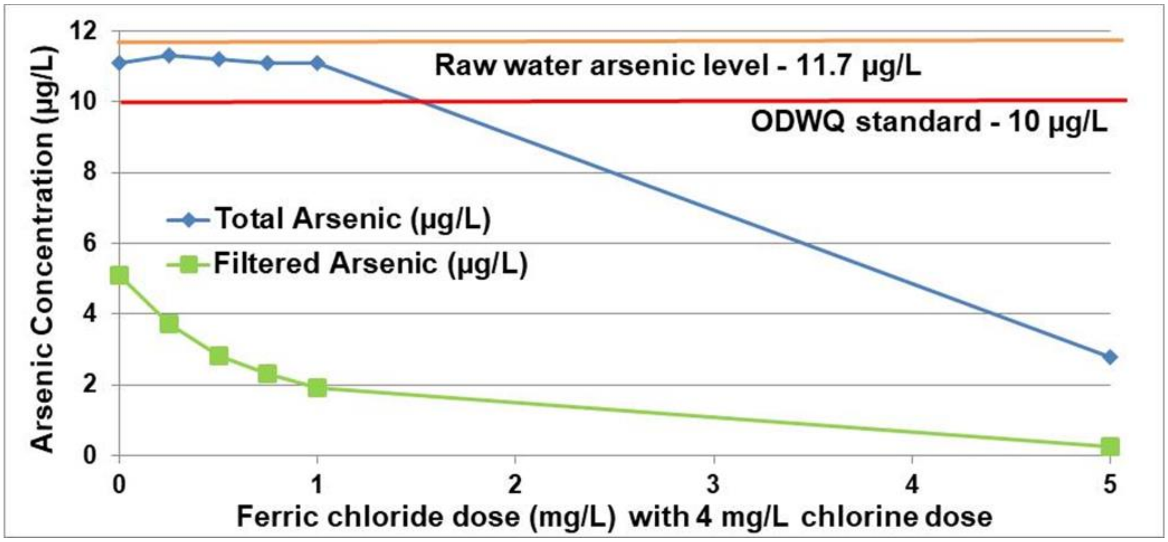

Figure 3. Arsenic Levels During Jar Test 2

The total arsenic level of the raw water during Jar Test 2 was 11.7 µg/L, which was higher than what was found during Jar Test 1 (10.9 µg/L), demonstrating that the arsenic level fluctuates over time. When a 4 mg/L dose of chlorine was added, the total arsenic level dropped to 11.1 µg/L. The total arsenic levels ranged from 11.1 - 11.3 µg/L when 0.25 - 1.00 mg/L of ferric chloride was added. The total arsenic level dropped to 2.76 µg/L when 5 mg/L ferric chloride was added to the water. In short, total arsenic levels were reduced proportionally as more ferric chloride was added, likely due to the arsenic adsorption to iron floc and co-precipitation (US EPA, 2019).

The filtered raw water had 11.3 µg/L of arsenic, which indicates that most of the arsenic was in the dissolved arsenite (III) form. When 4 mg/L chlorine was added to the raw water, the dissolved arsenic level was 5.09 µg/L, a 54% reduction, compared to total arsenic in the raw water. In Jar Test 1, the dissolved arsenic level was 77% of the total arsenic in the sample. When 0.25 to 1.0 mg/L of ferric chloride was added, dissolved arsenic linearly decreased from 3.71 to 1.91 µg/L. When a 5 mg/L dose of ferric chloride was added, the dissolved arsenic remaining was 0.25 µg/L. Overall, the dissolved arsenic levels were reduced with increasing doses of ferric chloride.

3.2.2 Iron

The total iron level in raw water was 0.72 mg/L which was slightly lower than the level measured in Jar Test 1 (0.76 mg/L). However, the dissolved iron was higher at 0.66 mg/L in Jar Test 2 compared to 0.56 mg/L in Jar Test 1. Total iron in the treated water increased as ferric chloride dose increased up to the dose of 1 mg/L. When 5 mg/L of ferric chloride was dosed though, the total iron level was reduced to 0.73 mg/L. It should be noted that all filtered samples had iron levels less than the 0.02 mg/L detection limit of indicating the majority of iron was insoluble and was being removed by filtration.

3.3 Pilot Testing Experiments 1-3

Experiments 1-3 conducted on-site tested a contact tank with 50-5 µm depth cartridge filter followed by a 1 µm and a 0.35 µm nominal pleated cartridge filter.

3.3.1 Arsenic

Arsenic levels in the raw water varied from 11.6 to 15.0 µg/L. During Experiment 2, arsenic concentrations increased to 15 µg/L, possibly due to flushing operations being conducted in the distribution system. This occurrence caused the well pump to draw water faster than usual and may have stirred up sediments. The average arsenic level in the raw water was 13.0 µg/L during Experiments 1-3. Most of the arsenic in the raw water was in dissolved form (66% avg.).

All arsenic results are presented in Figure 4 and tabulated in Table 4.

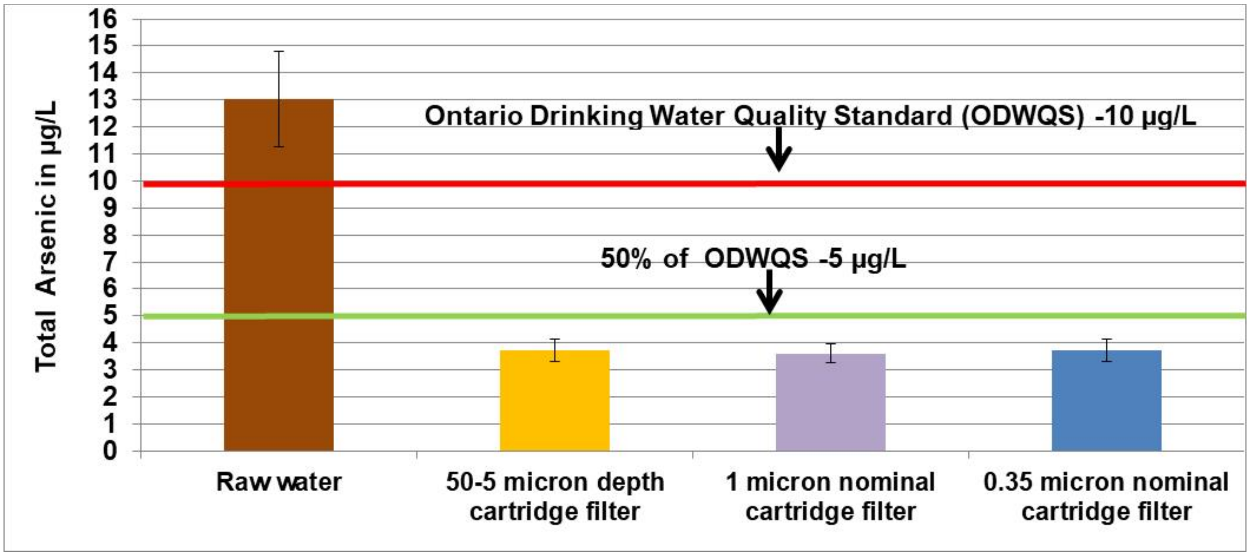

Figure 4. Arsenic Levels (with Standard Deviation) During Experiments 1-3

Average arsenic concentrations in all cartridge filter effluents were 3.7 µg/L or less. However, arsenic concentrations from the 50-5 µm depth cartridge filter, the 1 µm pleated nominal cartridge filter and the 0.35 µm pleated nominal cartridge filter effluents were not significantly different. The depth filter (50-5 µm) was able to remove most of the oxidized arsenic, perhaps due to its structure. Even when the raw water had arsenic levels reach 15 µg/L, the depth filter was efficient and able to reduce arsenic down to 4.2 µg/L which is less than the 5 µg/L target (50% of the Ontario MAC).

Table 4. Arsenic Levels in µg/L During Experiments 1-3

Experiment	Raw Water	50-5 µm Depth Cartridge Filter	1 µm Nominal Cartridge Filter	0.35 µm Nominal Cartridge Filter
1	11.6	3.7	3.6	3.6
2	15.0	4.2	4.0	4.2
3	12.5	3.3	3.3	3.4
Average	13.0	3.7	3.6	3.7

3.3.2 Iron

The iron concentration of the raw water was 0.68 mg/L during Experiments 1 and 3. Iron levels increased to 0.87 mg/L during Experiment 2 likely due to the flushing operations. Dissolved iron concentrations were 52 - 56% that of the total iron. In Experiment 2, dissolved iron concentrations were measured at only 18% of the total most likely due to the flushing occurrence and therefore this result was excluded. Most of the cartridge filter effluents were less than 0.02 mg/L of iron (method detection limit) which were significantly less than the recommended AO in Ontario (0.3 mg/L). One of the positive outcomes of this study was the pilot set-up not only reduced arsenic, but also iron in the treated water. Based on trends observed during the pilot, the village system could look into potentially eliminating the iron sequestration process.

3.4 Pilot Testing Experiments 4-5

Experiments 4 and 5 were conducted with the same filter series as Experiments 1-3 but operated without a contact tank. This tank bypass allowed us to investigate whether the added detention time was improving the treatment effectiveness.

3.4.1 Arsenic

The average raw water arsenic level was 10.4 µg/L which was lower than that measured during Experiments 1-3. The 50-5 µm depth filter reduced most of the arsenic and lowered the average arsenic concentration to 3.7 µg/L. The two pleated cartridge filters with 1 and 0.35 µm nominal sizes provided a polishing effect and each reduced an average additional 0.1 µg/L of arsenic concentration.

Arsenic results of Experiments 4 and 5 are presented in Figure 5 and values are provided in Table 5.

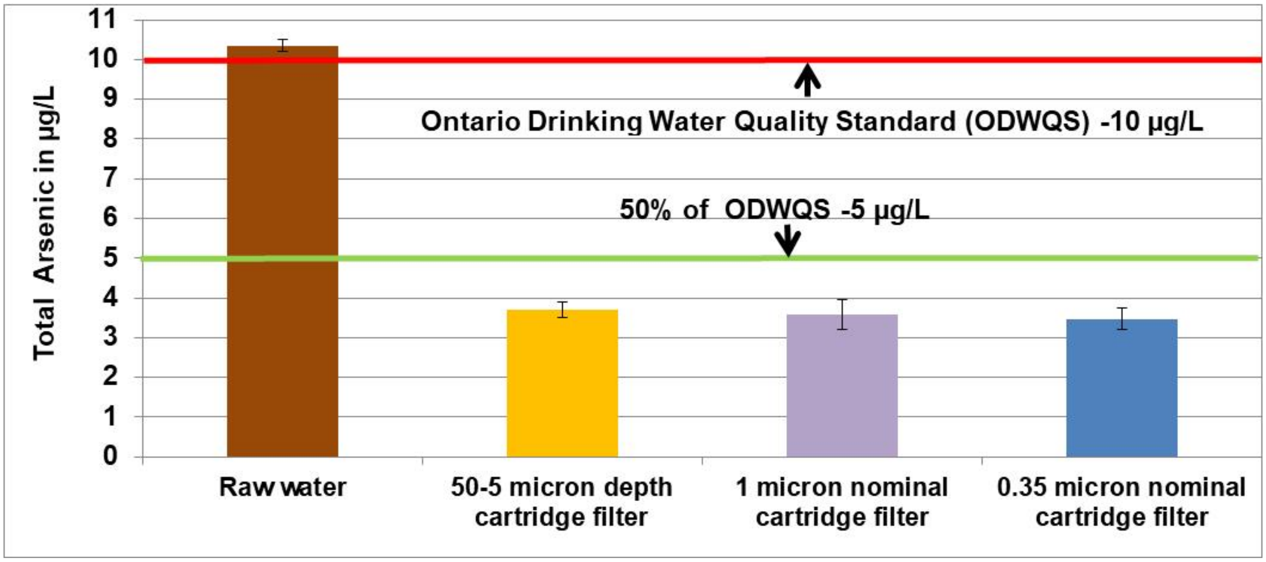

Figure 5. Arsenic Levels (with Max/Min) During Experiments 4 and 5

For Experiments 1-3 that utilized the contact tank and Experiments 4-5 that bypassed the contact tank, the arsenic reductions were 72% and 67%, respectively. It appears that the pilot set-up with the contact tank provided a slightly better result when considering the raw water arsenic concentrations. However, in terms of average arsenic concentration in treated water, levels were 3.7 µg/L with a contact tank and 3.5 µg/L without a contact tank. It should be noted again that the arsenic concentration was increased to 15 µg/L during Experiment 2 due to flushing operations on the day of testing. Overall, treated arsenic levels were similar with or without the use of a contact tank.

Table 5. Arsenic Levels in µg/L During Experiments 4 and 5

Experiment	Raw Water	50-5 µm Depth Cartridge Filter	1 µm Nominal Cartridge Filter	0.35 µm Nominal Cartridge Filter
4	10.2	3.5	3.2	3.20
5	10.5	3.9	3.95	3.72
Average	10.35	3.70	3.58	3.47

3.4.2 Iron

The average iron concentration of the raw water was 0.52 mg/L which was lower than the iron in Experiments 1 and 3 (0.68 mg/L). The average dissolved iron concentration was 48% of the total iron which was slightly lower than 52 - 56% during Experiments 1-3. During Experiment 4, iron concentrations of all cartridge filter effluents were less than 0.02 mg/L (method detection limit) which demonstrating that bypassing the contact tank in the pilot set up did not affect iron removal. Ultimately, treated iron concentrations were below 10% of Ontario's AO.

3.5 Pilot Testing Experiments 6-7

Similarly to Experiments 4 and 5, Experiments 6 and 7 were also conducted without a contact tank. The cartridge filter set-up was altered for this set of experiments and included a 75-55 µm depth cartridge filter, followed by a 5 and a 1 µm nominal cartridge filter. These coarser pore sized filters were tested as they may be more cost effective for operation if comparable arsenic removal results could be achieved.

3.5.1 Arsenic

The average arsenic concentration of the raw water was 9.95 µg/L, which was the lowest raw concentration observed during testing and complied with the Ontario MAC.

All Arsenic results are presented in Figure 6 and Table 6.

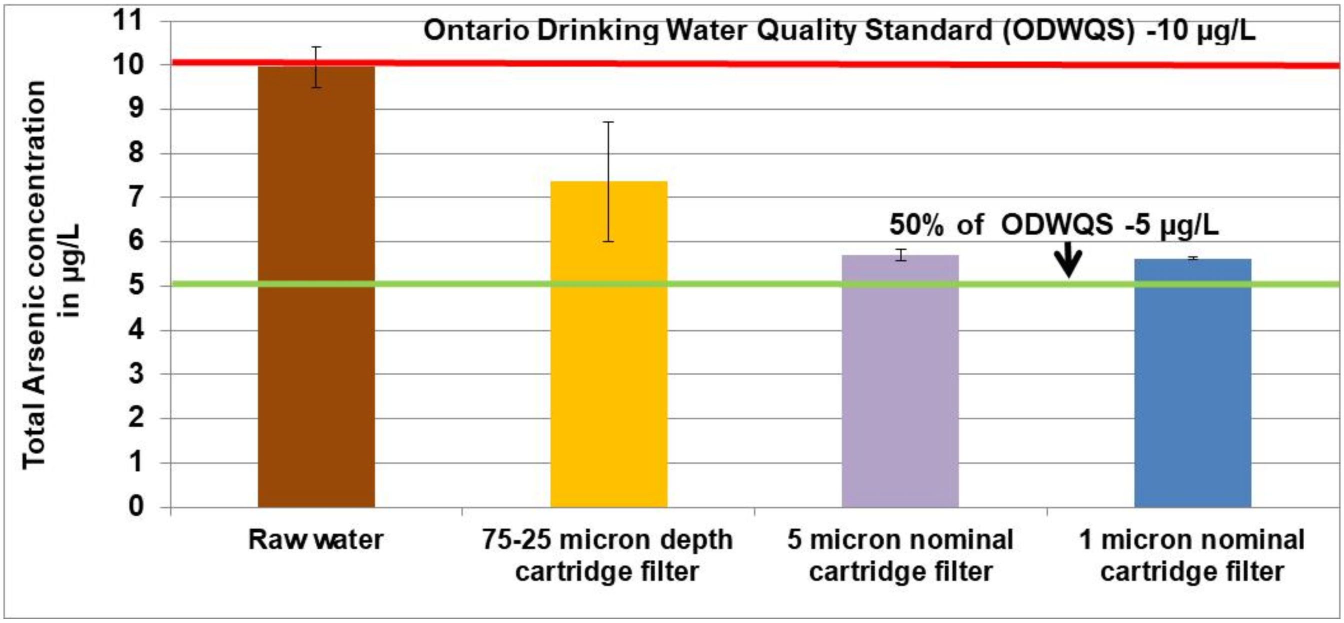

Figure 6. Arsenic Levels (with Max/Min) During Experiments 6 and 7

In spite of the lower raw arsenic concentration, the pilot set-up failed to reduce arsenic to less than the 5 µg/L target. The 75-25 micron depth cartridge filter lowered the average arsenic concentration to 7.36 µg/L (26% reduction). The 5 micron cartridge filter provided an additional 17% removal of arsenic down to 5.70 µg/L. The 1 micron cartridge filter only provided an additional 0.1 µg/L of arsenic reduction.

Table 6. Arsenic Levels in µg/L During Experiments 6 and 7

Experiment	Raw Water	75-25 µm Depth Cartridge Filter	5 µm Nominal Cartridge Filter	1 µm Nominal Cartridge Filter
6	10.4	6.00	5.82	5.65
7	9.5	8.72	5.57	5.6
Average	9.95	7.36	5.70	5.625

3.5.2 Iron

The average iron concentration of the raw water during this set of experiments was 0.44 mg/L which was lower than 0.68 mg/L observed in Experiments 1-3 and

0.52 mg/L observed in Experiments 4-5. Approximately 50% of the iron in the raw water was in dissolved form. In Experiment 6, the 5 and 1 micron cartridge filter effluents provided iron levels less than 0.02 mg/L (method detection limit). In Experiment 7 however, the iron level in the cartridge filter effluents was higher at 0.05 mg/L for the 1 micron cartridge filter effluent. All filtered effluents remained less than 0.3 mg/L, the Ontario AO.

3.6 Variations in Raw Water Quality

Table 7 presents raw water quality monitoring during all on-site pilot testing experiments.

Table 7. Raw Water Quality for On-site Pilot Testing Experiments

Parameter	Exp. 1 & 3* (June 24, July 3)	Exp. 4-5 (July 16, 23)	Exp. 6-7 (July 23, 26)
pH	7.7	7.5	7.6
Alkalinity (mg/L $CaCO_3$)	211	204	205
DOC (mg/L)	0.92	0.82	0.80
UV abs. at 254nm (cm^{-1})	0.040	0.029	0.026
True colour (PtCo units)	< 5 - 10	7	< 5 - 7
Apparent colour (PtCo units)	23	21	17
Total arsenic (µg/L)	12.1	10.4	10.0
Dissolved arsenic (µg/L)	9.0	8.30	9.70
Total iron(mg/L)	0.68	0.52	0.44
Dissolved iron(mg/L)	0.37	0.25	0.22
Turbidity (NTU)	4.07	2.20	1.99

Note: All values are an average of 2 experiments.

Raw water quality monitoring during the sets of experiment over a 2 month period demonstrated the source water's variability over time. In approximately one month's time, the arsenic level shifted from 12.1 µg/L to 10.0 µg/L and iron levels also changed from 0.68 mg/L to 0.44 mg/L. Similarly, DOC, UV absorbance, apparent colour and turbidity were variable with time as well. Groundwater is generally quite stable in water quality but one of the possible reasons for this variability may be the small size of the aquifer. When the water demand is lower, source raw water quality improved; while, when the water demand was higher (as observed during the Experiment 2 during flushing), the source raw water quality deteriorated.

4. Conclusion

The following conclusions were made for this pilot testing project:

- For this system, a chlorine dose of 4 mg/L was effective at reducing the arsenic and iron concentrations to below the target levels.
- Ferric chloride could provide additional arsenic reduction when applied with the optimal chlorine dosage.
- The pilot set-up using a contact tank followed by 50-5 µm depth filter, 1 and 0.35 µm nominal pleated cartridge filters, reduced the average arsenic concentration to 3.7 µg/L or less. Iron was reduced to less than 0.02 mg/L by the filters.
- When the contact tank was bypassed with the same cartridge filter setup the arsenic level was reduced to 3.5 µg/L. indicating there was no significant change in performance with or without the use of a contact tank.
- When the filter series of 75-25 µm depth filter, 5 and 1 µm pleated cartridge filters was tested, arsenic levels were reduced to 5.6 µg/L and iron levels to 0.05 mg/L. These results were higher than the project targets but remained below the Ontario MAC and AO guidelines and could still be considered effective in those respects.

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