Appendix C

2017

A Community Circle Approach to Evaluating Water Treatment Solution for the City of White Rock

PREPARED FOR: CITY OF WHITE ROCK

PREPARED BY: RES'EAU-WATERNET

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An NSERC Small Water System Strategic Network

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Executive Summary

This document serves as a technology assessment brief build on the pilot study evaluation of various water treatment processes for reducing manganese and arsenic level from groundwater (wells #6 and #7) at the city of White Rock through pilot study conducted by RES'EAU-WaterNET research team at University of British Colombia and Polytechnique Montréal, and in partnership collaboration with BI Pure Water, KWL, and other public and private partner organizations, from December 2016 to June 2017. The Pilot Plant consisted of two treatment trains that involved oxidation, filtration and adsorption stages. The main goal of this partnership is to assist the City of White Rock in addressing the challenges that are faced from changes in the Health Canada guideline pertain to reduction of arsenic and manganese delivering additional information that might assist the City of White Rock in planning and prioritizing its direction. The assessment of efficacy were performed on various treatment methods, where a combination of different processes and their removal efficiency were studied and compared in order to optimize their performances.

1.0 Background

1.1 Partnership with RES'EAU-WATERNET

The City of White Rock's water utility provides safe and clean drinking water to its residents. The drinking water is obtained from the Sunnyside Uplands Aquifer and six wells located throughout the City. To ensure water supplied is of the highest quality, the City of White Rock submitted a grant application to the Clean Water and Wastewater Fund (CWWF) for an arsenic and manganese water treatment project for the city's water system. Through collaboration with RES'EAU-WaterNET, the city aims to evaluate and identify technologies that are capable of providing a significant reduction of arsenic and manganese, and provide safe and high quality water that is also aesthetically acceptable for the public. The RES'EAU-WaterNET, through its Community Circle approach to problem solving has investigated the efficacy of different technologies with the aim of providing data and information towards the successful and sustainable solution to address the water quality parameters of concern.

The scope of this collaboration includes:

1. Stakeholders engagement: RES'EAU researchers will engage relevant public and private organizations to develop and implement Outreach and Awareness programs (e.g. Town Hall meetings, tours, conferences)
2. Water sampling and analysis: Over the course of the project, they will monitor changes in water quality.
3. Water research: Based on water quality results, research is conducted to develop possible water treatment options.
4. Pilot testing: Mobile water treatment plants are brought to source to engage community and operators.

The City intends to issue an RFP to contractors and consultants for the Design-build construction of a full scale water treatment plant. RES'EAU, along with Community Circle results, works to see that the community's feedback is considered during this step.

The partnership with RES'EAU-WaterNET will provide the City of White Rock access to experts and a wealth of knowledge and experience in drinking water treatment. Benefits of the partnership include:

- A network of Canada's top academic researchers with top knowledge of drinking water systems;
- Access to a seasoned team that has refined experience in outreach and public engagement activities;

- Access to leading Canadian industrial expertise through partners who understand utilities and community's perspective;
- The cumulative benefit of RES'EAU-WaterNET's knowledge sharing from international organizations with similar research and development programs; and
- Access to the Network's Mobile Water Treatment Plant, which will provide timely results and cost effective tests for potential water treatment technologies, operated on site at the Merklin Reservoir.

The partnership with RES'EAU-WaterNET will also provide an effective public and private stakeholders outreach based on scientific findings and peer reviewed articles.

1.2 Arsenic and Manganese Guidelines

Arsenic is a naturally occurring metal found in rocks and mineral deposits throughout the Earth's crust. Arsenic enters water sources when the rocks and mineral deposits that contain arsenic dissolve. In a study of arsenic in private drinking water wells commissioned by Fraser Health Authority and BC Ministry of Environment in 2008, it was concluded that arsenic is incredibly widespread throughout the Lower Mainland and deeper wells are associated with higher arsenic concentrations. In 2007, Health Canada Guidelines for Canadian Drinking Water Quality (GCDWQ) lowered the maximum allowable concentration (MAC) for arsenic from 0.025 mg/L to 0.010 mg/L. As indicated in the historical data of wells tables found in section 1.3, arsenic levels in wells 1, 2, 3 and 4 have been consistently below the MAC. Arsenic levels in wells 6 and 7 have either exceeded slightly the MAC or been very close to exceeding the MAC. Each well appears to have a stabilized average concentration of arsenic that increases or decreases slightly every two months.

Manganese is a naturally occurring element found in over 100 common rocks, salts and in the soils found on the floors of lakes and oceans. There is no MAC for manganese in Canada, but there is an Aesthetic Objective (AO) set at 0.05 mg/L by Health Canada in the GCDWQ. At levels exceeding 0.15 mg/L, manganese can leave black deposits in bathtubs and toilet bowls, stain laundry and plumbing fixtures and can cause an undesirable taste in beverages. Manganese levels in well 5 have been consistently below the AO and well 2 has only had two samples above the AO. Wells 1, 3, 4, 6 and 7 have had manganese levels that exceeded the AO with almost every single sample.

1.3 Mobile Water Treatment System

The pilot plant contained a number of technologies to assess their effectiveness of treating the water from White Rock City's well water. There were three main treatment technologies investigated during this pilot study including Oxidation/Filtration, Adsorption and Biological filtration. Since the biological media did not grow enough during this pilot study, this method is not further discussed in this report. The treatment systems were contained in a 6 m trailer, shown in Figure 1.1. Source water was provided from well #6 and well #7 (Merklin street reservoir) by connecting the inlet of the pilot directly to the outlet of the well pumps. The system inside the pilot was designed to have two treatment trains running in parallel. Each train contained one filter designed for the removal of manganese followed by a second filter considered for the removal of arsenic. This design provided the ability to investigate the efficiency of each filter for the removal of either manganese or arsenic. The process flow diagram of the system is shown in Figure 1.2.

Figure 1.1 *RES'EAU mobile pilot deployed in Merklin street reservoir*

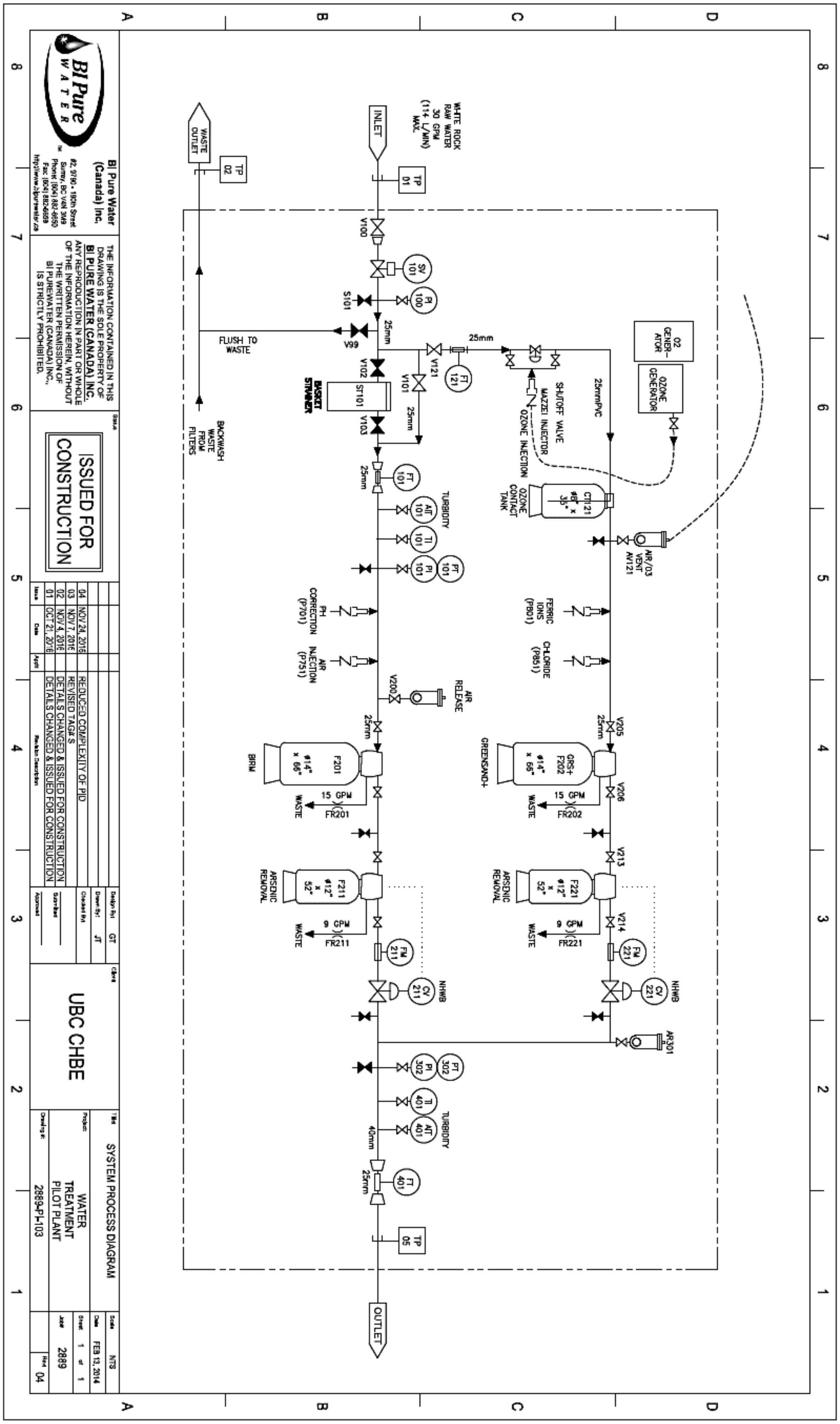


Figure 1.2 *RES'EAU mobile water treatment pilot plant process flow diagram*

1.4 Oxidation

The oxidation process turns the dissolved form of the metals into solid (precipitate) form which can then be removed through filtration. The effectiveness of various chemical oxidants for iron, manganese, and arsenic is shown in Table 1.1.

Table 1.4.1 *Relative effectiveness of various oxidants (Attached EPA report).*

Oxidant	Iron (Fe)	Manganese (Mn)	Arsenic (As)
Oxygen (aeration)	Effective	Not effective	Not effective
Chlorine	Effective	Somewhat effective	Effective
Chloramine	Not effective	Not effective	Not effective
Ozone	Effective	Effective	Effective
Chlorine dioxide	Effective	Effective	Not effective
Potassium permanganate	Effective	Effective	Effective

The stoichiometric amount of oxidant necessary to oxidize As(III), Fe(II), and Mn(II) is important when approximating chemical feed dosage in the treatment systems. It is important not to under-dose the oxidant because under-dosing can result in incomplete oxidation of these metals. Table 1.2 presents the stoichiometric relationships between relevant oxidants and Fe(II), Mn(II) and As(III). Note that the oxidant demand of Fe(II) and Mn(II) dominates relative to that of arsenic. Other water quality constituents also may have an oxidant demand (e.g., ammonia, dissolved organic matter). Thus, when determining the oxidant dose, the total oxidant demand of the source water must be determined.

Table 1.4.2 *Stoichiometry of various chemical oxidants (Attached EPA report).*

Oxidant	Iron (Fe) (mg oxidant /mg Fe)	Manganese (Mn) (mg oxidant /mg Mn)	Arsenic (As) (µg oxidant /µg As[III])
Chlorine (Cl_2)	0.64	1.29	0.95
Chloramine (NH_2Cl)	0.46	0.94	0.69
Ozone (O_3)	0.43	0.88	0.64
Chlorine dioxide (ClO_2) (1-electron transfer)	----	2.45	1.80
Chlorine dioxide (ClO_2) (5-electron transfer)	0.24	----	0.36
Potassium permanganate ($KMnO_4$)	0.94	1.92	1.40

In this project, chlorine (Sodium Hypochlorite solution 12%) and ozone were selected for the oxidation stage. Detailed information about the concentration of each oxidant and their effectiveness for the removal of manganese and arsenic are provided in next sections.

1.4.1 Chlorine

Chlorine has long been used as the disinfectant of choice for most drinking water supplies. The oxidizing power of chlorine is not only effective for metals in the water, but also for many other contaminants found in raw water, both organic and inorganic. Chlorine also effectively oxidizes As(III), Fe(II) and Mn(II). The simple oxidation reactions between chlorine and arsenic, iron, and manganese are as follows:

$$NaOCl + H_3AsO_3 \rightarrow H_2AsO_4{}^{-} + Na^{+} + Cl^{-} + H^{+}$$
$$HOCl + 5H_2O + 2Fe^{2+} \rightarrow 2Fe(OH)_{3_{(s)}} + Cl^{-} + 5H^{+}$$
$$HOCl + H_2O + Mn^{2+} \rightarrow MnO_{2_{(s)}} + Cl^{-} + 3H^{+}$$

Oxidation of As(III), Fe(II), and Mn(II) by chlorine occurs fairly rapidly in pH ranges of 6.5-8.0. Water with manganese requires 1.29 mg/L of chlorine (as Cl_2) to oxidize 1.0 mg/L of manganese. Arsenic typically is present at microgram levels, so negligible amounts of additional oxidant are required. It is common practice to use the stoichiometric value plus 10% when establishing initial dosages.

In recent years, the use of chlorine gas has come under increased scrutiny for safety reasons; sodium hypochlorite and calcium hypochlorite are two common alternatives, especially in smaller plants. Sodium hypochlorite is delivered in bulk by tankers or in smaller quantities such as carboys and 5-gallon cartons. It is pumped directly into the raw water stream to oxidize soluble iron, manganese and arsenic. Calcium hypochlorite, on the other hand, is provided in a dry form and is typically used in low-flow applications. It can be provided in tablet form for use in automatic feed equipment or in a dry powder. Degradation occurs over time. It is the most expensive of the three forms of chlorine and can lead to scale formation in hard waters.

1.4.2 Ozone

Ozone (O_3) has been shown to effectively oxidize iron and manganese at the same time removing arsenic and other metals to below detection limits. An ozone generator can be used to produce ozone, which can then be dispensed into the water stream to convert Fe(II) to Fe(III) and As(III) to As(V). It is also a potential disinfectant, but unlike chlorine, ozone does not impart a lasting residual to treated water. Research has shown that the effectiveness of ozonation can be significantly affected by the presence of organic matter and sulfide (S^{2-}) (Ghurye and Clifford, 2001 and 2004). The simple oxidation reactions between ozone and arsenic, iron, and manganese are as follows:

$$O_3 + H_3AsO_3 \rightarrow H_2AsO_4^{-} + O_2 + H^{+} \ \ (@pH\ 6.5)$$
$$O_3 + H_3AsO_3 \rightarrow HAsO_4^{2-} + O_2 + 2H^{+} \ \ (@pH\ 8.5)$$
$$O_3 + 5H_2O + 2Fe^{2+} \rightarrow 2Fe(OH)_{3_{(s)}} + O_2 + 4H^{+}$$
$$O_3 + H_2O + Mn^{2+} \rightarrow MnO_{2_{(s)}} + O_2 + 2H^{+}$$

1.5 Arsenic Speciation

The species and valence state of inorganic arsenic depend on the oxidation-reduction conditions and pH of water. In general, arsenite, the reduced, trivalent form [As(III)], is found in groundwater (assuming anaerobic conditions); and arsenate, the oxidized, pentavalent form [As(V)], is found in surface water (assuming aerobic conditions). This rule, however, does not always hold true for groundwater. Some groundwaters have been found to contain only As(III), others with only As(V), and still others with a combination of both As(III) and As(V). Arsenate exists in four forms in aqueous solution, depending on pH: H_3AsO_4, $H_2AsO_4^-$, $HAsO_4^{2-}$, and AsO_4^{3-}. Similarly, arsenite exits in five forms: $H_4AsO_3^+$, H_3AsO_3, $H_2AsO_3^-$, $HAsO_3^{2-}$ and AsO_3^{3-}.

The result of arsenic speciation for different wells in City of White Rock is shown in Figure 1.3. As it can be seen, arsenate is more than arsenite for all the wells except well #7. The more recent results (24-Oct-16 and 25-Jan-17) indicate that arsenite and arsenate have almost the same concentration in well #7.

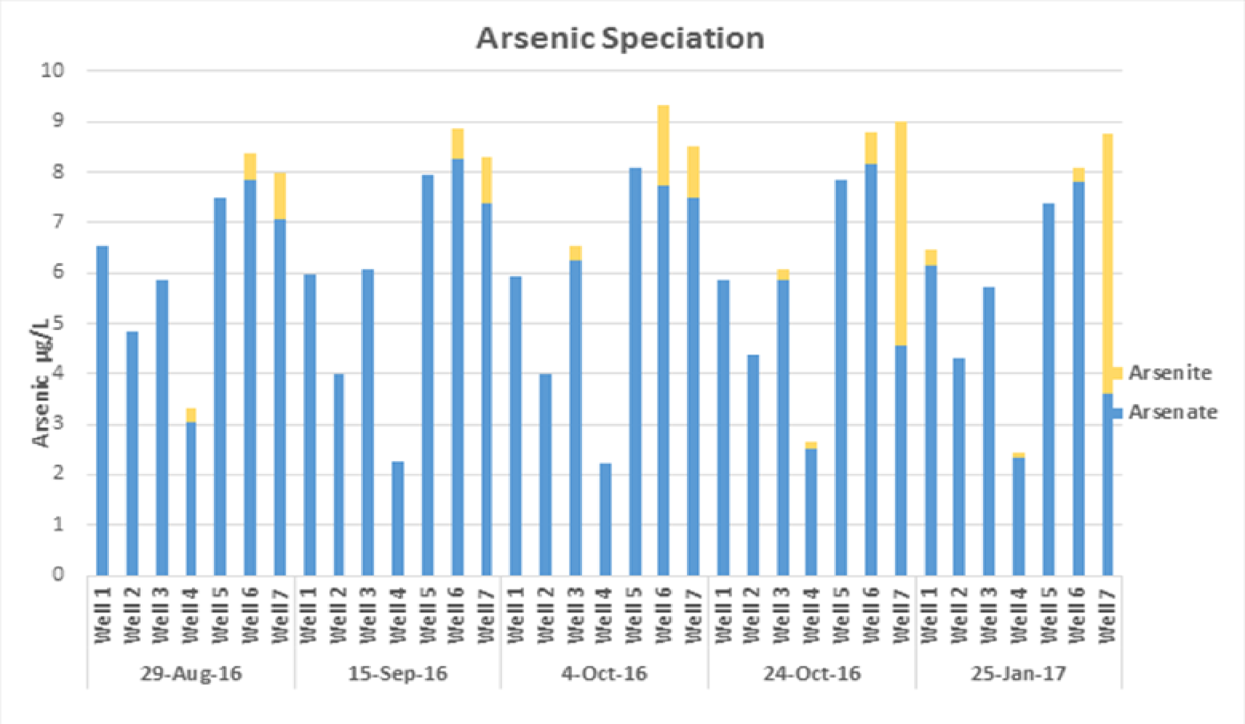


Figure 1.3 *Arsenic speciation results for different wells.*

1.6 Filtration

After the oxidation step (with or without a detention or settling tank), the source water is filtered through a filter media in either a pressure vessel or a gravity filter to remove the solids formed as a result of oxidation. The filtration media in the systems may consist of sand, sand and coal anthracite (dual media), or proprietary/patented products, such as Pyrolox, Filox-R, Birm, GreensandPlus and Mangazur (Biological media). Some media, such as GreensandPlus, have the ability to both oxidize and filter iron and manganese effectively and at the same time. GreensandPlus, pyrolusite, Birm, or any medium coated with manganese dioxide has the capacity to oxidize iron and manganese and filter the insoluble precipitates with the filter bed. These media also have some, but limited, capacity for As(III) oxidation and arsenic adsorption.

1.6.1 GreensandPlus

GreensandPlus is a black filter media used for removing soluble iron, manganese, hydrogen sulfide, arsenic and radium from groundwater supplies. The manganese dioxide coated surface of GreensandPlus acts as a catalyst in the oxidation reduction reaction of iron and manganese. The silica sand core of GreensandPlus allows it to withstand waters that are low in silica, total dissolved solid (TDS), and hardness without breakdown. GreensandPlus is effective at higher operating temperatures and higher differential pressures than standard manganese greensand. Tolerance to higher differential pressure can provide for longer run times between backwashes and a greater margin of safety. GreensnadPlus is available in a 18 × 60 mesh with an effective size of 0.30-0.35 mm and a specific gravity of 2.4. To be effective, it must be used in water with a pH range of 6.2-8.5. Filter loading rates should be between 4.9-29.4 m/h (2-12 gpm/ft^2) with a bed depth of 30 inches. The combination of a strong oxidant and GreensandPlus filtration media for iron and manganese removal is commonly referred to as the "Manganese GreensandPlus Process." Either potassium permanganate or chlorine can be used to effectively regenerate GreensandPlus filters. It can be used in Catalytic Oxidation (CO) or Intermittent Regeneration (IR) applications and requires no changes in backwash rate or times or chemical feeds. Manufacturer information is available at http://www.inversand.com. Figures 1.4 and 1.5 provide information for normal service pressure drops and backwash bed expansion characteristics for GreensandPlus filter.

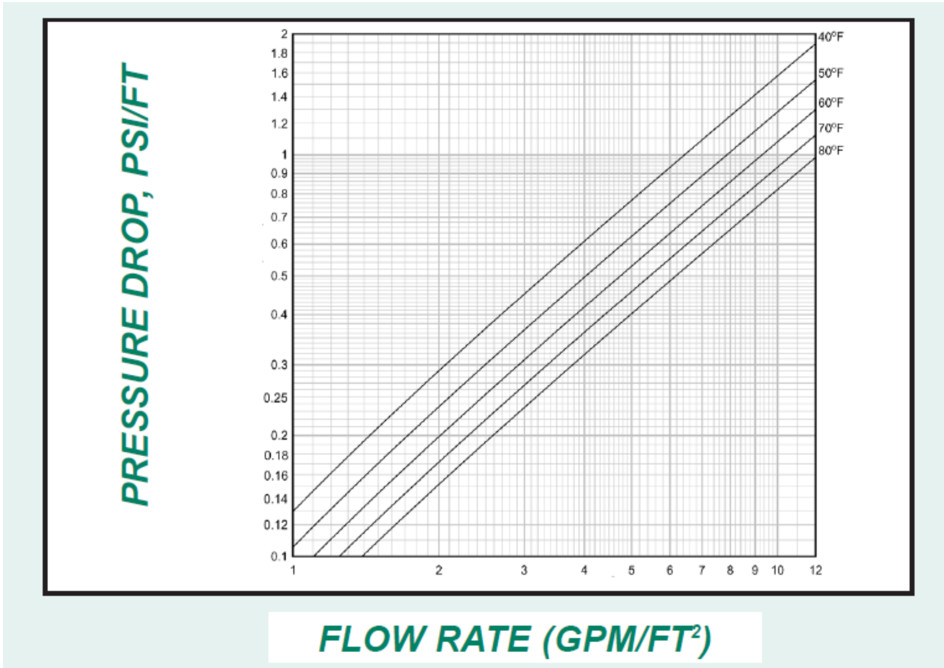


Figure 1.4 *Service Flow Clean Bed Pressure Drop through GreensandPlus Media (Source: Inversand Company)*

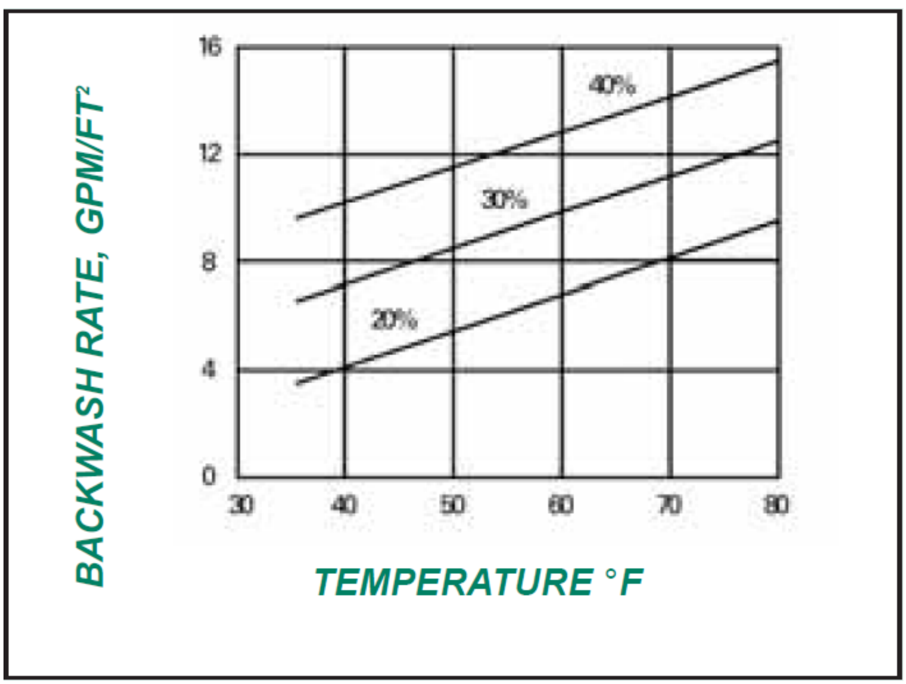


Figure 1.5 *Backwash Bed Expansion Characteristics for GreensandPlus Media (Source: Inversand Company)*

1.7 Solid Oxidizing Filtration Media

Two media that are for filtration use in iron and manganese removal are Pyrolusite and Birm. Pyrolusite is manganese dioxide in a granular form that can be used within a pressure vessel for filtration. Birm, on the other hand, is a manufactured material that begins with a base material coated with manganese dioxide. In this project, Birm was selected as the solid oxidizing filtration media to be tested for the removal of manganese and arsenic.

1.7.1 Birm

Birm is an acronym that stands for the “Burgess Iron Removal Method” and is a proprietary product manufactured by the Clack Corporation in Wisconsin. Typical applications have been point-of-use treatment, but it has been used in municipal treatment plants. Birm is produced by impregnating manganous salts to near saturation on aluminum silicate sand, a base material. The manganous ions then are oxidized to a solid form of manganese oxide with potassium permanganate. This process is similar to that used to manufacture manganese greensand. The manufacturer indicates that the presence of dissolved oxygen is necessary for Birm to function as an oxidizing media. Birm is available in a 10 × 40 mesh with an effective size of 0.48 mm and a specific gravity of 2.0. To be effective, it must be used in water with a pH range of 6.8-9.0. Alkalinity should be greater than two times the combined sulfate and chloride concentration. Injection of compressed air ahead of the media to maintain a dissolved oxygen content of at least 15% of the iron content may be required, especially for source water with iron at concentrations of 3 mg/L or greater. The dissolved oxygen oxidizes iron with Birm media serving as a catalyst that enhances the reaction between dissolved oxygen and dissolved iron and manganese in the water. Filter loading rates should be between 8.5-12.2 m/h (3.5-5.0 gpm/ft^2) with a bed depth of 30-36 inches. Chlorination greatly reduces Birm’s effectiveness and at high concentrations can deplete the catalytic coating. Polyphosphates can coat the media, thus reducing its effectiveness for iron removal. Manufacturer information is available at www.clackcorp.com. No chemical addition or regeneration is required for Birm. Backwash rates should be controlled in the range of 24.4-29.4 m/h (10-12 gpm/ft^2) in order to achieve suitable bed expansion of approximately 30% for cleaning. An excessively high backwashing rate and air scour should be avoided to minimize attrition loss. Underdrains may include a gravel support bed or may be of the gravel-less type. Figures 1.6 and 1.7 provide information for normal service pressure drops and backwash bed expansion characteristics for Birm.

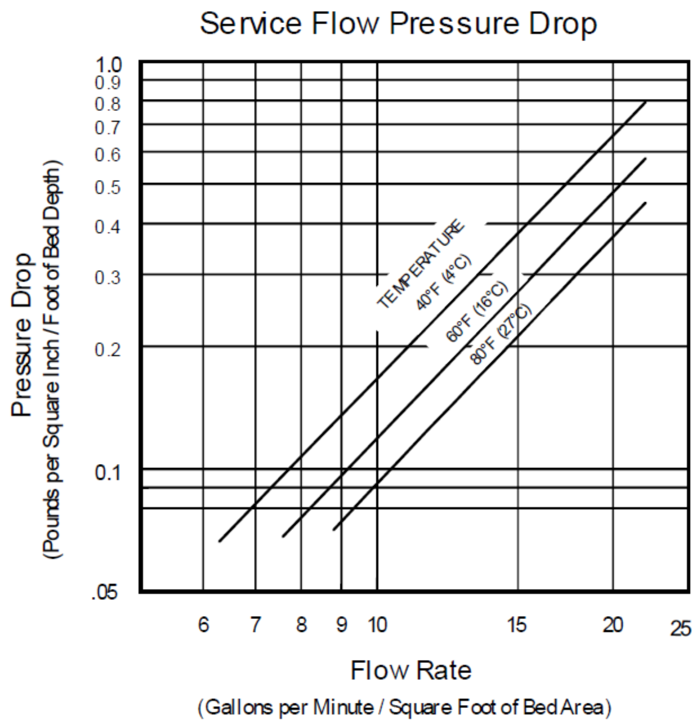


Figure 1.6 *Service Flow Pressure Drop through Birm Media (Source: Clack Corporation)*

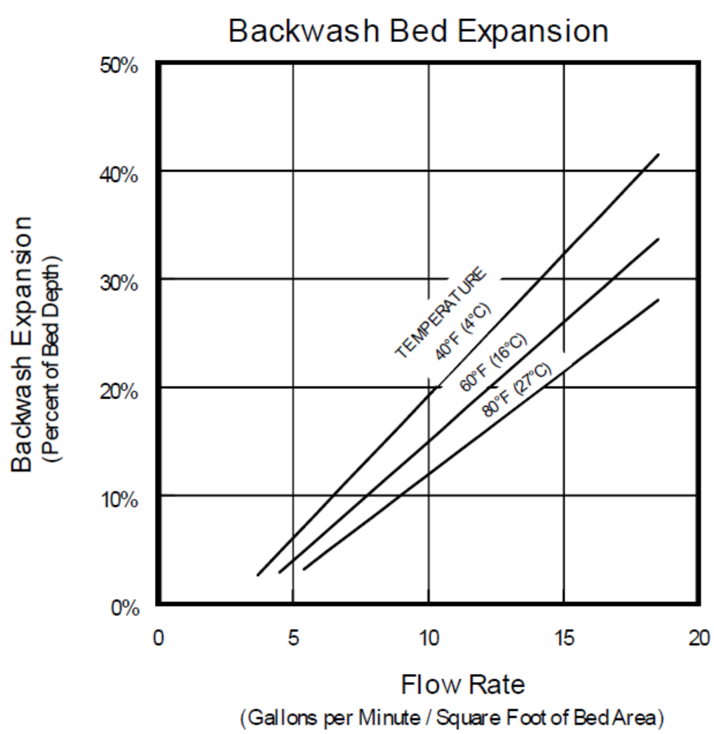


Figure 1.7 *Backwash Bed Expansion Characteristics for Birm (Source: Clack Corporation)*

1.8 Granular adsorptive media

Newly developed adsorptive media for arsenic removal consist primarily of iron-based materials or iron-modified activated alumina products. Some of these materials are not capable of regeneration and, thus, are used solely on a replacement basis (throwaway). Some of these media, mainly the iron-based products, have demonstrated arsenic removal capacities that exceed that of activated alumina particularly at pH above the optimum pH 5.5 level for alumina treatment. The adsorptive capacity of these new materials also is affected by pH; however, their pH sensitivity does not resemble that of activated alumina. The benefit of pH adjustment may come more from the elimination of competition for adsorptive site by ions such as silica and phosphate. Consequently, these materials can be employed economically on a spent media replacement basis without the incorporation of pH adjustment chemicals and equipment.

1.8.1 E33 Bayoxide

AdEdge Technologies' Bayoxide® E33 media is the adsorptive media for arsenic reduction that reduces total arsenic, including both arsenic (III) and arsenic (V). It is an iron-based granular adsorption media. The E33 media can be discarded when spent and requires no chemicals or regeneration. It can be effective for the removal of arsenic in the range of 10 to 100 µg/L. Its expected life bed volumes based on the manufacturer data sheet is from 15000 to 125000 bed volumes depending on the water quality. Its empty bed contact time is typically around 3 minutes. Manufacturer information is available in: https://www.adedgetech.com.

1.9 Biological filtration process-Mangazur

Mangazur is the name for the biological filtration process for the removal of manganese, and potentially arsenic from groundwater sources. During the process, bacteria attach to the Biolite filter media; designed specifically for biological removal of metals. Biolite media acts as a support for bacteria, enables high-rate filtration, and does not require periodic replacement or regeneration. The bacteria remain in the media even after backwashing, allowing continual operation for indefinite time periods. Based on manufacturer data sheet, the media requires less water for backwashing compared to other filters, higher metals retention on the Biolite media allows longer filters runs, it needs very low operating costs and due to rapid biological oxidation rates, Mangazur systems are designed at filtration rates up to 20 gpm/ft^2 (50 m/h). Manufacturer information is available in: www.degremont-technologies.com

1.10 Sampling

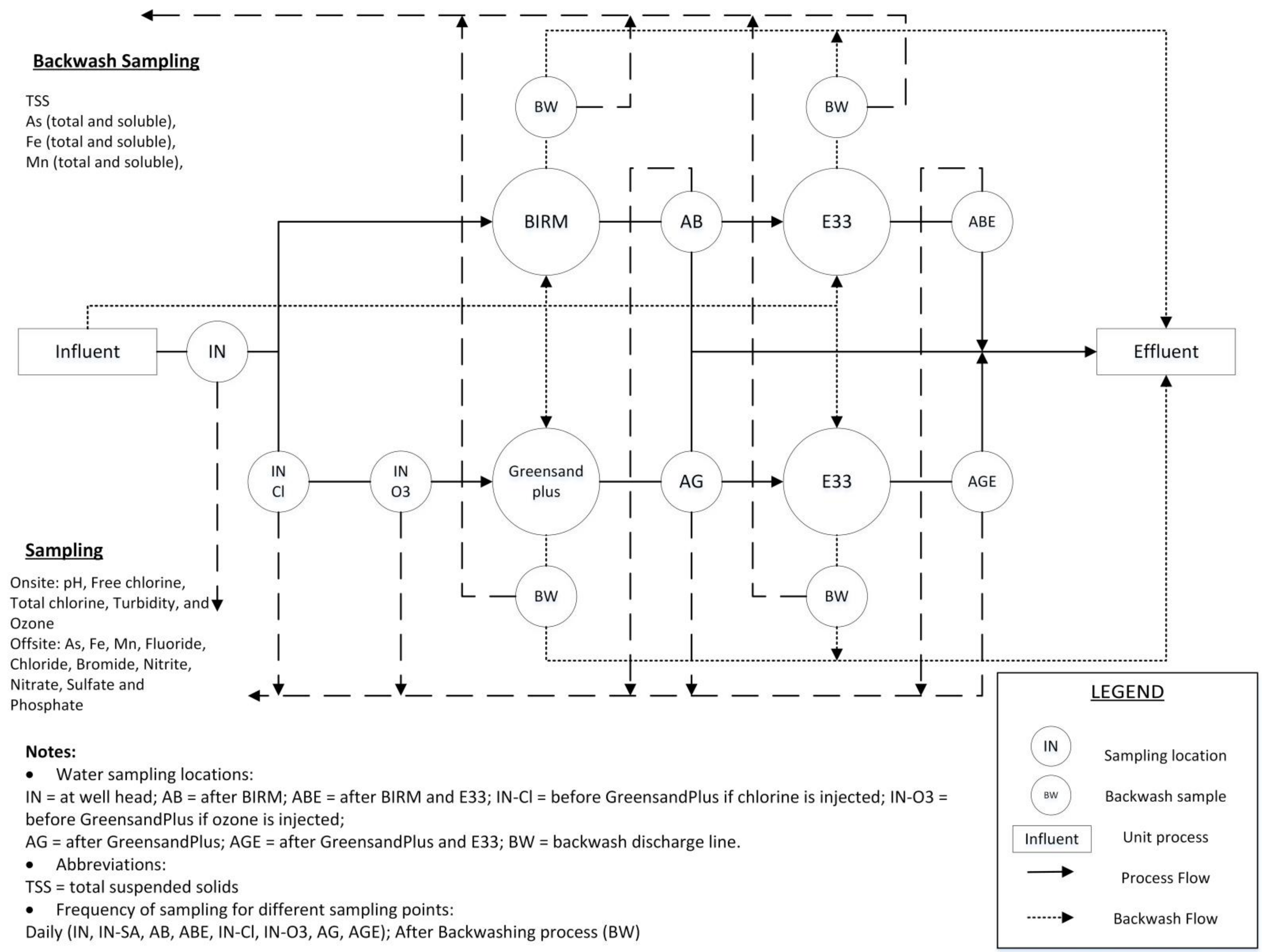
The water samples (both the raw water and after each treatment stage) were analyzed for various parameters. The on-site analyses included free chlorine, total chlorine, pH and turbidity measurements. The off-site analyses included measurements for metals (Arsenic, Manganese and Iron) and anions (Fluoride, Chloride, Bromide, Nitrite, Nitrate, Sulfate and Phosphate). Water samples were collected from the pilot plant facility (refer to sampling locations in Figure 1.8) and delivered to the Exova Lab, Surrey, BC for filter effluent and backwash water metal analysis and to University of British Columbia (UBC) for both anion and metal analyses. The metal effluent testing was switched to be done only at UBC after two weeks. No significant difference was observed between the two labs' results.

An ion chromatograph was used for the analysis of different anions. The instrument was programed to test three different injections for each sample. The IC value for each anion presented in this study is the average of the three injections.

Metal analysis was conducted by an inductively coupled plasma (ICP) system coupled with mass spectrometry (ICP-MS). The instrument was set to analyze the metal content of five different injections from each sample. The concentration reported for each metal in this study is the average value of five injections.

For both IC and ICP-MS analysis, the CV value (coefficient of variation) of the analysis (three injections in IC and five injections in ICP-MS) was calculated to ensure it was less than 5% for each sample. This method was useful to ensure for each sample the results of the instrument were repeatable.

Samples were collected using 250mL pre-cleaned bottles (acid washed) for metal analysis and 250mL laboratory-grade bottles IC analysis. Samples were transported in coolers with ice packs and taken to the corresponding laboratories for the analyses.



Notes:

- Water sampling locations:

IN = at well head; AB = after BIRM; ABE = after BIRM and E33; IN-Cl = before GreensandPlus if chlorine is injected; IN-O3 = before GreensandPlus if ozone is injected;
AG = after GreensandPlus; AGE = after GreensandPlus and E33; BW = backwash discharge line.

- Abbreviations:

TSS = total suspended solids

- Frequency of sampling for different sampling points:

Daily (IN, IN-SA, AB, ABE, IN-Cl, IN-O3, AG, AGE); After Backwashing process (BW)

Figure 1.8 Process flow diagram and sampling location

2.0 Results and Discussion

In this chapter, we present the results and findings related to the performance of each technology and the implications associated with such results on the overall treatment process.

2.1 Preliminary performance evaluation of Birm, GreensandPlus and E33 Bayoxide

During the first two weeks of the pilot operation, the system was tested for its general performance for the removal of arsenic and manganese. This section highlights the experimental procedure and the results of the preliminary tests on the efficacy of the treatment systems (Birm, GreensandPlus, and E33) for the removal of manganese and arsenic.

The system was started to operate on Wednesday December 14, 2016. The flowrate for each treatment train, Birm followed by E33 Bayoxide in train 1, and Greensand Plus followed by E33 Bayoxide in train 2, was adjusted to the around 18 L/min. The filtration rate for either Birm or GreensandPlus was around 10m/h and for E33 Bayoxide was around 15 m/h. The detailed information related to each of the filters is provided in Table 2.1. On three different days (Friday December 16, Monday December 19 and Wednesday December 21, 2016), samples from the sampling locations of the system (Figure 1.8) were collected and analyzed for both on-site and off-site measurements.

The concentrations of manganese and arsenic at different sampling locations are shown in Figures 2.1 and 2.2, respectively. At the inlet (raw water), the manganese concentration varied between 116 µg/L and 141 µg/L and the inlet arsenic concentration was between 9.5 µg/L and 10.1 µg/L on different sampling dates. Both Birm and GreensandPlus filters showed high efficiency in terms of Mn removal (brining the outlet concentration to less than 10µg/L); however, they were ineffective at reducing the concentration of arsenic. The Bayoxide E33 adsorptive media after either Birm or GreensandPlus reduced the concentration of arsenic to below 2µg/L.

Table 2.1.1 *Design features of the manganese and arsenic Removal system at RES'EAU mobile pilot*

Design Parameter	Value	Remarks
Pretreatment (Manganese Removal)		
No. of Vessels	2	-
Configuration	Parallel	-
Vessel size (in)	14 D * 65 H	1.07 ft^2 cross section area
Depth of Birm Media (in)	~33.6	Quantity of Birm ÷ cross section area of the vessel
Quantity of Birm Media (ft^3)	3	
Birm Hydraulic Loading Rate (gpm/ft^2)	3.5-5	Data sheet
Depth of GreensandPlus Media (in)	~28	Quantity of GreensandPlus÷ cross section area of the vessel
Quantity of GreensandPlus Media (ft^3)	2.5	(0.5 ft^3 Anthracite)
GreensandPlus Hydraulic Loading Rate (gpm/ft^2)	2-12	Data sheet
Clean Bed Pressure Drop (psi)	4.6	-
under bedding	Gravel	1/4-in × 1/8-in
Bed Expansion For Birm/GreensandPlus (%)	40	Data sheet
Backwash Rate (gpm/ft^2)	11-12	Data sheet: 10-12 (Birm); 12-16 (GreensandPlus)
Backwash Duration (min)	14	-
Greensand Plus Design Backwash Frequency (day)	2-24	calculation
Birm Design Backwash Frequency (day)	periodically	Data sheet
Adsorption (Arsenic removal)		
No. of Vessels	2	-
Configuration	Parallel	-
Vessel size (in)	12 D * 52 H	0.79 ft^2 cross section area
Type of Media	E33 Bayoxide	-
Quantity of Media (ft^3)	2	-
Media Bed Depth (in)	30	-
Maximum Hydraulic Loading Rate (gpm/ft^2)	7.6	Data sheet
Maximum Flow Rate (gpm)	6	Data sheet
Maximum Empty Bed Contact Time (EBCT) (min)	4.2	-
Clean Bed Pressure Drop (psi)	4.6	-
Under bedding	Gravel	1/4-in × 1/8-in
Backwash Rate (gpm/ft^2)	5	Data sheet
Backwash Duration (min)	14	-
Bed Expansion (%)	40	Data sheet
Backwash cycles (per month)	2 ×	Data sheet
Expected life bed volumes (with pretreatment)	15000 to 125000	Data sheet

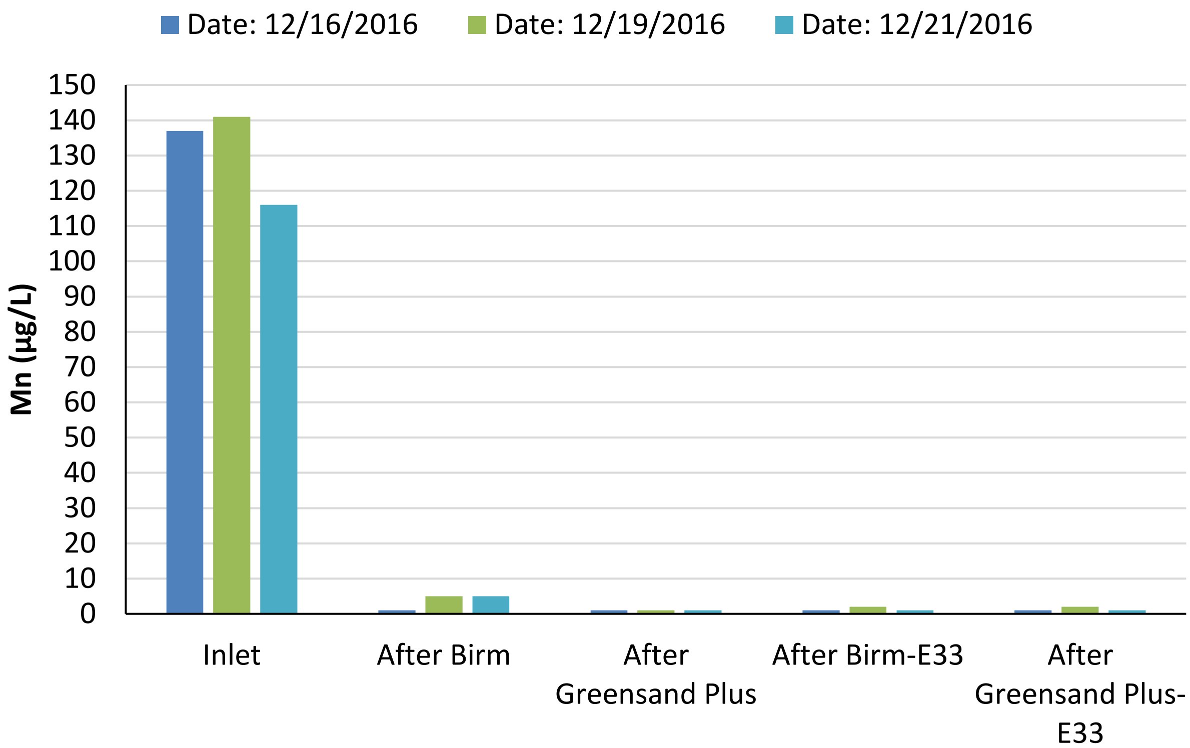


Figure 2.1 *Concentration of manganese at different sampling locations and different sampling dates.*

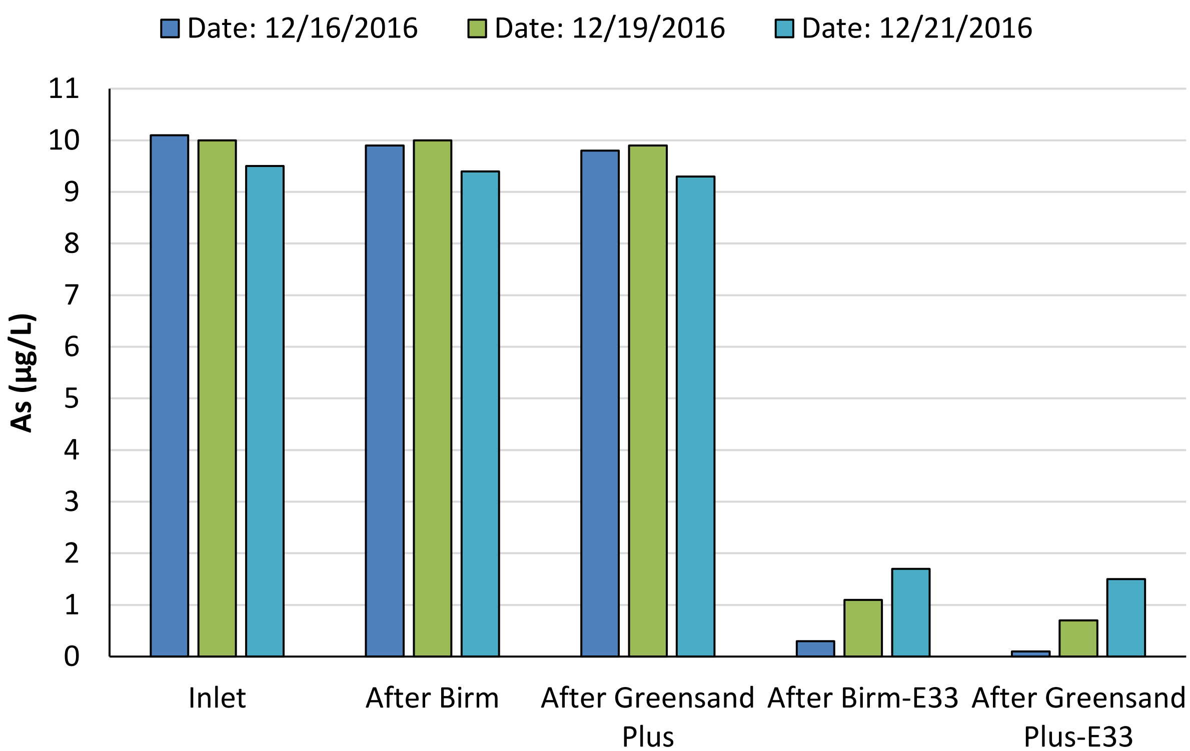


Figure 2.2 *Concentration of arsenic at different sampling locations and different sampling dates.*

2.2 Long-term efficacy evaluation

The results of preliminary tests conducted during the month of December 2016 confirmed the efficacy of GreensandPlus and Birm at removing manganese, and that of E33 Bayoxide at removing arsenic in the White Rock city's groundwater. The pilot system was operated again between January and February 2017, to further evaluate the performances of various units and assess the long-term operational indicators, e.g., pressure drop. Experimental procedure and the results of this set of experiments are highlighted in this section.

The system was started to operate on Thursday January 19, 2017. The filers were backwashed thoroughly before starting the experiment. Based on the manufacturer data sheet, the adsorptive media could not be regenerated; however, it was backwashed the same as other filters to check if there is a possibility of removing its arsenic content. The flowrate for each treatment train, Birm followed by E33 Bayoxide and Greensand Plus followed by E33 Bayoxide, was adjusted to the desired value (around 10m/h for Birm or GreensandPlus and around 15m/h for E33 Bayoxide). The operational parameters are provided in details in Table 2.1. A total of 8 water samples were collected from different stages on different days between January 23 and February 10, 2017. At the end of the experiment on February 10, 2017, the system was backwashed again and samples were collected from backwash water.

2.2.1 Long-term efficacy evaluation-manganese removal through Birm and GreensandPlus

The concentrations of manganese before and after Birm and GreensandPlus on different sampling dates are presented on Figures 2.3 and 2.4, respectively. As it can be seen in Figure 2.3, manganese concentration in the outlet stream of Birm increased gradually, eventually reaching above the Aesthetic Objective (50 µg/L) after nearly 300 cumulative volumes. On the other hand, GreensandPlus performed well consistently, with the outlet manganese concentration being below 2µg/L throughout the operation (up to around 550 cumulative volumes). it is concluded that GreensandPlus outperformed Birm by providing consistent and effective removal of manganese.

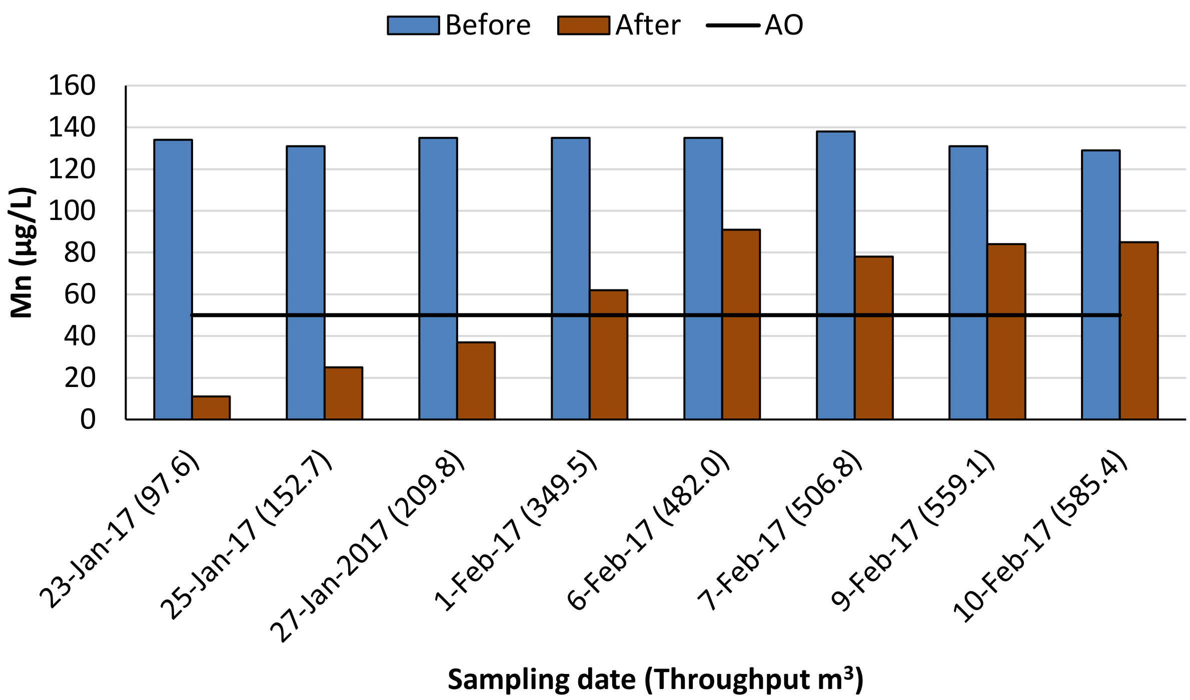


Figure 2.3 *Manganese removal through Birm filter at different sampling dates; values in the brackets represent the cumulative throughput volume of the water.*

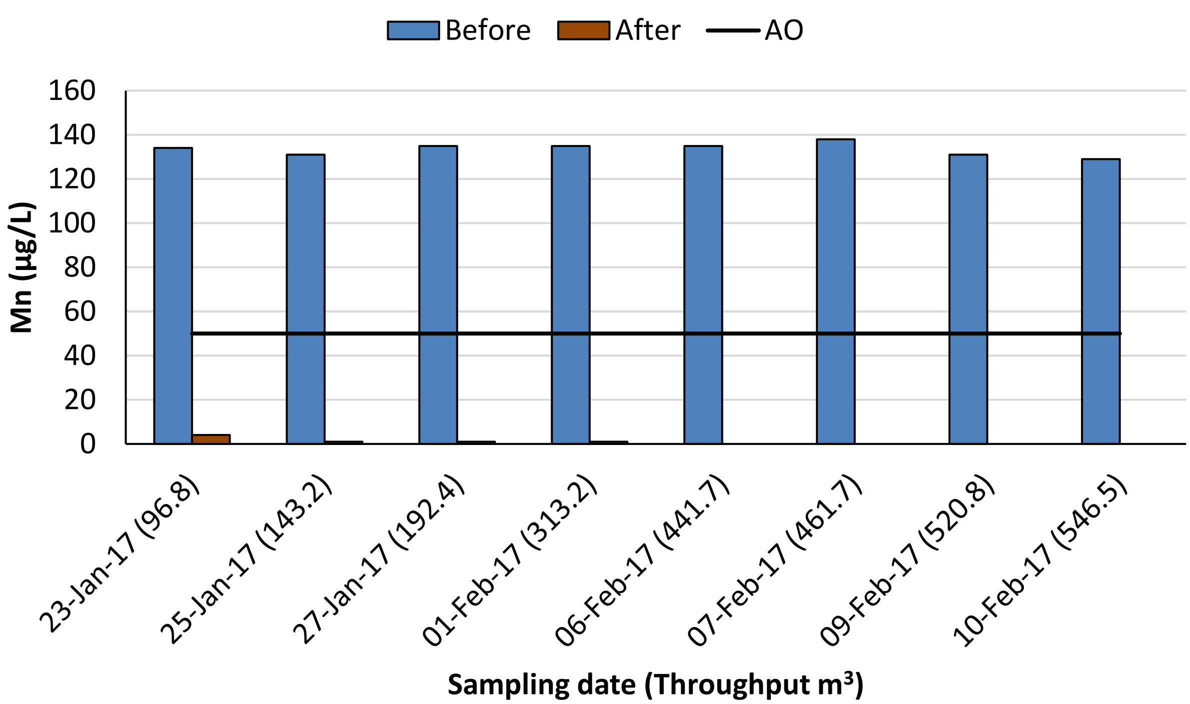


Figure 2.4 *Manganese removal through GreensandPlus filter at different sampling dates; values in the brackets represent the cumulative throughput volume of the water.*

2.2.2 Long-term efficacy evaluation-arsenic removal through E33 Bayoxide

The concentration of arsenic before and after the E33 Bayoxide adsorptive media after Birm and GreensandPlus are shown in Figures 2.5 and 2.6, respectively. It must be noted that the calculated cumulative bed volumes for these medias are based on the start date of the pilot operation (on December 16, 2016). As it is shown in Figures 2.5 and 2.6, after around 12000 cumulative bed volumes, the arsenic concentration after both adsorptive media (after Birm and after GreensandPlus) reached to 5µg/L. Although manganese concentration after Birm and before E33 Bayoxide passed the Aesthetic Objective (50µg/L) between 12000 and 16000 cumulative bed volumes, the arsenic removal efficiency of this media was similar to that after GreensdandPlus. Based on Figures 2.5 and 2.6, it can be predicted that after around 24000 cumulative bed volumes, the arsenic concentration in the E33 adsorptive media treated water will reach to around 10 µg/L (i.e., equivalent to the inlet concentration and the MAC).

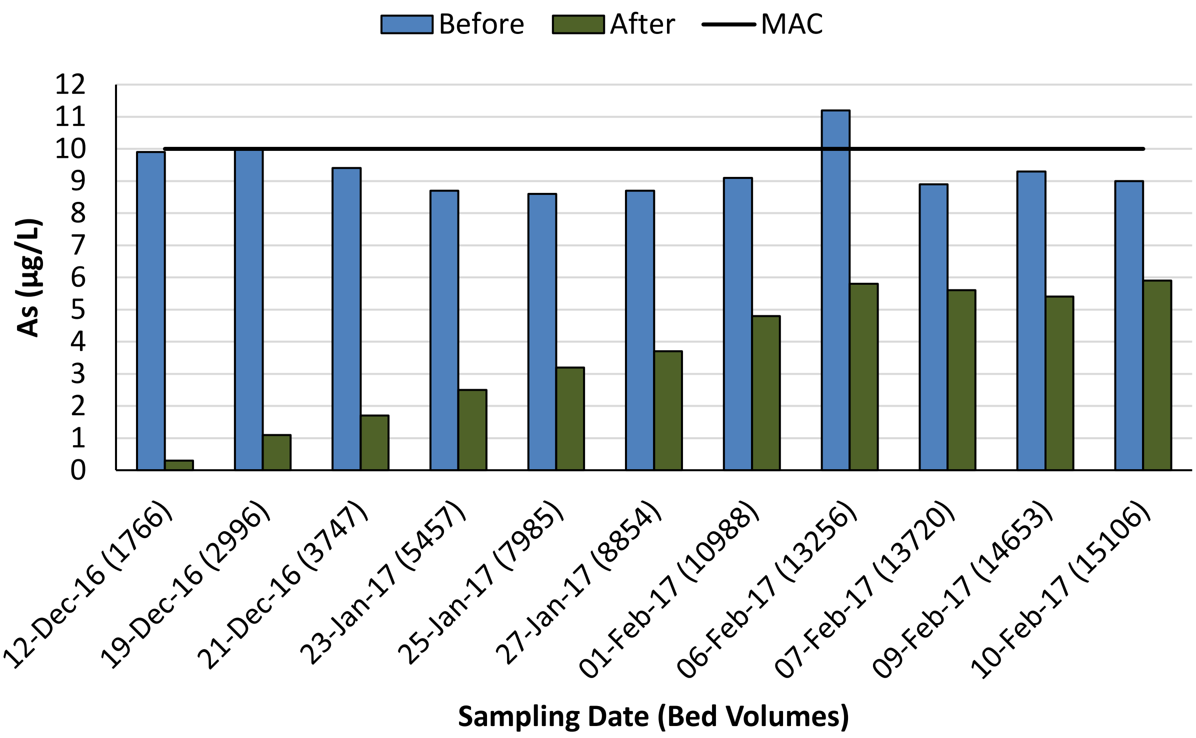


Figure 2.5 *Arsenic removal through E33 Bayoxide adsorptive media (After Birm) at different sampling dates; values in the brackets represent the Bed Volumes.*

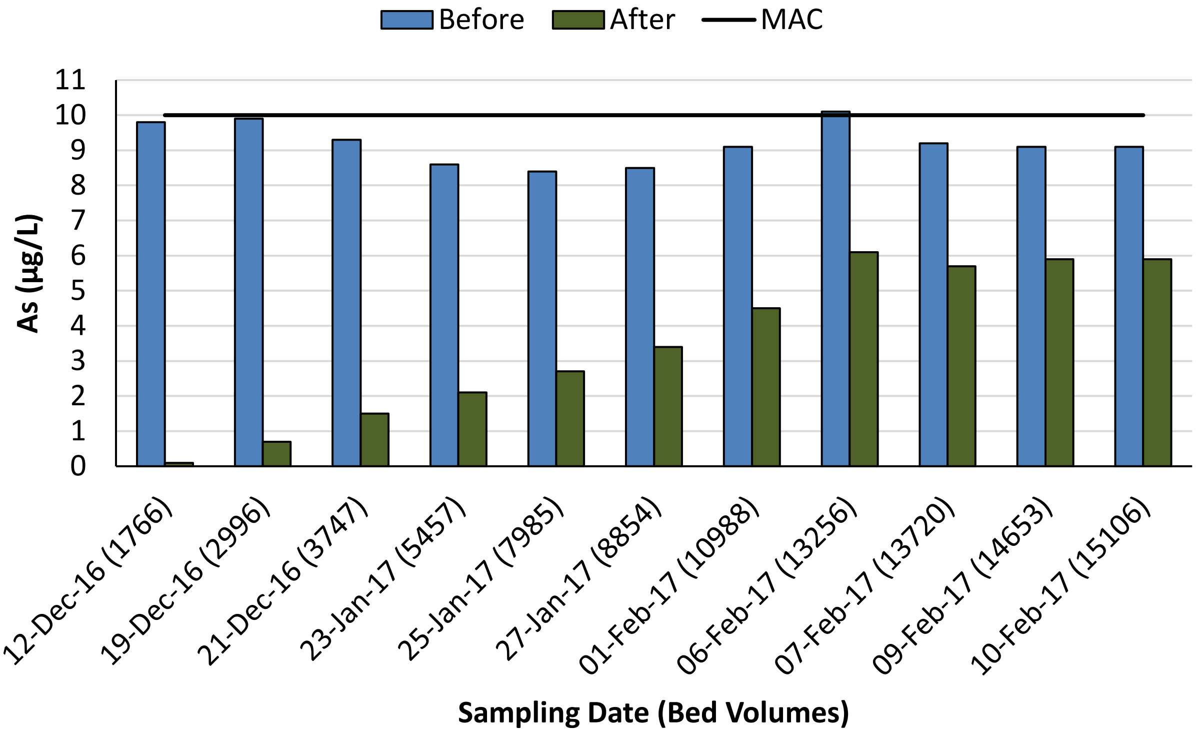


Figure 2.6 *Arsenic removal through E33 Bayoxide adsorptive media (After GreensandPlus filter) at different sampling dates; values in the brackets represent the Bed Volumes.*

2.2.3 Long-term efficacy evaluation-Manganese removal through E33 Bayoxide

Figure 2.7 shows the performance of E33 Bayoxide adsorptive media when it is introduced to high levels of manganese. As it is shown, this media is able to remove some levels of manganese, even though it is not considered for manganese removal in the industry. This feature can be considered useful because if there is any residual manganese in the water in case of breakthrough in the manganese removal filter, E33 can adsorb that along with arsenic adsorption.

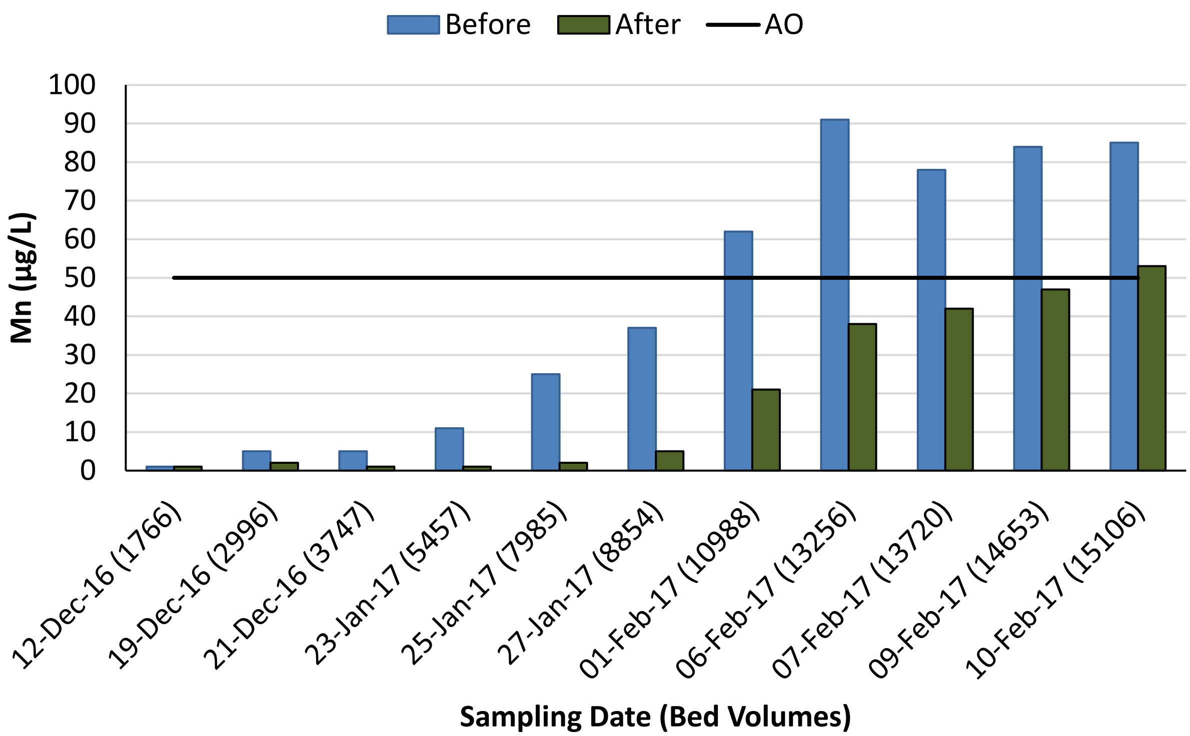
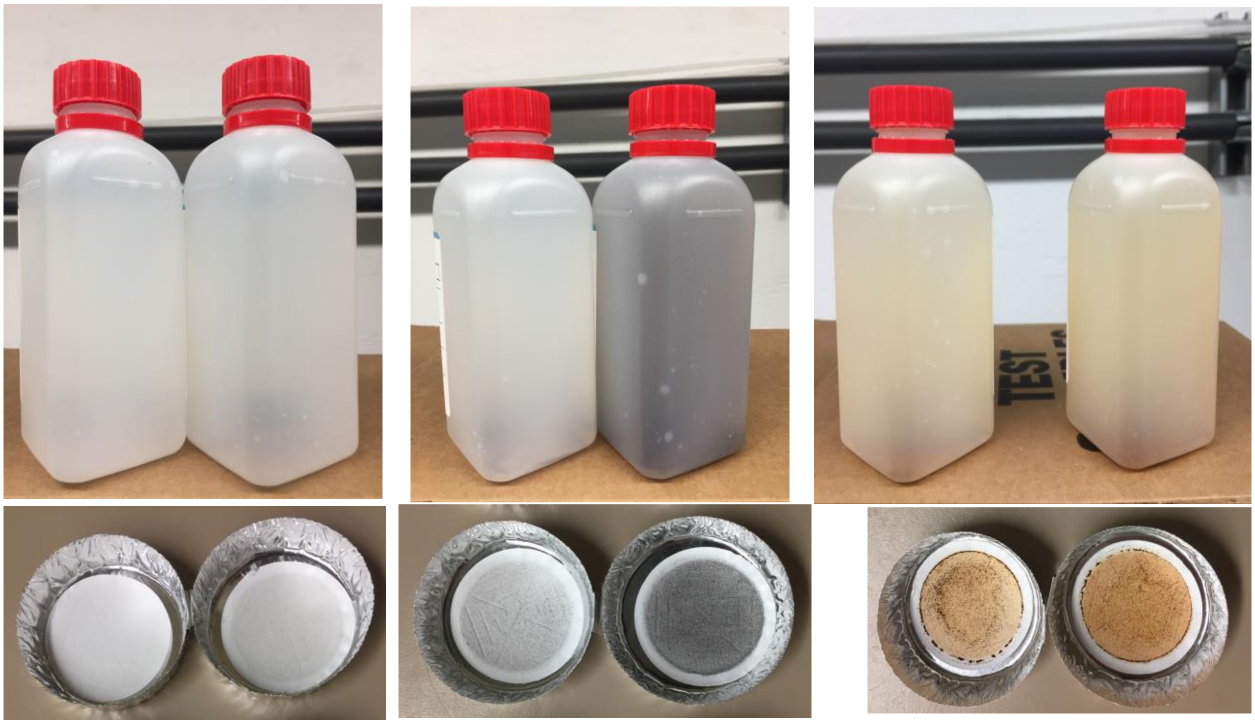


Figure 2.7 *Manganese removal through E33 Bayoxide adsorptive media (After Birm) at different sampling date; values in the brackets represent the Bed Volumes.*

2.2.4 Long-term efficacy evaluation-Backwash water quality

The total suspended solids and the manganese levels in the backwash water for January 19, 2017 and February 10, 2017 are available in Table 2.2 and Table 2.3, respectively. Comparing these results indicates that 10 minutes is not enough for the backwash and the water quality does not reach that of the feed water. In addition, for the E33 Bayoxide, backwashing did not remove the adsorbed arsenic on the media confirming the fact that these media cannot be regenerated at least through backwash cycle.



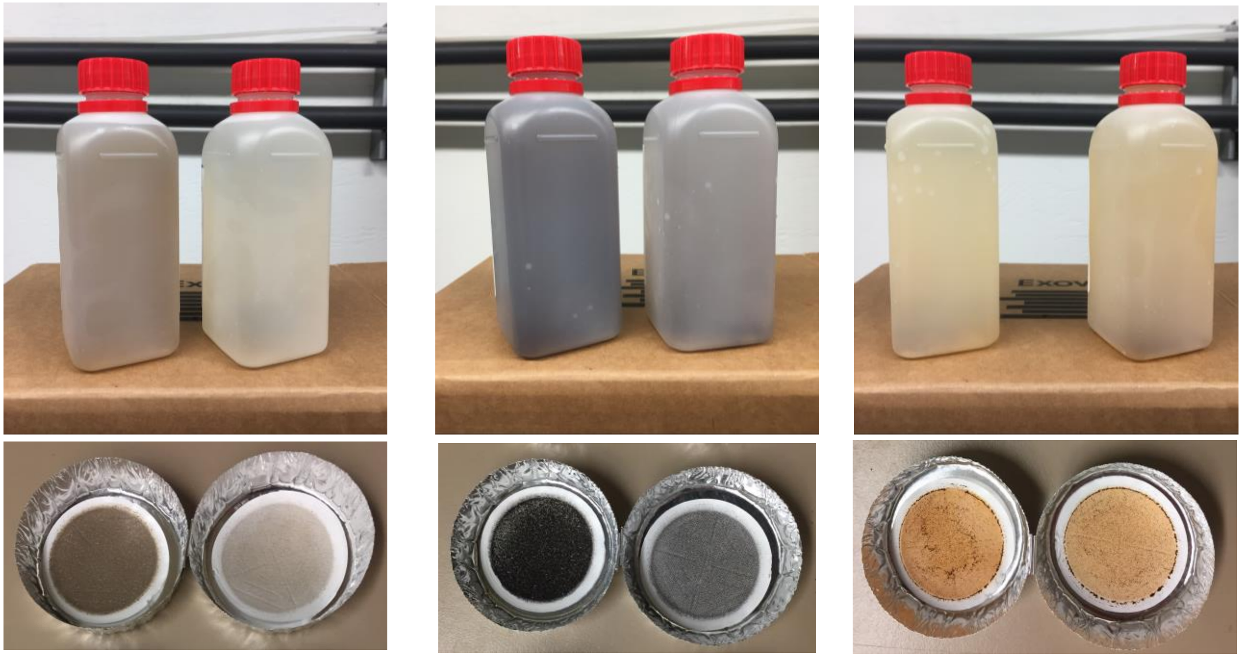
a *b* *c*

Figure 2.8 *Backwash water samples and TSS test results (Thursday January 19, 2017): a) Left: Birm-after 2min, Right: Birm-after 10min, b) Left: GreensandPlus-after 2min, Right: GreensandPlus-after 10min, c) Left: Birm-E33-after 4min Right: GreensandPlus-E33-after 4min.*

Table 2.2.1 *Analytical data for backwash water samples (Thursday January 19, 2017)*

Media	Birm				GreensandPlus				Birm-E33				GreensandPlus-E33			
Time (min)	As (mg/L)	Mn (mg/L)	Fe (mg/L)	TSS (mg/L)	As (mg/L)	Mn (mg/L)	Fe (mg/L)	TSS(mg/L)	As (mg/L)	Mn (mg/L)	Fe (mg/L)	TSS (mg/L)	As (mg/L)	Mn (mg/L)	Fe (mg/L)	TSS (mg/L)
2	0.01	0.04	0.02	0	0.01	2.06	0.09	5.5	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-		0.01	0.2	31.3	127.1	0.01	0.3	51.9	108.0
10	0.01	1.75	0.22	10	0.01	10.6	0.56	29.0	-	-	-	-	-	-	-	-
Guideline*	**1**	**5**	**10**	**600**	**1**	**5**	**10**	**600**	**1**	**5**	**10**	**600**	**1**	**5**	**10**	**600**

**Greater Vancouver sewerage and drainage district sewer use bylaw no. 299, 2007*



a *b* *c*

Figure 2.9 *Backwash water samples and TSS test results (Friday February 10th 2017): a) Left: Birm-after 5min, Right: Birm-after 10min, b) Left: GreensandPlus-after 5min, Right: GreensandPlus-after 10min, c) Left: Birm-E33-after 4min Right: GreensandPlus-E33-after 4min.*

Table 2.2.2 *Analytical data for backwash water samples (Friday February 10, 2017)*

Media	Birm				GreensandPlus				Birm-E33				GreensandPlus-E33			
Time (min)	As (mg/L)	Mn (mg/L)	Fe (mg/L)	TSS (mg/L)	As (mg/L)	Mn (mg/L)	Fe (mg/L)	TSS(mg/L)	As (mg/L)	Mn (mg/L)	Fe (mg/L)	TSS (mg/L)	As (mg/L)	Mn (mg/L)	Fe (mg/L)	TSS (mg/L)
4	-	-	-	-	-	-	-	-	0.01	0.35	3.62	63.0	0.01	0.1	5.96	85.0
5	0.01	3.02	2.1	73.0	0.01	5.43	0.17	57.0	-	-	-	-	-	-	-	-
10	0.01	0.92	0.46	22.0	0.01	2.1	0.08	20.0	-	-	-	-	-	-	-	-
Guideline*	**1**	**5**	**10**	**600**	**1**	**5**	**10**	**600**	**1**	**5**	**10**	**600**	**1**	**5**	**10**	**600**

**Greater Vancouver sewerage and drainage district sewer use bylaw no. 299, 2007*

2.3 High filtration rate-GreensandPlus filter

The experiments conducted during the month of February 2017 showed that GreensandPlus provided better manganese removal efficiency than Birm did. So, it was decided to further evaluate the performance of GreensandPlus at higher flowrates. The experimental procedure and the results of this set of experiments are presented in this section.

The system was started to operate on Monday February 20, 2017. In order to provide the maximum possible flowrate through the GreensandPlus filter, the inlet valve for the second train (i.e., Birm filter) was closed and the water was directed into the GreensandPlus filter line. The pressure values before and after the filter were recorded and used to evaluate the pressure differential change in the system during the operation. A total of eight water samples were collected before and after the filter on different days between February 21 and March 3, 2017. The flow rate was adjusted to around 35 L/min (20 m/h filtration rate) and the free chlorine concentration after filter was monitored to be between 0.5 to 1 mg/L.

At the end of the experiment on March 3, 2017, the system was backwashed and the backwash samples were collected at different times for detailed analyses. The flowrate for the backwash was adjusted between 44 and 48 L/min to ensure the suspension of the bed could happen inside the filter. The chlorine dosing pump was stopped and feed water was used for the backwash.

2.3.1 High filtration rate-GreensandPlus filter-Long term evaluation

The pressure drop and the flowrate in the GreensandPlus filter line are presented in Figures 2.10 and 2.11, respectively. The pressure differential increased by about 6psi psi during the experiment (Figure 2.10), while the flowrate decreased by around 10 LPM in the same period of time (Figure 2.11). This means that the pressure build up in the filter would affect the adjusted flowrate for the filter when it is running at high flow rates.

The manganese concentration in the outlet of GreensandPlus filter was consistently below 1 µg/L throughout the operation, up to around 415 m^3 cumulative volumes (Figure 2.12). This means that the GreensandPlus filter performs efficiently even at high flowrates (i.e., up to 20 m/h bed velocity). In other words, decreasing the retention time in the filter would not affect the efficiency of the filter for the removal of manganese.

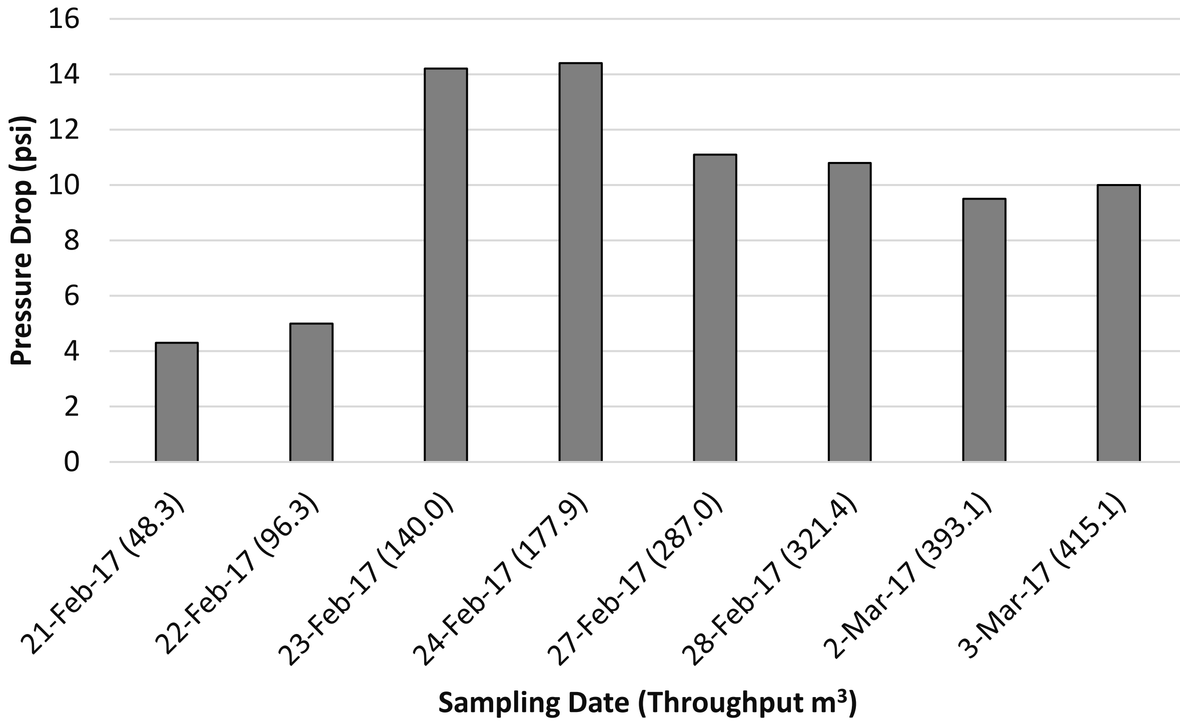


Figure 2.10 *Pressure drop across the GreensandPlus filter at different sampling dates; values in the brackets represent the cumulative throughput volume of the water.*

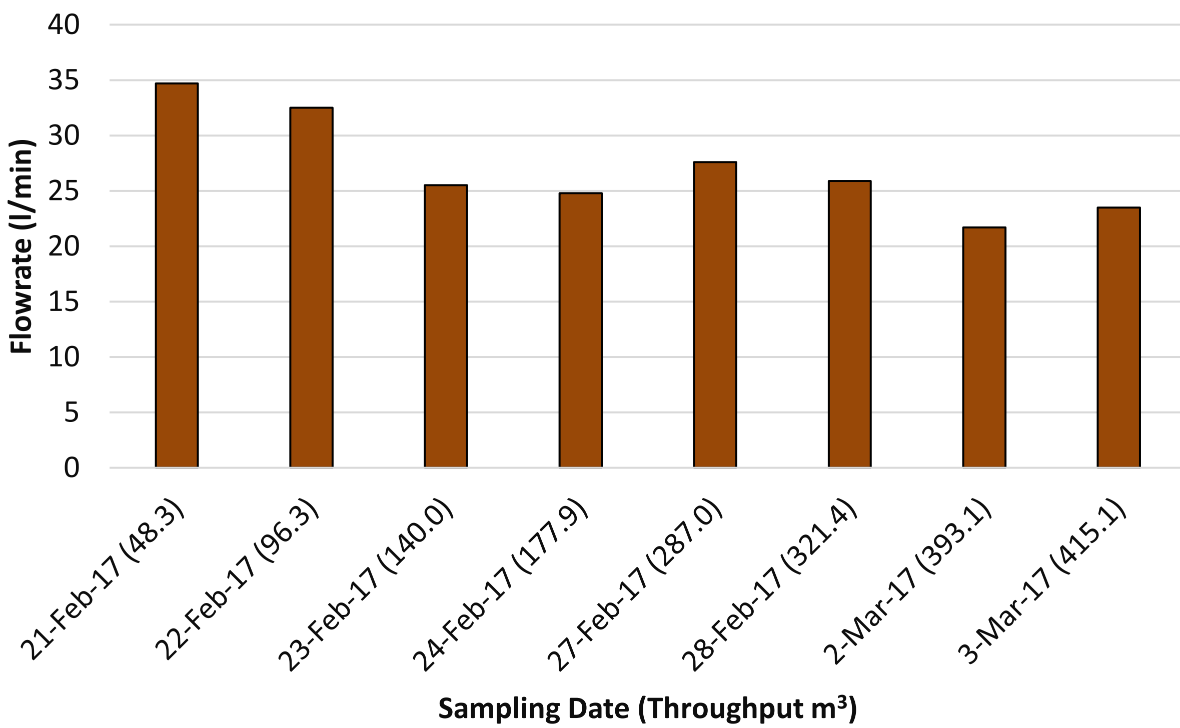


Figure 2.11 *Flow rate in GreensandPlus filter at different sampling dates; values in the brackets represent the cumulative throughput volume of the water.*

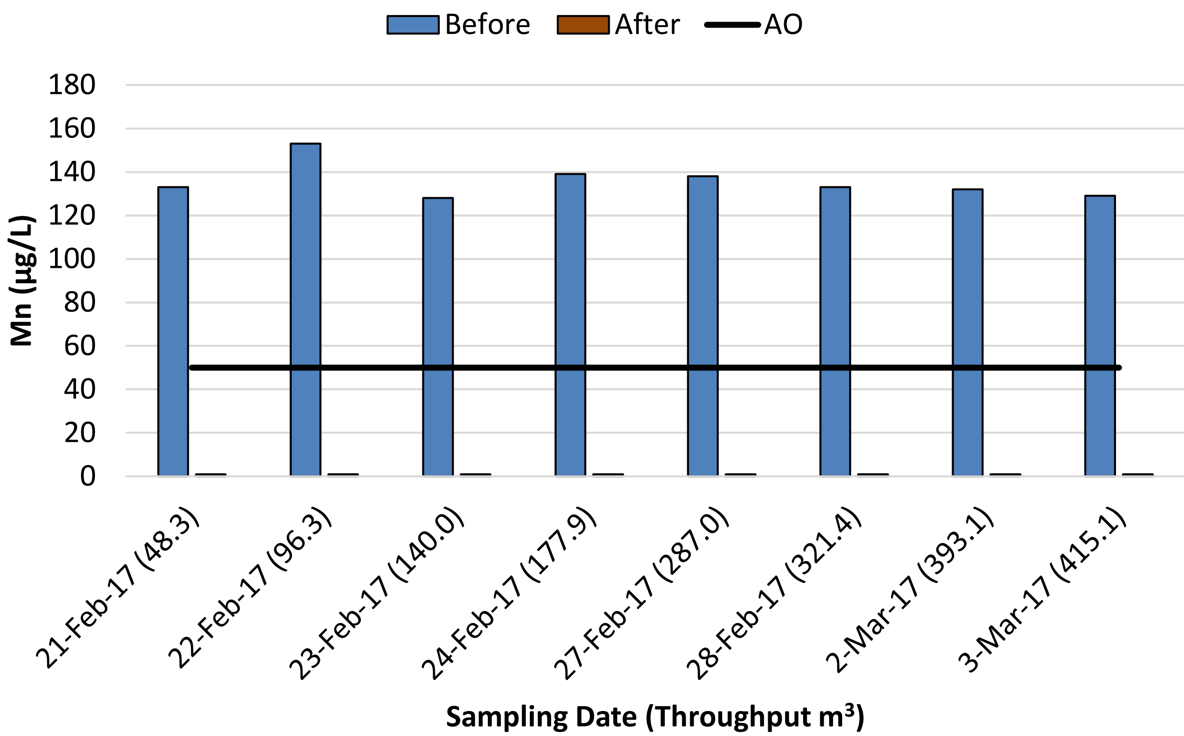


Figure 2.12 *Manganese removal through GreensandPlus filter at high flowrate at different sampling dates; values in the brackets represent the cumulative throughput volume of the water.*

2.3.2 High filtration rate-Back wash water quality

The total suspended solids and the manganese levels in the backwash water are shown in Figures 2.14 and 2.15, respectively (January and February data are included). For the January 19, 2017, backwash water, the samples were collected after 2min and 10min. Comparing these two samples showed an increase in both TSS and manganese levels; however, for the February 10, 2017, backwash water, the water sample taken after 5min did not follow the same trend. It was higher in both TSS and manganese level than 10-min sample. The results of March 3, 2017, backwash water showed the same trend as February 10, 2017, data. Based on the results, it can be concluded that the peak value for manganese and TSS concentrations in the GreensandPlus backwash water happens within 10-15 minutes from the start of the process and after around 25 to 30 minutes, the backwash water quality reaches that of the feed water.

5min 10min 15min 20min 25min 30min

Figure 2.13 *Backwash water samples and Total Suspended Solids test results at different times.*

Table 2.3.1 *Analytical data for backwash water samples.*

Time (min)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	As (mg/L)	Mn (mg/L)	Fe (mg/L)	TSS (mg/L)
0 (Raw water)	0	0	0.0093	0.129	0.004	0
5	>2.2	>2.2	0.0168	22.5	2.1	48
10	>2.2	>2.2	0.0110	6.83	0.548	13
15	1.43	>2.2	0.0093	3.08	0.263	4
20	1.14	1.76	0.0094	2.64	0.191	3
25	0.78	1.24	0.0091	1.40	0.104	1
30	0.77	1.42	0.0090	1.56	0.103	2
Average	-	-	0.011	6.22	0.48	12
Guideline*	-	-	**1**	**5**	**10**	**600**

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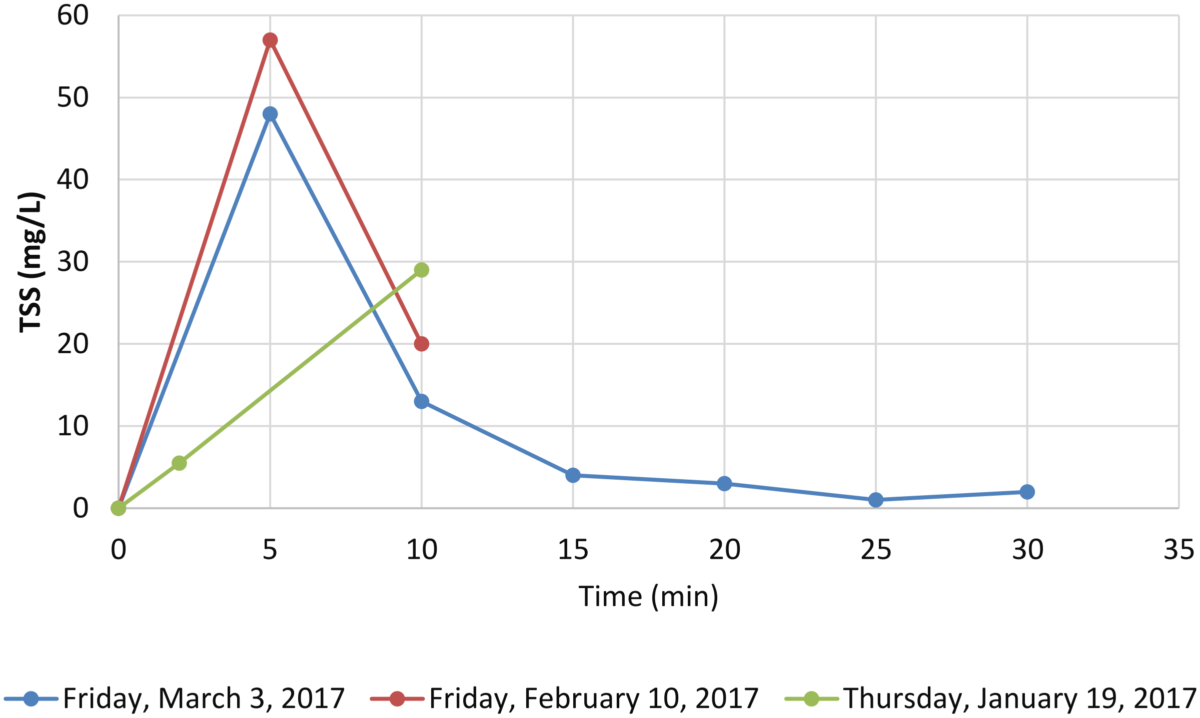

Figure 2.14 *Total suspended solids in backwash water versus time.*

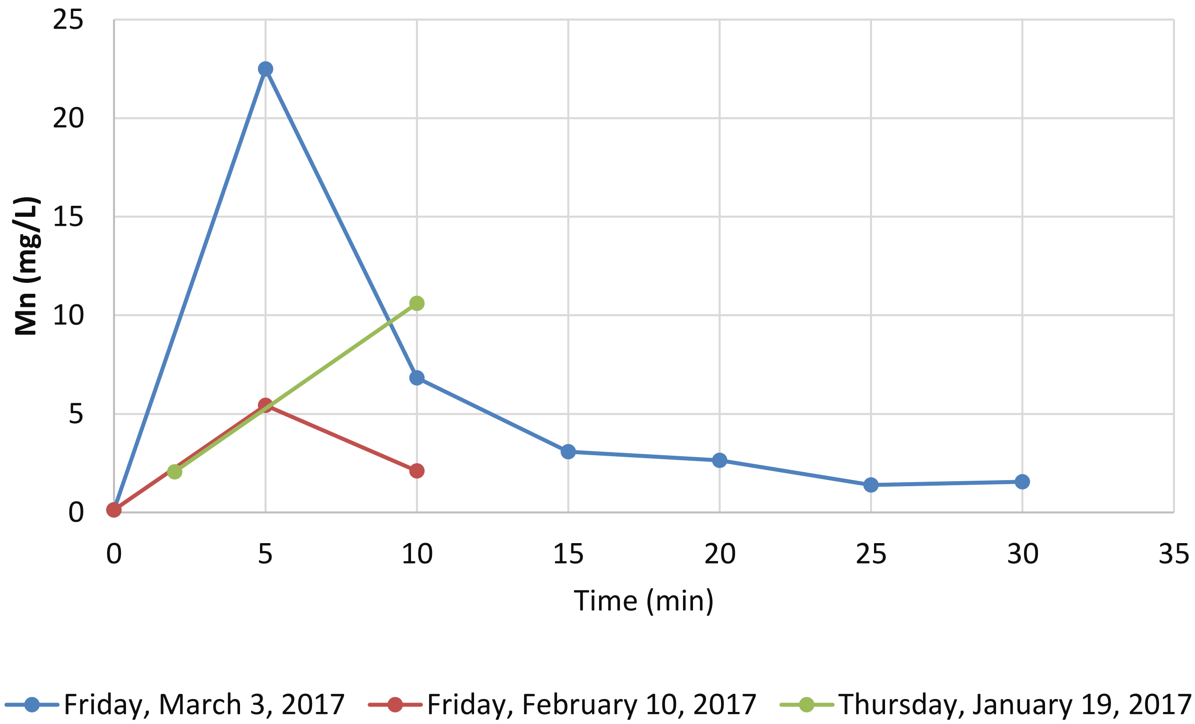

Figure 2.15 *Manganese concentrations in backwash water versus time.*

2.4 Ozone oxidation

Results of the experiments, conducted in February and March 2017, showed that adding sodium hypochlorite as an oxidant followed by GreensandPlus filter would effectively remove manganese from water; however, this combination did not have a significant impact on the arsenic concentration. Considering the fact that ozone is a stronger oxidant, it was evaluated to investigate its efficacy at converting As (III) to As (V), and thereby removing arsenic in the GreensandPlus filter. The experimental procedure and the results of this set of experiments are presented in this section.

The system was started on Thursday March 30, 2017. During the first three days, March 30-April 1, 2017, different system configurations were tested to establish reliable experimental conditions and stable injection of ozone to the system. Upon reaching stable ozone injection and concentration in the water, the filter was backwashed on Thursday April 6, 2017. The main experiment started on April 7, 2017. Two ozone concentrations, 0.5mg/L and 1mg/L, were applied over the course the experiment to assess their impacts on both manganese and arsenic removal through the GreensandPlus filter. The pressure differential across the filter was measured right before and after the filter by reading the corresponding pressure monitors. A total of thirty water samples were collected before and after the filter on different days between March 30 and April 27, 2017. To compare ozone injection result with that of chlorine injection, the system flow rate was adjusted to 18 L/min over the course of experiment.

At the end of the experiment on April 27, 2017, the system was backwashed and the backwash samples were collected at different times for detailed analyses. The flowrate was set between 44 and 48 L/min and the source water was used for the backwash.

2.4.1 Ozone oxidation- arsenic speciation

To evaluate the effect of ozone on oxidation of arsenic, samples were collected before and after ozone injection on different days. The results are shown in Figure 2.16. For well #6, arsenite As(III) was oxidized completely to arsenate As(V) using 0.5mg/L of ozone. In addition, increasing the concentration to 1mg/L did not have any significant impact on the conversion of As(III) to As(V) for this well. More tests for Well #7 which has more As(III) concentration is in progress.

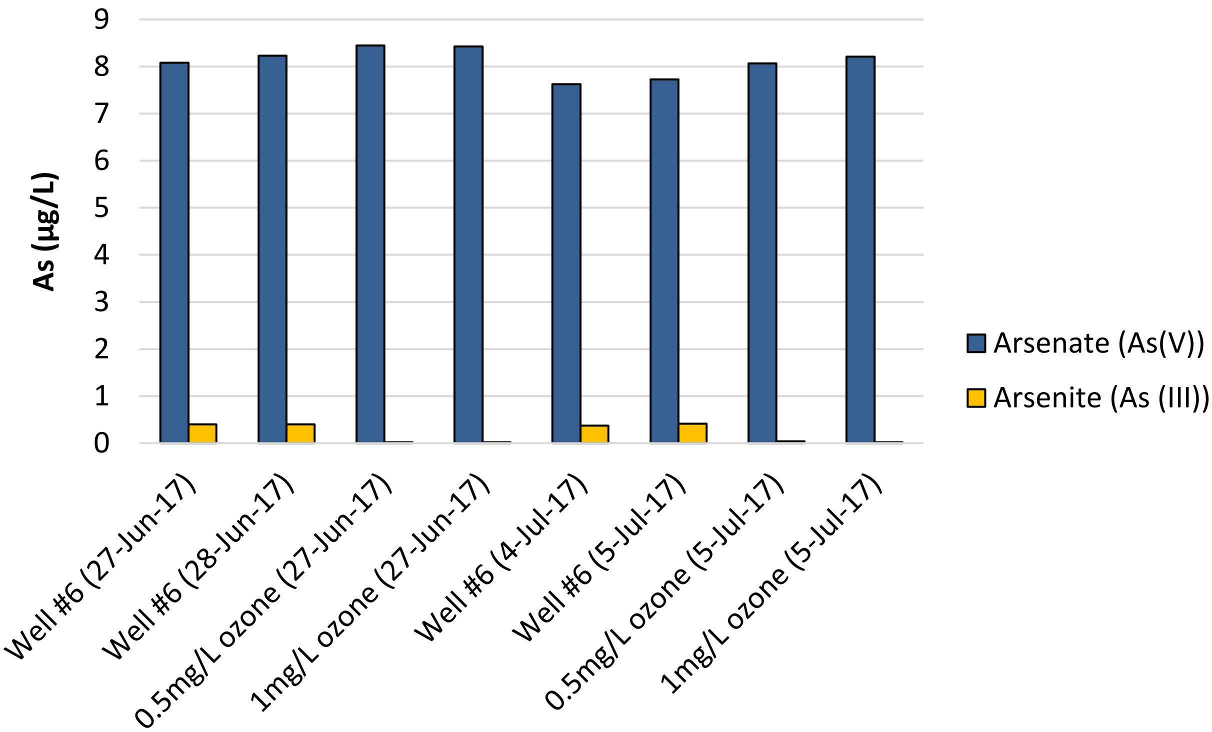

Figure 2.16 *Oxidation of As (III) to As (V) by ozone.*

2.4.2 Ozone oxidation - long-term evaluation

The pressure drop data in the GreensandPlus filter are presented in Figure 2.17. As this graph shows, the pressure differential across the filter increased by about 4.2 psi over the course of the experiment. It started from 2.8 psi considered as the clean bed head loss and reached 7 psi after treating 67.1m^3 cumulative volume of water.

The concentration of manganese in the outlet of the GreensandPlus filter was consistently below 5µg/L throughout the operation (Figure 2.18); however, arsenic concentration did not change significantly after filtration (Figure 2.19), indicating that application of ozone up to 1mg/L did not have any impact on the removal of arsenic in the GreensandPlus filter.

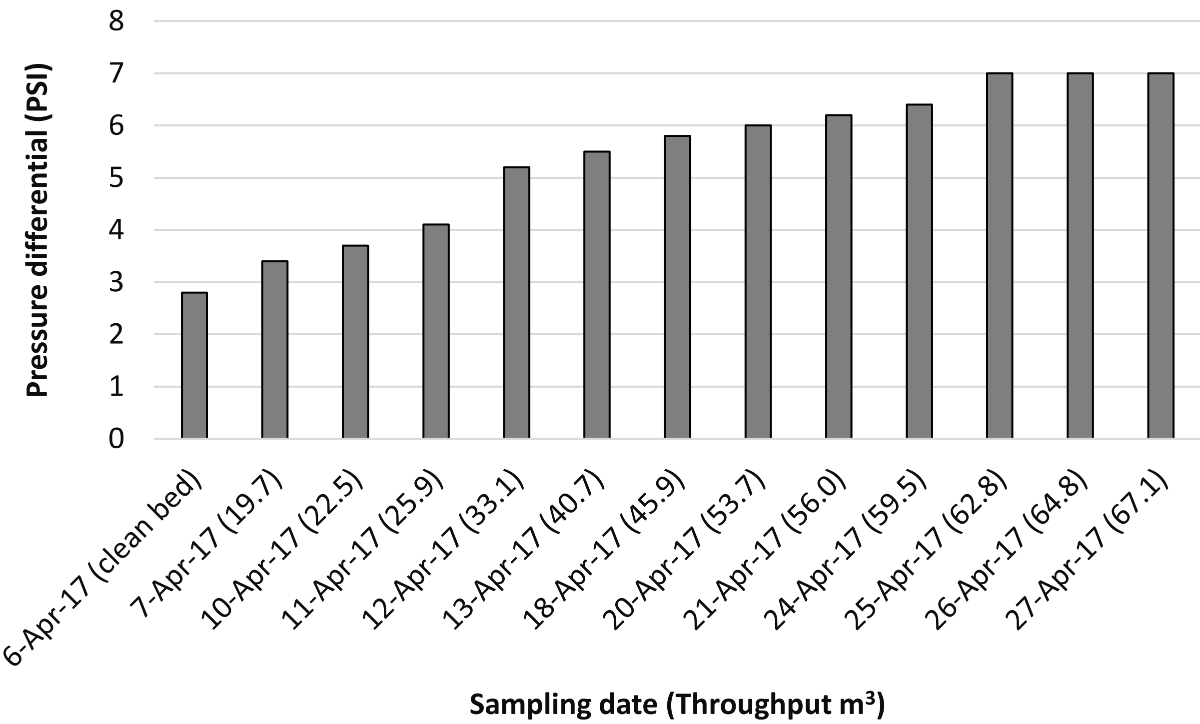

Figure 2.17 *Pressure drop across the GreensandPlus filter at different sampling dates; values in the brackets represent the cumulative throughput volume of the water.*

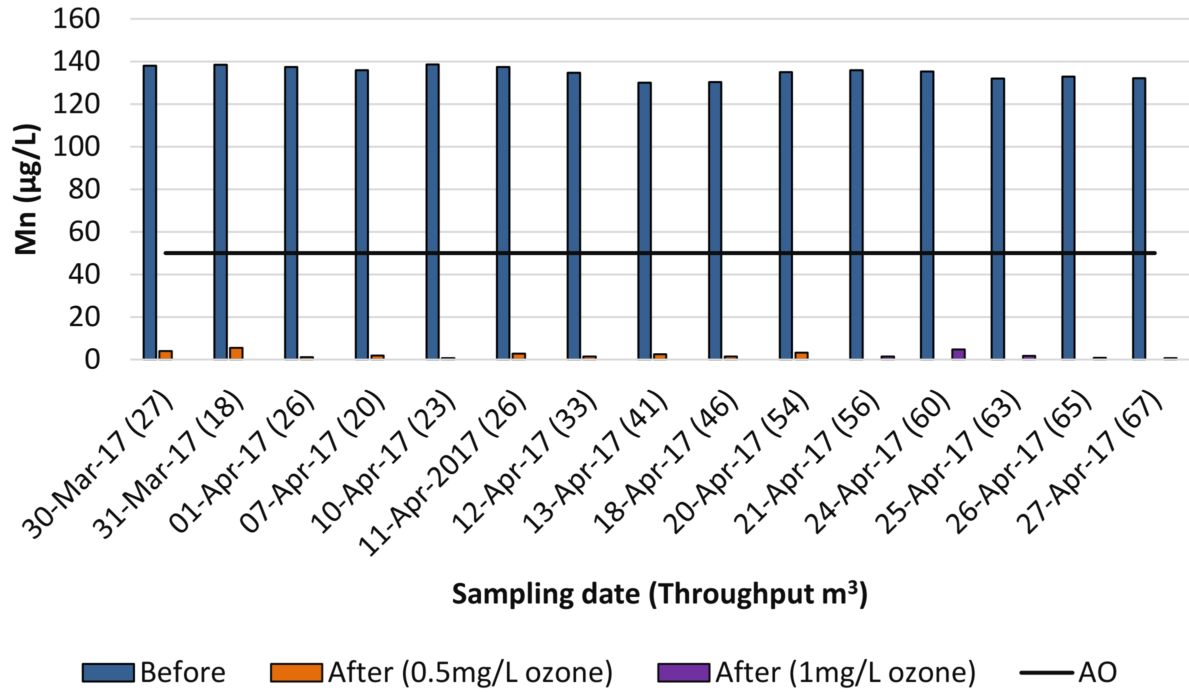

Figure 2.18 *Manganese concentrations before and after GreensandPlus at different sampling dates; values in the brackets represent the cumulative throughput volume of the water.*

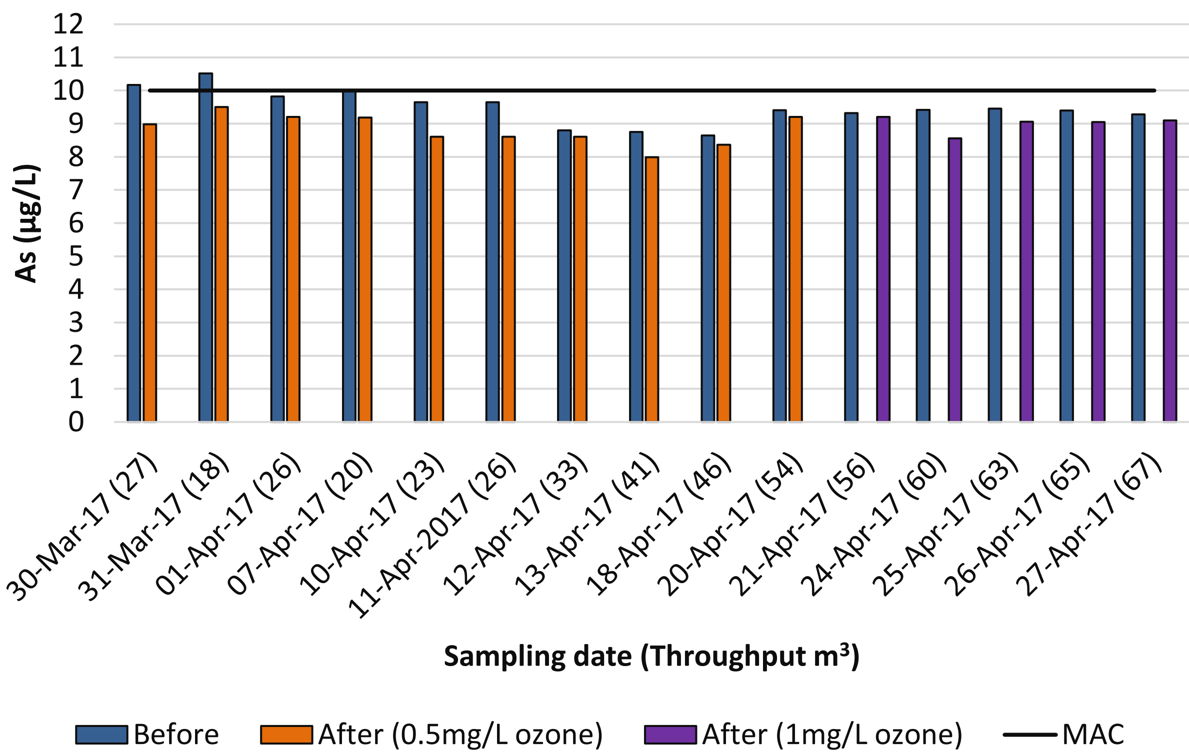

Figure 2.19 *Arsenic concentrations before and after GreensandPlus at different sampling dates; values in the brackets represent the cumulative throughput volume of the water.*

2.4.3 Ozone oxidation-Backwash water quality

The total suspended solids and the manganese levels in the backwash water are shown in Figures 2.21 and 2.22, respectively. As it can be seen in both figures, 30min backwash period was not enough to bring the water quality back to that of the feed water. In addition, the average manganese level in the backwash water was 17.23 mg/L (Table 2.5) which is above the standard level. This means that the filter is holding more of the precipitants during the operation.

Start   3min   5min   8min   10min   15min   20min   25min   30min

Figure 2.20 *Backwash water samples and Total Suspended Solids test results at different times, after ozonation study.*

Table 2.4.1 *Analytical data for backwash water samples, after ozonation study.*

Time (min)	As (mg/L)	Mn (mg/L)	Fe (mg/L)	TSS (mg/L)
0	0.13	53	3.3	12
3	0.055	29	1.2	59
5	0.059	30	1.3	60
8	0.049	27	1.1	55
10	0.0450	24	0.97	44
15	0.026	12	0.48	23
20	0.019	7.3	0.31	8
25	0.018	6.20	0.27	9
30	0.0150	4.4	0.18	6
Average	0.04	17.23	0.77	27.40
Guideline*	**1**	**5**	**10**	**600**

**Greater Vancouver sewerage and drainage district sewer use bylaw no. 299, 2007*

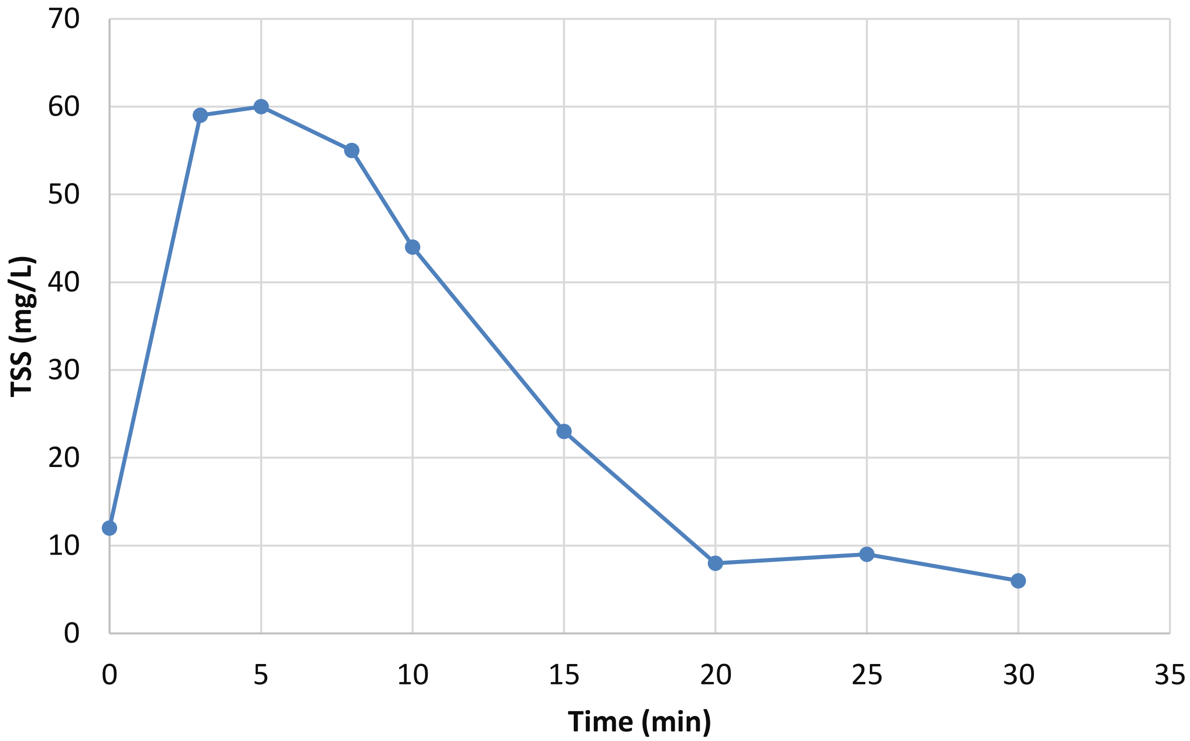

Figure 2.21 *Total suspended solids in the backwash water versus time, after ozonation study.*

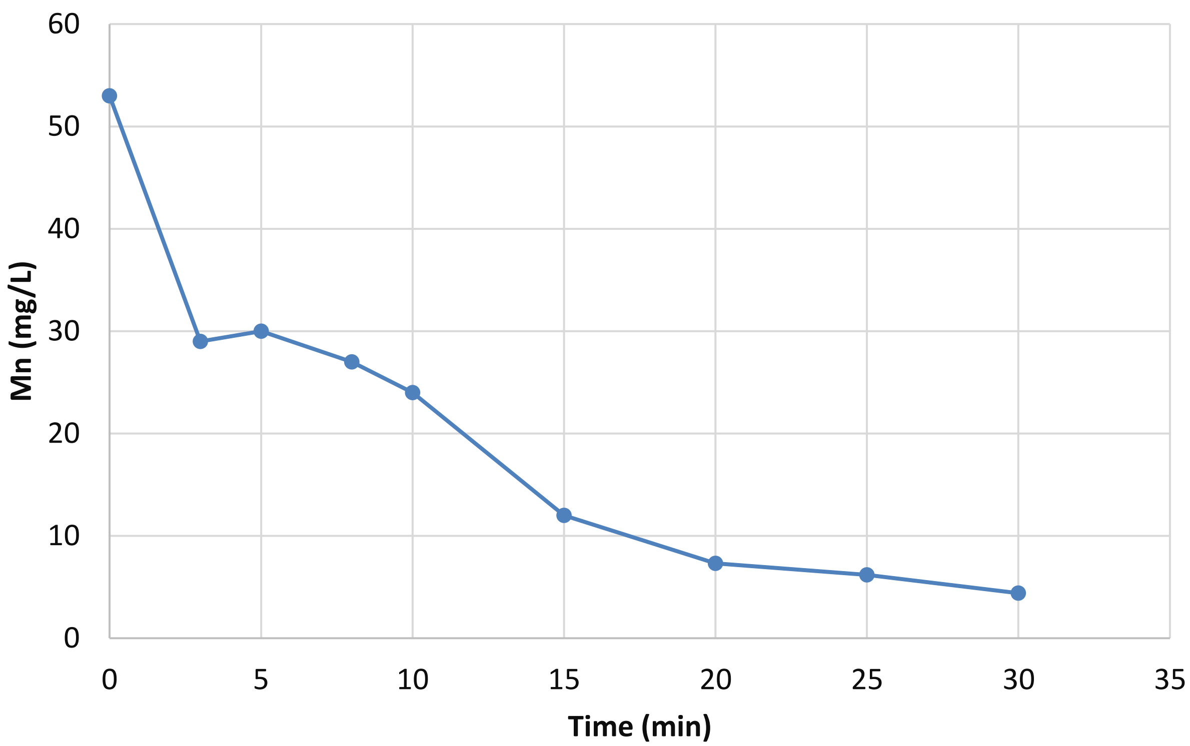

Figure 2.22 *Manganese concentrations in the backwash water versus time, after ozonation study.*

2.5 Iron injection

The results of the experiments, conducted in December 2016 to March 2017, showed that GreensandPlus filter effectively removes manganese from water; however, it does not have a significant impact on the arsenic concentration. From previous studies in the field, it is known that the coagulation process using iron could potentially improve the arsenic removal in the GreensandPlus filter. Therefore, it was decided to investigate the efficacy of the ferric chloride injection at removing arsenic in the GreensandPlus filter. The experimental procedure and the results of this set of experiments are presented in this part.

The filter configuration was changed on Monday May 8, 2017. The height of the GreensandPlus media was decreased to 20 inches. Around 12inches of the anthracite was added on top of the filter. Two different stock solution of ferric chloride, 1000ppm and 10000ppm, were prepared in the lab by dissolving ferric chloride hexahydrate in DI water. By using these stock solutions and changing the flow rate of the dosing pump, ferric chloride was injected at different concentrations before the filter.

Preliminary tests were conducted on Monday May 10, 2017, and on three different days the week after, May 16-18, 2017, to determine the concentration of iron that could potentially provide maximum arsenic removal from water. For each injection, the pumping rate was adjusted and after running the filter for around 45 minutes, two samples, one before and one after the filter, were collected. Manganese, arsenic and iron concentrations of each sample were tested in the lab. After evaluating these preliminary results, 1ppm of iron was selected for continuous injection and further testing.

Prior to conducting the experiment with 1ppm iron, the filter was backwashed on Wednesday May 31, 2017. Continuous experiment was then started and samples were collected between Thursday June 1 and Saturday June 3, 2017. The pressure differential across the filter was measured before and after the filter by reading the corresponding pressure gages. The system flow rate was set to 18 L/min and the chlorine concentration after the filter was adjusted to 0.5 to 1 mg/L free chlorine.

At the end of the experiment on Saturday June 3, 2017, the system was backwashed and the backwash water samples were collected at different times for detailed analyses.

The Jar test was performed in the pilot to evaluate the effect of flocculation on the removal of arsenic in the presence of manganese in water. The water sample with a volume of 500mL was collected after the iron injection point in the pipeline. It was mixed at lowest possible mixing rate of the stirrer (60 rpm). After different mixing time, 5min, 10min and 20min, 50mL of the sample was filtered through the 0.45µm filter. The experiment was repeated three times and the samples were analyzed for manganese, arsenic and iron concentration.

2.5.1 Iron injection-Preliminary test

The iron, manganese and arsenic concentrations before and after the filter for each injection experiment are presented in Figures 2.23, 2.24 and 2.25, respectively. The main purpose of the iron injection was to evaluate its impact on the removal of arsenic; however, the concentration of iron was also tested after the filter to ensure it did not go beyond the iron MAC level (300ppb). As Figure 2.23 shows, the iron level in the effluent was always below 50ppb, even when 3ppm of iron was injected before the filter. In addition, the manganese removal performance of the filter did not change with this level of iron injected (Figure 2.24). Arsenic removal efficiency of the filter was also evaluated for each injection (Figure 2.25). As it is shown, increasing the concentration of iron to more than 1ppm did not have any impact on the arsenic removal (Figure 2.26). Hence, it was determined that 1ppm of iron would be sufficient to remove 7.5 ppb of arsenic.

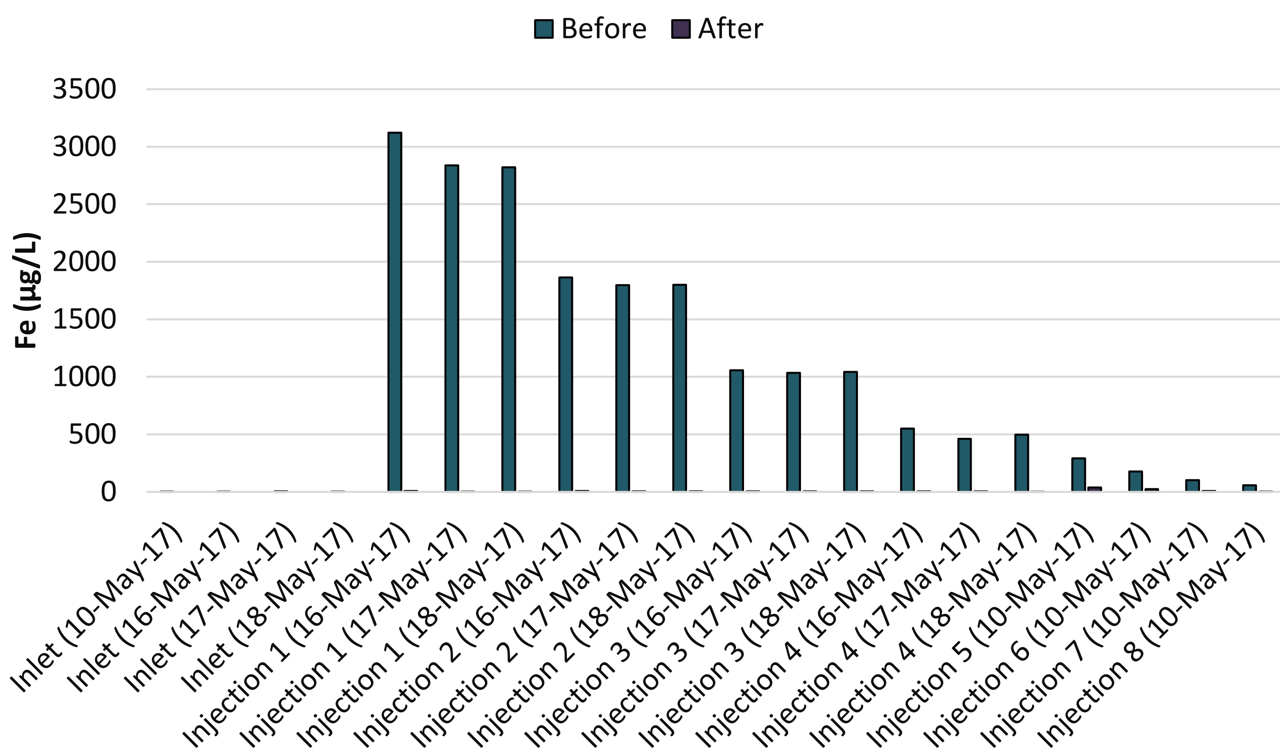

Figure 2.23 *Iron concentration before and after the filter at different injections and dates.*

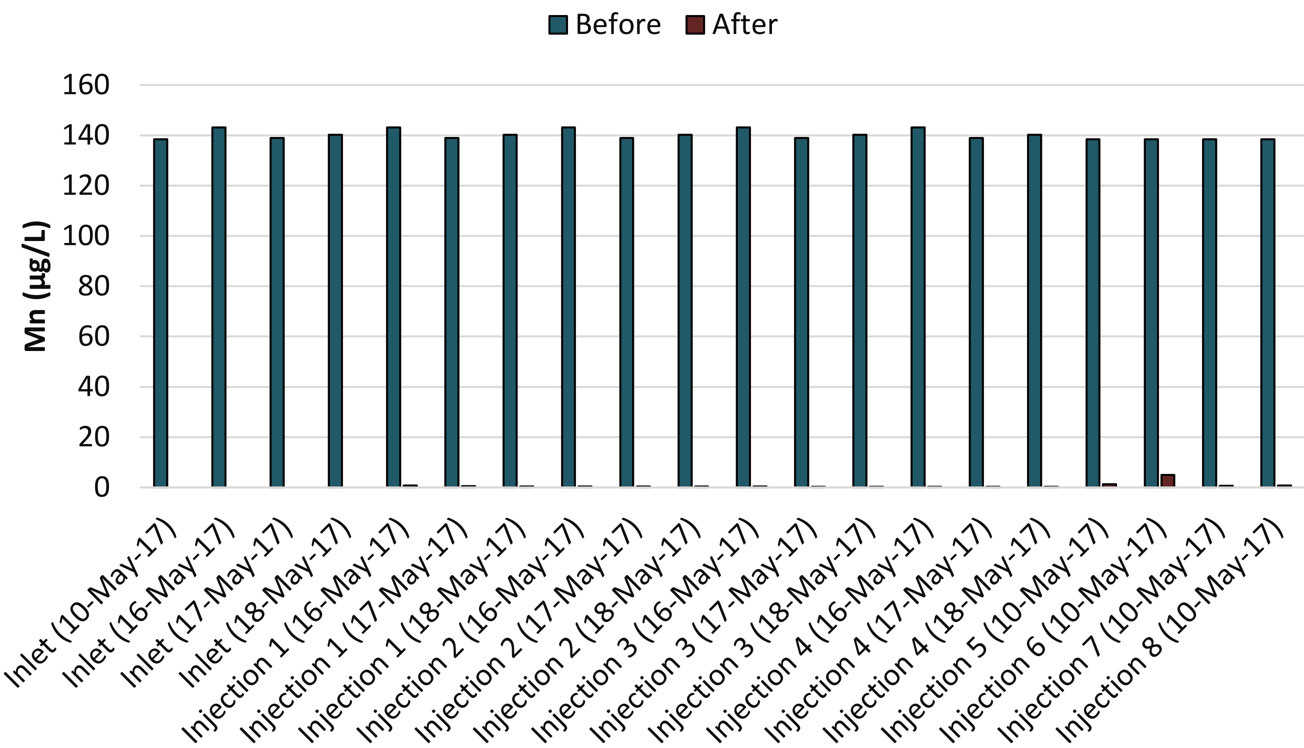

Figure 2.24 *Manganese concentration before and after the filter at different injections and dates.*

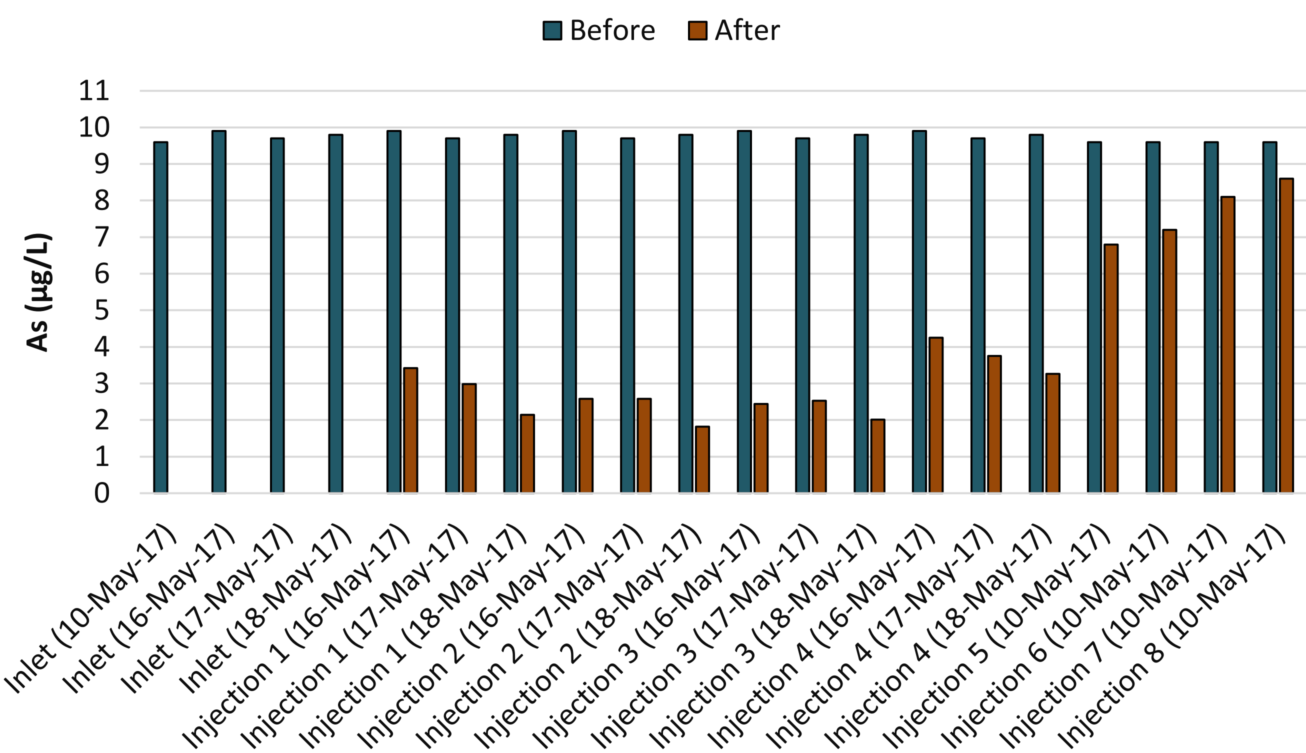

Figure 2.25 *Arsenic concentration before and after the filter at different injections and dates.*

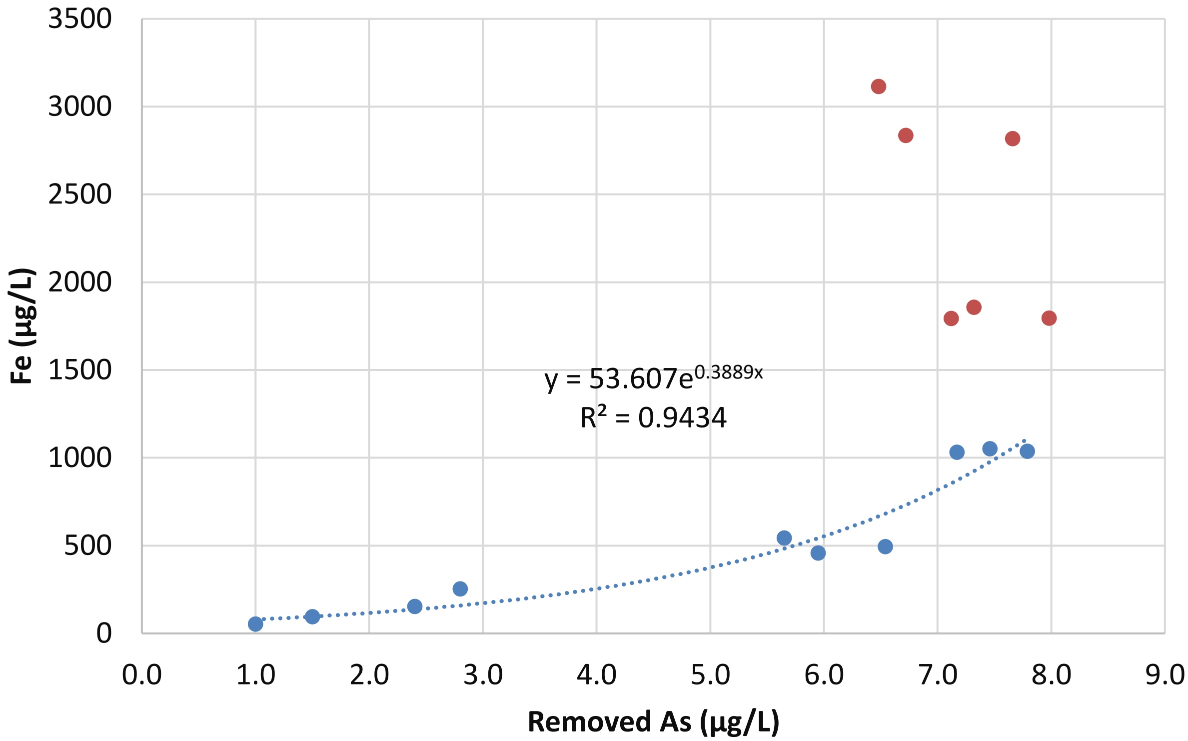

Figure 2.26 *Experimental data obtained on the required iron concentration for the removal of arsenic.*

2.5.2 Iron injection - Continuous injection of 1ppm iron

The pressure drop data in the GreensandPlus filter during continuous injection of iron is presented in Figure 2.27. The pressure differential across the filter increased by about 6psi over the course of the experiment (i.e., over three days). It started from 2.4psi, considered as the clean bed headloss, and reached 7.9psi after treating 71.7m^3 cumulative volume of water.

The concentration of manganese in the outlet of the GreensandPlus filter was consistently below 5µg/L throughout the operation (Figure 2.28); however, outlet concentration of arsenic increased from 4.4µg/L to 7.2µg/L (Figure 2.29). In addition, iron concentration in the effluent increased from 61µg/L to 524µg/L (Figure 2.30). Comparing the results to that of the preliminary test, it was concluded that at constant injection of iron, the performance of the filter in terms of removing arsenic decreased. In addition, accumulation of iron inside the filter did not enhance the arsenic removal efficiency of the filter.

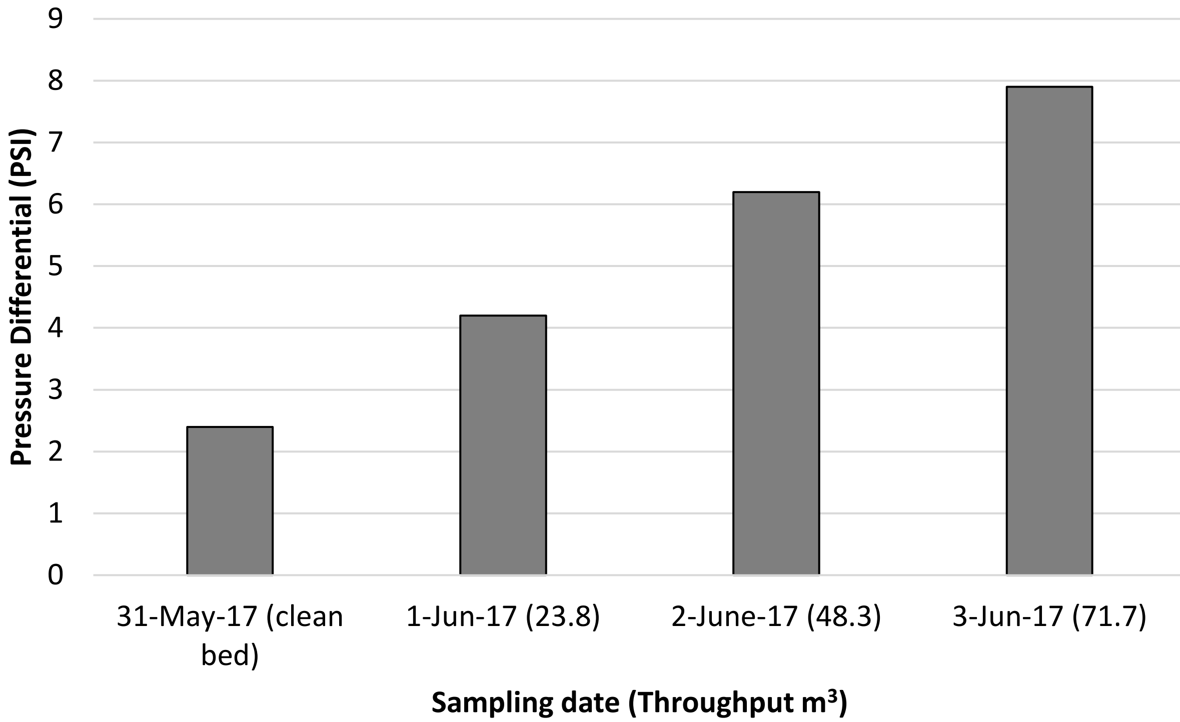

Figure 2.27 *Pressure drop across the filter at different sampling dates; values in the brackets represent the cumulative throughput volume of the water.*

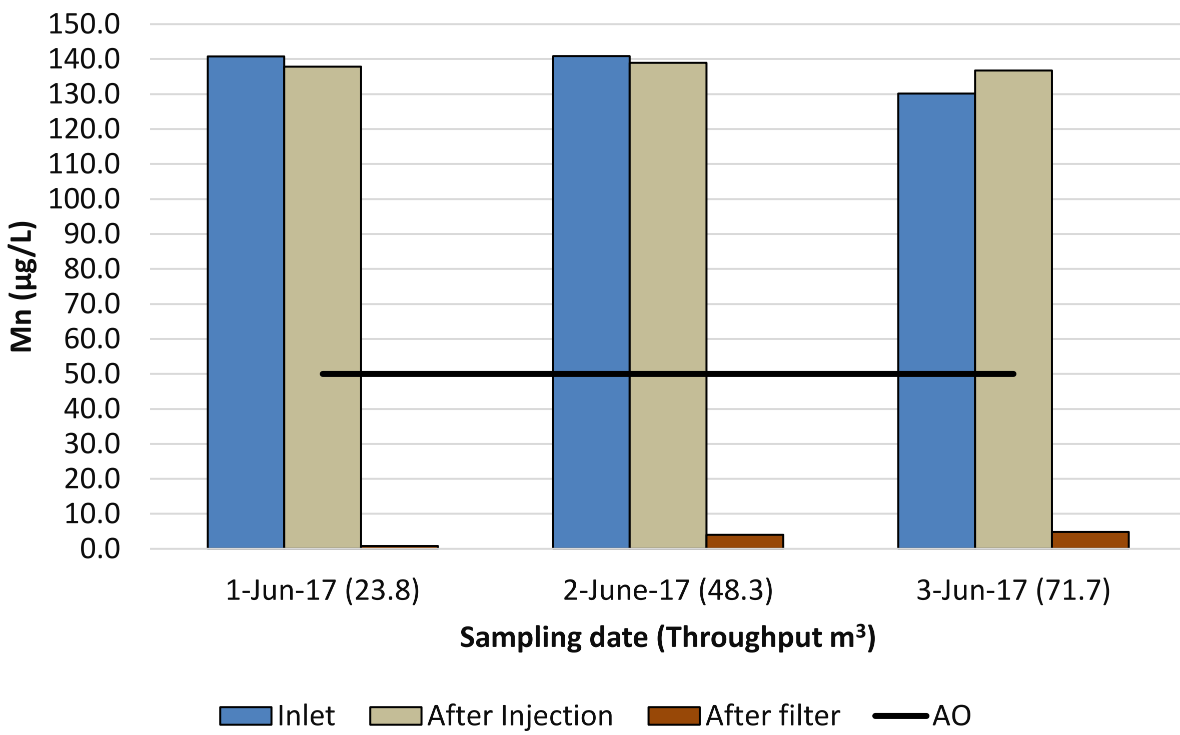

Figure 2.28 *Manganese concentrations before and after filter at different sampling date; values in the brackets represent the cumulative throughput volume of the water.*

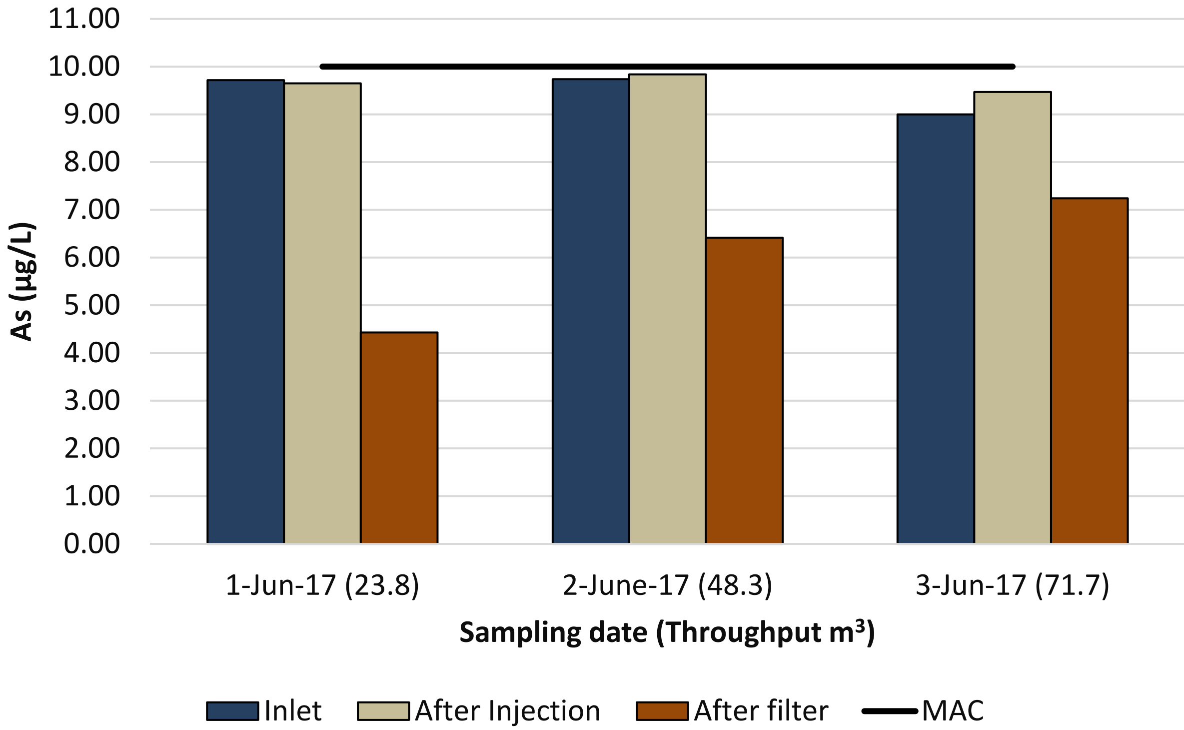

Figure 2.29 *Arsenic concentrations before and after at different sampling dates; values in the brackets represent the cumulative throughput volume of the water.*

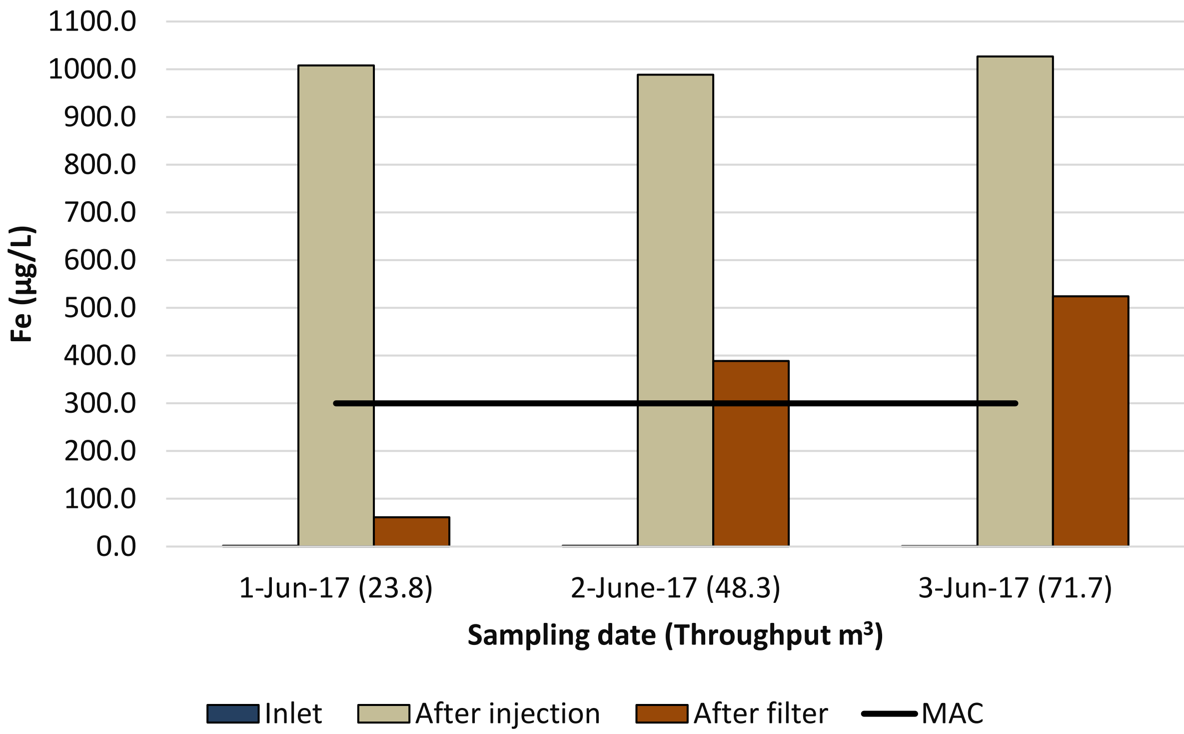

Figure 2.30 *Iron concentrations before and after at different sampling dates; values in the brackets represent the cumulative throughput volume of the water.*

2.5.3 Iron injection-Backwash water quality

The total suspended solids, manganese, arsenic and iron concertation in the backwash water are shown in Figures 2.32 to 2.35, respectively. The average level of TSS and each metal during the 30 minute backwash were calculated (Table 2.6). Iron concentration (70.4mg/L) was found to be the only parameter exceeding the guideline (10mg/L).

Start 5min 10min 15min 20min 25min 30min

Figure 2.31 *Backwash water samples and Total Suspended Solids test results at different times, after iron injection study.*

Table 2.5.1 *Analytical data for backwash water samples, after iron injection study.*

Time (min)	As (mg/L)	Mn (mg/L)	Fe (mg/L)	TSS (mg/L)	Chlorine (mg/L)
0	0.014	0.16	2.4	1	0.59
5	1.5	11	300	720	0.28
10	0.41	3.2	93	206	0.22
15	0.1	0.69	21	34	0.35
20	0.027	0.19	4.8	8	0.12
25	0.013	0.20	1.4	3	0.07
30	0.016	0.22	1.9	2	0.16
Average	0.34	2.58	70.39	162.08	0.24
Guideline*	**1**	**5**	**10**	**600**	-

**Greater Vancouver sewerage and drainage district sewer use bylaw no. 299, 2007*

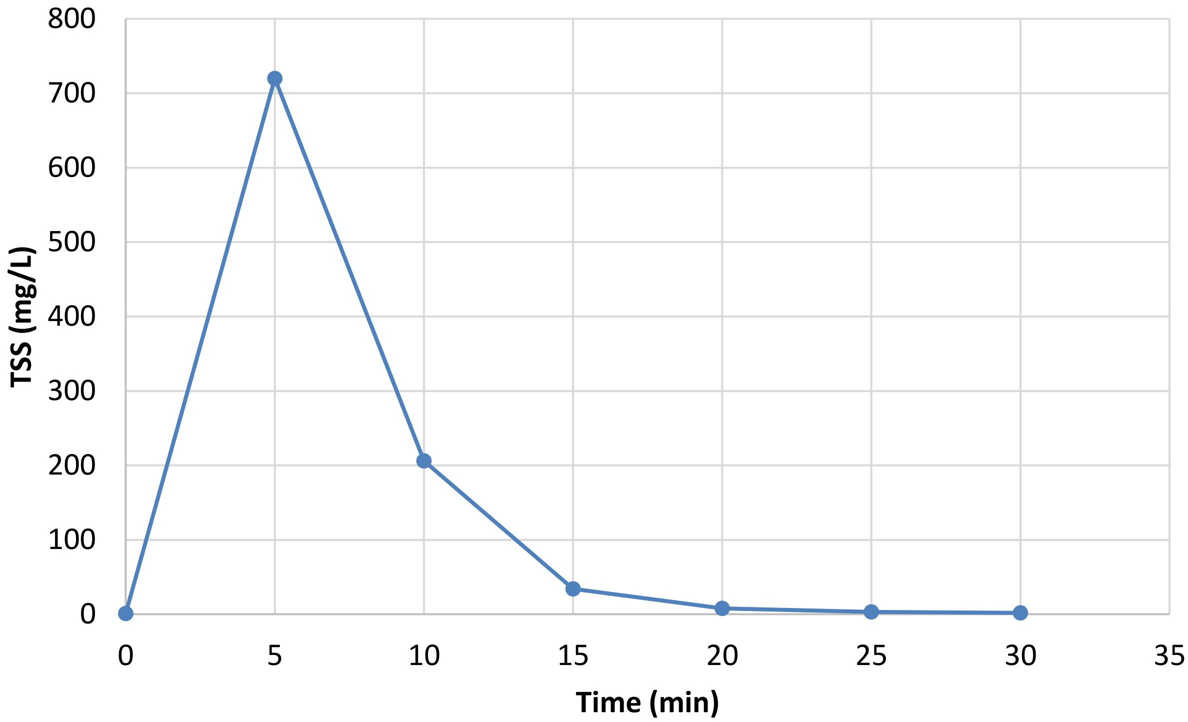

Figure 2.32 *Total suspended solids in backwash water versus time, after iron injection study.*

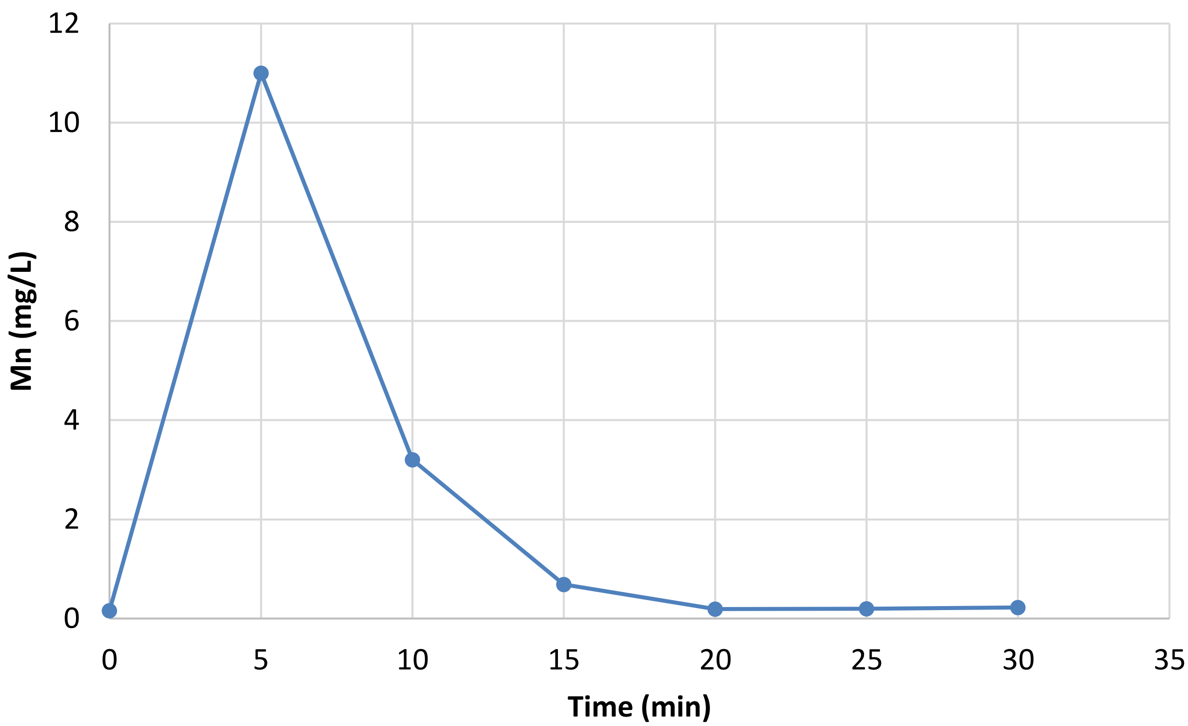

Figure 2.33 *Manganese concentrations in backwash water versus time, after iron injection study.*

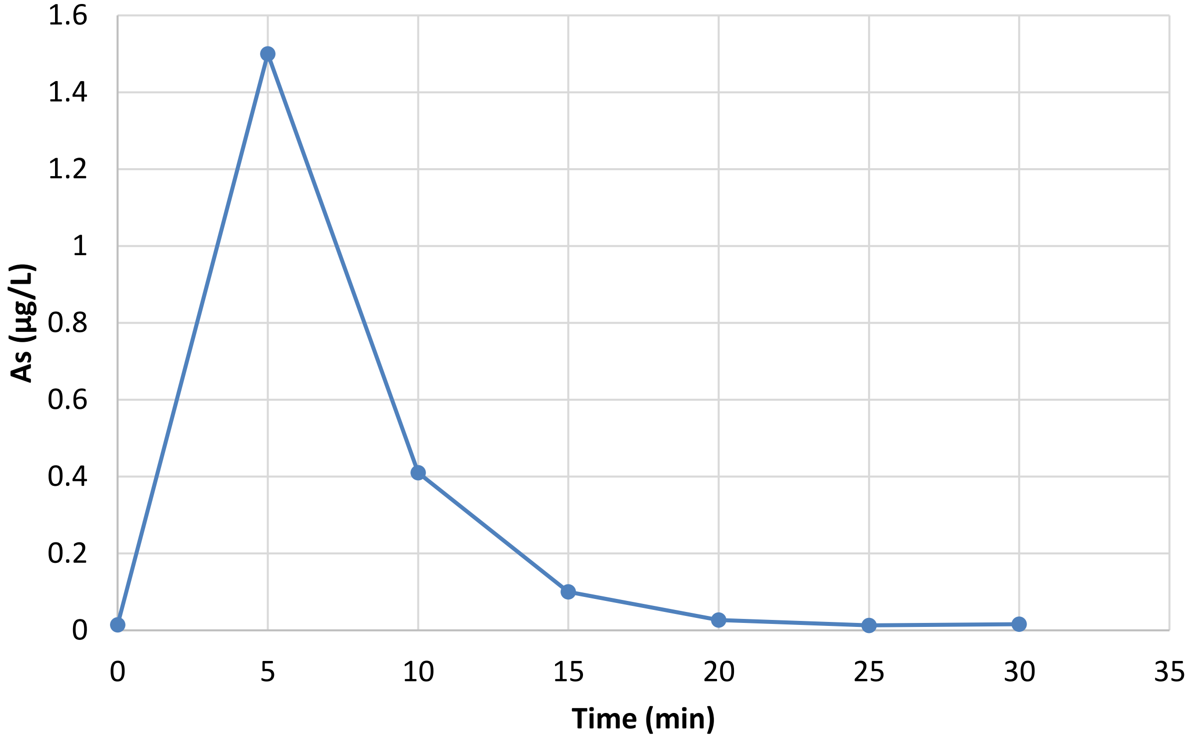

Figure 2.34 *Arsenic concentrations in backwash water versus time, after iron injection study.*

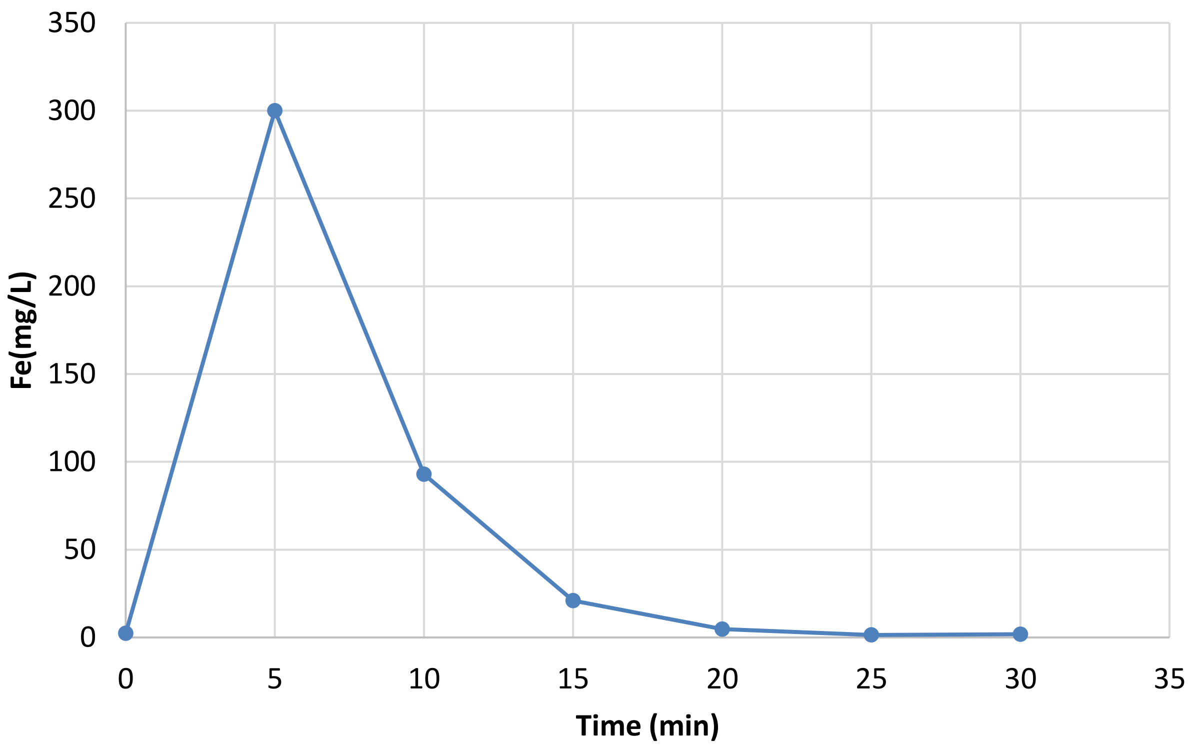

Figure 2.35 *Iron concentrations in backwash water versus time, after iron injection study.*

2.5.4 Iron injection-Jar test

The results of the Jar test are shown in Figures 2.36-2.38. After 5min of flocculation with iron, the arsenic level decreased from 9µg/L to 6µg/L, with no significance change observed beyond that time (Figure 2.36). The manganese level decreased with more flocculation time, from around 142µg/L to 87µg/L after 20 minutes, meaning that flocculation with iron can be effective for the removal of manganese as well (Figure 2.37). Considering the main purpose of this experiment which was to evaluate the effect of flocculation time on the removal of arsenic, it can be concluded that 5minute residence time (i.e., flocculation) would be sufficient if 1ppm of iron is used for coagulation.

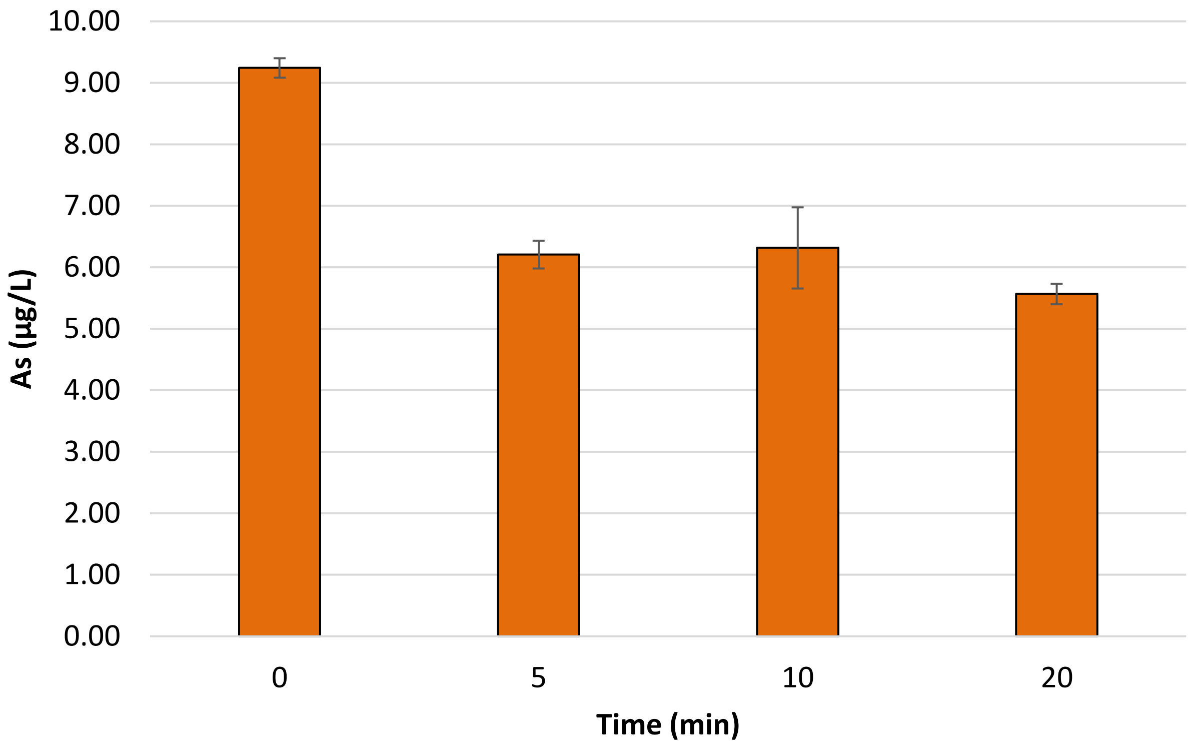

Figure 2.36 *Arsenic concentration at different flocculation time.*

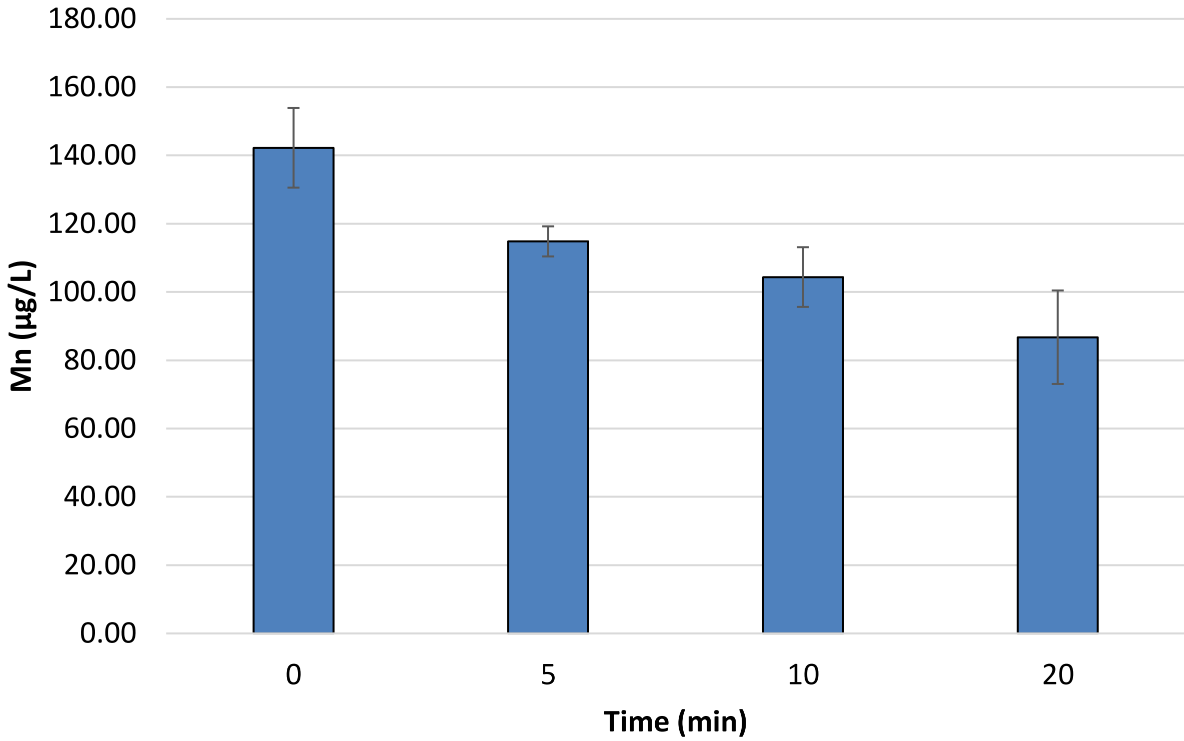

Figure 2.37 *Manganese concentration at different flocculation time.*

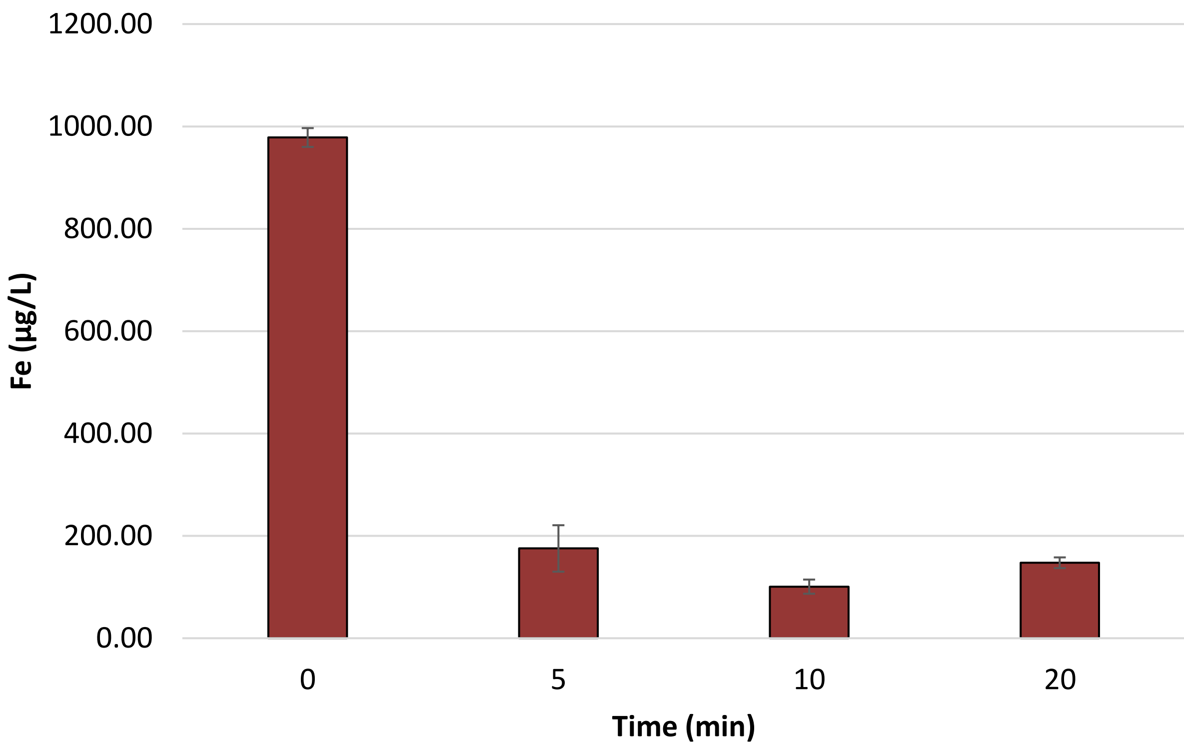

Figure 2.38 *Iron concentration at different flocculation time.*

2.6 Mangazur

The filter media was received on Monday April 3, 2017 and it started to operate on Tuesday April 4, 2017. The flowrate was adjusted to 16.5 L/min and the dissolved oxygen (DO) was set to around 8mg/L by injecting air before the filter. The water has been running through the filter since the installation date. The following tables include the most recent sampling results before and after the media. Since there is no significant change of concentration through the filter, the acclimation of the filter has not happened yet and more time is needed for the media to become active.

Table 2.6.1 *Manganese concentration before and after the biological filter.*

Before	After	Date
138.18	137.46	17-Jun-17 (Saturday)
138.03	133.95	19-Jun-17 (Monday)
133.34	132.39	20-Jun-17 (Tuesday)
132.11	130.87	21-Jun-17 (Wednesday)
131.47	130.57	22-Jun-17 (Thursday)
130.08	129.15	23-Jun-17 (Friday)
129.58	129.09	24-Jun-17 (Saturday)
136.77	135.11	27-Jun-17 (Tuesday)
135.53	136.18	4-Jul-17 (Tuesday)
134.56	134.11	7-Jul-17 (Friday)
135.28	131.14	10-Jul-17 (Monday)

Table 2.6.2 *Arsenic concentration before and after the biological filter.*

Before	After	Date
9.25	9.48	17-Jun-17 (Saturday)
9.33	9.21	19-Jun-17 (Monday)
9.12	8.80	20-Jun-17 (Tuesday)
9.19	8.94	21-Jun-17 (Wednesday)
9.00	9.06	22-Jun-17 (Thursday)
8.96	8.97	23-Jun-17 (Friday)
8.89	8.93	24-Jun-17 (Saturday)
9.22	8.85	27-Jun-17 (Tuesday)
9.29	9.06	4-Jul-17 (Tuesday)
8.89	9.21	7-Jul-17 (Friday)
9.19	8.71	10-Jul-17 (Monday)

3.0 Conclusions and Future Work

This report summarizes the results of a pilot study, which was a collaboration between the City of White Rock, RES'EAU-WaterNET, University of British Columbia, and Ecole Polytechnique de Montreal. The overall goal of the study was to assess a number of water treatment processes and determine the extent to which they can effectively remove manganese and arsenic from the City's water supplies. The study was conducted from December 2016 to June 2017 using a pilot plant facility, consisting of two treatment trains that involved oxidation, filtration and adsorption stages. Source water was provided from the City's well #6 and Well #7 with manganese level of around 130-140µg/L and arsenic level of around 10µg/L. Highlights of the results obtained from the study are as follows:

- Injecting around 0.5-1mg/L of chlorine as an oxidant followed by GreensandPlus filter could consistently decrease manganese level to below 4µg/L. In addition, increasing the filtration rate from 10m/h to 20m/h did not have any impact on the performance of the GreensandPlus filter in terms of the removal of manganese. At both conditions, no significant change was observed in arsenic concentration before and after the filter.
- Adsorptive media, E33 Bayoxide, removed arsenic effectively during the experiment; however, the concentration of arsenic in the outlet increased gradually, reaching 5µg/L after around 12000 bed volumes. It was estimated that after 25000-30000 bed volumes, the E33 Bayoxide media will be fully exhausted and the complete breakthrough will take place. Presence of manganese did not have any significant impact on the performance of the adsorptive media. Moreover, E33 Bayoxide showed around 30-40% manganese removal over the experiment.
- Ozone demonstrated to be as efficient as chlorine in removing Mn through the GreensandPlus filter. Injecting ozone at 0.5mg/L to 1mg/L, resulted in Mn concentration to decrease below 5 µg/L in the outlet of the GreensandPlus filter.
- Adding ozone before the GreensandPlus filter had very small (statistically insignificant) impact on the removal of arsenic. About 1µg/L decrease in arsenic concentration was observed through the GreensandPlus filter when ozone are injected in the water. This was independent of the ozone dosage, as increasing dosage from 0.5mg/L to 1mg/L did not have any impact on the performance of the filter for the removal of arsenic.
- Self-oxidizing media such as Birm could remove manganese from water; however, after treating certain volume of the water (around 350m3 cumulative volume of water in this study) the manganese level after the filter reached to the aesthetic objective. In addition, arsenic could not be removed effectively through the filter.
- Preliminary tests showed that injecting iron up to around 1mg/L could improve the arsenic removal through the filter; however, increasing the iron concentration to more than 1mg/L would not change the arsenic removal through the filter.

- Continuous injection of 1mg/L iron before the filter decreased the arsenic level to around 4µg/L in the water; however, the performance of the filter was not stable over the course of the experiment. Iron level after the filter reached over the MAC level and consequently the final arsenic level after filter reached to around 7µg/L.

The following experiments should be considered as part of the future work for this project:

- Increasing chlorine concentration to more than 1.5mg/L before injecting iron to determine if it can have any impact on arsenic removal through GreensandPlus filter.
- Adding ozone before the injection of iron and chlorine to the system and evaluating the performance of the GreensandPlus filter for the removal of arsenic.
- For well #6, arsenite As(III) was oxidized completely to arsenate As(V) using 0.5mg/L of ozone. In addition, increasing the concentration to 1mg/L did not have any significant impact on the conversion of As(III) to As(V) for this well. More tests for Well #7 which has more As(III) concentration is in progress.
- Continue collecting samples from biological media

3.1 Limitation

RES'EAU-WaterNET is a research program, funded by the Natural Sciences and Engineering Research Council (NSERC) of Canada and many private and public partner organizations, working towards solutions for small, rural and First Nations communities to improve the quality of their drinking water. RES'EAU-WaterNET does not act as an engineering consulting firm and therefore does not provide professional engineering services. Therefore, preparation and release of this report is not for the final detail design or construction purposes of a new water treatment plant. RES'EAU recommends the City to retain a third party engineering firm which can use the contents of this report towards the detailed design of a new drinking water treatment facility. Research professionals from RES'EAU group will be happy to assist the community in coordinating efforts and communications to develop an integrated approach to address the City's drinking water issues.

3.2 Closure

The Conclusions of this document represent the information available at the time of its completion and as appropriate for the project scope of work. No warranty, express or implied, is made. The report was prepared by personnel with experience in the field covered and conducted in a manner consistent with level and skills ordinarily exercised by researchers practicing under similar conditions. Additional consultations and work by third parties are required to finalize and complete the detail design and construction of a new water treatment plant.

4.0 References

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- Guidelines for Canadian Drinking Water Quality: Guideline Technical Document – Iron https://www.canada.ca/en/health-canada/services/publications/healthy-living/guidelines-canadian-drinking-water-quality-guideline-technical-document-iron.html
- Greater Vancouver sewerage and drainage district sewer use bylaw no. 299, 2007

5.0 Appendix

Figure 5.1 *System operational and analytical data at sampling dates*

Sampling Date		12/16/2016					12/19/2016					12/21/2016				
Sampling Location		In	B	B-E	G	G-E	In	B	B-E	G	G-E	In	B	B-E	G	G-E
Parameters	Unites															
Flowrate	L/min	35.4	18.4	18.4	17	17	36.2	17.9	17.9	18.3	18.3	34.7	17.2	17.2	17.5	17.5
Throughput	m^3	-	102.61	102.61	100	100	-	178.28	178.28	169.68	169.68	-	220.71	220.71	212.2	212.2
Bed volumes		-	-	1812	-	1766	-	-	3148	-	2996	-	-	3897	-	3747
Filtration rate	m/h	-	11.08	15.01	10.25	13.88	-	10.78	14.62	11.03	14.93	-	10.37	14.03	10.54	10.27
Pressure drop	psi	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
pH		7.04	7.13	7.24	7.18	7.16	7.03	7.10	7.01	7.04	7.20	6.93	7.06	7.10	7.13	7.10
Temperature	ºC	11.8	11.8	12.4	12.3	11.3	14.8	14.3	14.7	14.3	14.7	11.6	12.4	12.5	11.8	11.6
Free chlorine	mg/L	-	-	-	1.03	0.78	-	-	-	0.66	0.38	-	-	-	0.82	0.59
Total chlorine	mg/L	-	-	-	1.49	1.00	-	-	-	1.1	0.63	-	-	-	1.12	0.76
As (Total)	mg/L	0.0101	0.0099	0.0003	0.0098	0.0001	0.0100	0.0100	0.0011	0.0099	0.0007	0.0095	0.0094	0.0017	0.0093	0.0015
Mn (Total)	mg/L	0.137	0.001	<0.001	<0.001	0.001	0.141	0.005	0.002	<0.001	0.002	0.116	0.005	<0.001	<0.001	<0.001
Fe (Total)	mg/L	0.004	<0.004	<0.004	0.027	0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Fluoride	mg/L	0.27	0.22	0.24	0.30	0.24	0.26	0.24	0.24	0.22	0.23	0.21	0.18	0.22	0.19	0.21
Chloride	mg/L	16.02	15.91	16.14	18.51	18.80	17.97	17.91	17.93	20.01	20.00	10.33	10.19	10.29	12.31	12.37
Nitrite	mg/L	BDL*	BDL	BDL	0.20	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Nitrate	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Bromide	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Phosphate	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Sulfate	mg/L	19.13	19.06	19.18	19.14	19.09	20.45	20.56	20.34	20.53	20.46	15.00	15.03	15.16	14.96	15.25
Turbidity	NTU	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04

BDL*: Below Detection Limit

Figure 5.1 *(continued) System operational and analytical data at sampling dates.*

Sampling Date		01/23/2017					01/25/2017					01/27/2017				
Sampling Location		In	B	B-E	G	G-E	In	B	B-E	G	G-E	In	B	B-E	G	G-E
Parameters	Unites															
Flowrate	L/min	38	19.2	19.2	18.8	18.8	37.2	19.6	19.6	17.6	17.6	38.2	18.7	18.7	19.5	19.5
Throughput	m^3	-	97.56	318.27	96.84	309.04	-	152.71	470.98	143.19	452.23	-	209.77	528.04	192.41	501.45
Bed volumes		-	-	5619.8	-	5456.8	-	-	8316	-	7985	-	-	9324	-	8854
Filtration rate	m/h	-	11.57	15.67	11.33	15.34	-	11.81	16.00	10.60	14.36	-	11.27	15.26	11.75	15.91
Pressure drop	psi	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
pH		7.4	7.44	7.00	7.62	7.06	6.79	6.85	6.98	7.13	7.46	6.97	7.15	7.34	7.48	7.67
Temperature	°C	11.6	11.9	11.6	11.8	11.8	11.1	11.6	11.7	11.3	11.3	10.8	11.2	11.2	11.2	11.0
Free chlorine	mg/L	-	-	-	0.96	0.53	-	-	-	0.78	0.60	-	-	-	0.61	0.35
Total chlorine	mg/L	-	-	-	1.36	0.82	-	-	-	1.12	0.79	-	-	-	0.83	0.73
As (Total)	mg/L	0.0087	0.0087	0.0025	0.0086	0.0021	0.0086	0.0086	0.0032	0.0084	0.0027	0.0085	0.0087	0.0037	0.0085	0.0034
Mn (Total)	mg/L	0.134	0.011	<0.001	0.004	0.004	0.131	0.025	0.002	<0.001	<0.001	0.135	0.037	0.005	<0.001	<0.001
Fe (Total)	mg/L	<0.004	<0.004	<0.004	<0.004	<0.004	0.008	<0.004	0.005	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Fluoride	mg/L	0.26	0.21	0.38	0.25	0.26	0.38	0.37	0.27	0.27	0.27	0.29	0.27	0.25	0.26	0.26
Chloride	mg/L	78.71	21.28	25.79	59.21	42.43	16.70	16.83	17.92	19.20	19.08	17.44	17.18	17.17	19.12	18.78
Nitrite	mg/L	BDL(c)	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Nitrate	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Bromide	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Phosphate	mg/L	1.40	1.24	1.10	1.38	0.94	1.27	1.27	0.96	1.23	0.95	1.28	1.25	1.01	1.21	0.99
Sulfate	mg/L	19.27	19.37	19.58	19.32	19.49	19.64	19.78	19.71	19.77	19.68	19.37	19.49	19.52	19.41	19.53
Turbidity	NTU	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04

Figure 5.1 *(continued) System operational and analytical data at sampling dates*

Sampling Date		02/01/2017					02/06/2017					02/07/2017				
Sampling Location		In	B	B-E	G	G-E	In	B	B-E	G	G-E	In	B	B-E	G	G-E
Parameters	Unites															
Flowrate	L/min	36.6	18.7	18.7	17.9	17.9	37.7	18.3	18.3	19.4	19.4	36.9	18.1	18.1	18.8	18.8
Throughput	m^3	-	349.49	667.76	313.24	622.28	-	482.04	800.31	441.69	750.73	-	506.78	825.05	467.97	777.01
Bed volumes		-	-	11791	-	10988	-	-	14131	-	13256	-	-	14568	-	13720
Filtration rate	m/h	-	11.27	15.26	10.78	15.91	-	11.03	14.93	11.69	15.83	-	10.90	14.77	11.33	15.34
Pressure drop	psi	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
pH		6.98	6.90	6.85	6.99	7.40	7.42	7.60	7.81	7.83	7.86	7.56	7.71	7.79	7.88	7.98
Temperature	^oC	11.7	11.4	11.8	11.2	11.9	10.7	11.1	10.9	11	11.2	10.8	11	10.9	10.9	11.2
Free chlorine	mg/L	-	-	-	0.66	0.55	-	-	-	0.22	0.1	-	-	-	0.46	0.35
Total chlorine	mg/L	-	-	-	1.19	0.96	-	-	-	0.94	0.89	-	-	-	1.17	0.84
As (Total)	mg/L	0.0092	0.0091	0.0048	0.0091	0.0045	0.0099	0.0112	0.0058	0.0101	0.0061	0.0094	0.0089	0.0056	0.0092	0.0057
Mn (Total)	mg/L	0.135	0.062	0.021	<0.001	<0.001	0.135	0.091	0.038	0.000	0.000	0.138	0.078	0.042	0.000	0.000
Fe (Total)	mg/L	0.006	0.004	<0.004	<0.004	<0.004	0.005	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Fluoride	mg/L	0.27	0.27	0.26	0.25	0.31	0.26	0.32	0.37	0.25	0.25	0.26	0.25	0.25	0.25	0.26
Chloride	mg/L	18.60	17.51	17.75	19.56	19.60	17.25	17.38	17.41	18.62	18.64	17.36	17.25	17.17	19.28	19.27
Nitrite	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Nitrate	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Bromide	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Phosphate	mg/L	1.22	1.23	1.09	1.20	1.07	1.22	1.24	1.11	1.24	1.14	1.26	1.25	1.15	1.21	1.15
Sulfate	mg/L	19.56	19.24	19.40	19.39	19.43	20.48	20.55	20.70	20.48	20.58	20.53	20.36	20.28	20.20	20.39
Turbidity	NTU	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04

Figure 5.1 *(continued) System operational and analytical data at sampling dates*

Sampling Date		02/09/2017					02/10/2017					2/21/2017		2/22/2017		2/23/2017	
Sampling Location		In	B	B-E	G	G-E	In	B	B-E	G	G-E	In	G	In	G	In	G
Parameters	Unites																
Flowrate	L/min	35.8	17.9	17.9	17.9	17.9	35.4	18	18	17.4	17.4	34.7	34.7	32.5	32.5	25.5	25.5
Throughput	m^3	-	559.08	877.35	520.83	829.87	-	585.39	903.66	546.48	855.52	-	48.25	-	96.29	-	139.98
Bed volumes		-	-	15492	-	14653	-	-	15956	-	15106	-	-	-	-	-	-
Filtration rate	m/h	-	10.78	14.61	10.78	14.61	-	10.84	14.69	10.48	14.20	-	20.91	-	19.58	-	15.36
Pressure drop	psi	-	-	-	-	-	-	-	-	-	-	-		-		-	
pH		7.55	7.70	7.74	7.86	7.92	7.66	7.91	7.97	7.94	8.02	6.86	7.10	7.10	7.42	7.31	7.79
Temperature	°C	11.2	10.9	10.9	10.9	10.9	10.5	11	11.3	11.4	11.7	11.3	11.1	11.3	10.5	11.5	10.9
Free chlorine	mg/L	-	-	-	0.51	0.19	-	-	-	0.5	0.2	-	0.19	-	0.86	-	1.31
Total chlorine	mg/L	-	-	-	1.19	0.82	-	-	-	1.21	0.79	-	0.96	-	1.57	-	1.96
As (Total)	mg/L	0.0094	0.0093	0.0054	0.0091	0.0059	0.0092	0.0090	0.0059	0.0091	0.0059	0.0094	0.0090	0.0106	0.0093	0.0091	0.0091
Mn (Total)	mg/L	0.131	0.084	0.047	0.000	0.000	0.129	0.085	0.053	0.000	0.000	0.133	<0.001	0.153	<0.001	0.128	<0.001
Fe (Total)	mg/L	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Fluoride	mg/L	0.27	0.27	0.25	0.26	0.26	0.26	0.28	0.25	0.25	0.25	0.26	0.25	0.25	0.25	0.25	0.25
Chloride	mg/L	16.76	16.91	16.96	19.20	19.13	16.80	16.87	16.88	19.11	19.09	16.41	17.34	16.37	20.24	16.43	19.60
Nitrite	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Nitrate	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Bromide	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Phosphate	mg/L	1.23	1.21	1.16	1.28	1.16	1.21	1.22	1.16	1.24	1.14	1.20	1.19	1.20	1.21	1.21	1.20
Sulfate	mg/L	20.22	20.20	20.26	20.18	20.11	20.16	20.08	20.19	20.10	20.11	20.10	20.11	20.07	20.18	20.09	20.00
Turbidity	NTU	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.07	0.07	0.05	0.05	0.04

Figure 5.1 *(continued) System operational and analytical data at sampling dates*

Sampling Date		2/24/2017		2/27/2017		2/28/2017		3/2/2017		3/3/2017	
Sampling Location		In	G	In	G	In	G	In	G	In	G
Parameters	Unites										
Flowrate	L/min	24.8	24.8	27.6	27.6	25.9	25.9	21.7	21.7	23.5	23.5
Throughput	m^3	-	177.88	-	286.95	-	321.35	-	393.06	-	415.07
Bed volumes		-	-	-	-	-	-	-	-	-	-
Filtration rate	m/h	-	14.94	-	16.63	-	15.60	-	13.07	-	14.16
Pressure drop	psi	-		-		-		-		-	
pH		7.26	7.41	7.43	7.26	7.57	7.40	7.57	7.40	7.22	7.41
Temperature	°C	10.8	10.8	10.8	11	10.6	10.9	10.7	10.8	10.8	10.8
Free chlorine	mg/L	-	0.38	-	0.36	-	0.31	-	0.35	-	0.28
Total chlorine	mg/L	-	1.17	-	1.15	-	1.08	-	1.08	-	1.07
As (Total)	mg/L	0.0094	0.0094	0.0093	0.0092	0.0091	0.0092	0.0090	0.0090	0.0093	0.0091
Mn (Total)	mg/L	0.139	<0.001	0.138	<0.001	0.133	<0.001	0.132	<0.001	0.129	<0.001
Fe (Total)	mg/L	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Fluoride	mg/L	0.28	0.30	0.29	0.25	0.24	0.29	0.27	0.27	0.29	0.29
Chloride	mg/L	16.41	18.32	16.53	18.07	16.57	18.06	16.45	18.03	16.75	18.24
Nitrite	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Nitrate	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Bromide	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Phosphate	mg/L	1.22	1.20	1.20	1.20	1.22	1.21	1.21	1.16	1.21	1.18
Sulfate	mg/L	20.07	19.96	19.87	19.85	19.90	19.92	19.80	19.78	19.88	19.80
Turbidity	NTU	0.05	0.07	0.06	0.04	0.05	0.04	0.07	0.04	0.05	0.04

Figure 5.1 *(continued) System operational and analytical data at sampling dates*

Sampling Date		3/30/2017		3/31/2017		4/1/2017		4/7/2017		4/10/2017		4/11/2017		4/12/2017	
Sampling Location		In	G	In	G	In	G	In	G	In	G	In	G	In	G
Parameters	Unites														
Flowrate	L/min	19.8	19.8	13.1	13.1	12.7	12.7	18.7	18.7	19.9	19.9	20.0	20.0	19.9	19.9
Throughput	m^3	-	27	-	17.98	-	26.29	-	19.75	-	22.54	-	25.92	-	33.1
Bed volumes		-	-	-	-	-	-	-	-	-	-	-	-	-	-
Filtration rate	m/h	-	11.93	-	7.89	-	7.65	-	11.27	-	11.98	-	12.05	-	11.99
Pressure drop	psi	-	-	-	-	-	-	-	3.4	-	3.7	-	4.1	-	5.2
pH		7.57	7.55	7.31	7.53	7.44	7.54	7.35	7.35	7.3	7.25	7.22	7.19	7.7	7.64
Temperature	°C	10.1	11.0	10.5	10.6	10.3	11.0	10.9	11.1	12.0	10.6	11.1	11.8	10.3	10.4
Ozone	mg/L	0.1	0	0.5	0	0.5	0	0.4	0	0.5	0	0.5	0	0.5	0
As (Total)	mg/L	0.0010	0.0090	0.0011	0.0090	0.0098	0.0092	0.0010	0.0092	0.0097	0.0086	0.0088	0.0086	0.0088	0.0084
Mn (Total)	mg/L	0.138	0.004	0.138	0.005	0.137	0.001	0.136	0.002	0.139	0.001	0.137	0.003	0.135	0.001
Fe (Total)	mg/L	0.018	<0.004	0.008	<0.004	0.007	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Fluoride	mg/L	0.22	0.21-	0.21	0.21	0.21	0.21	0.21	0.21	0.22	0.21	0.21	0.21	0.21	0.20
Chloride	mg/L	17.45	15.88	16.08	15.81	15.97	15.79	13.53	15.56	15.39	15.42	16.12	15.51	15.77	15.76
Nitrite	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Nitrate	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Bromide	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Phosphate	mg/L	1.23	1.19	1.17	1.19	1.19	1.18	1.17	1.13	1.15	1.15	1.16	1.16	1.15	1.15
Sulfate	mg/L	20.09	20.11	20.20	20.00	20.80	19.11	19.65	18.5	18.56	19.56	20.68	20.21	20.85	20.16
Turbidity	NTU	0.04	0.08	0.04	0.09	0.04	0.07	0.05	0.07	0.04	0.06	0.04	0.07	0.04	0.07

Figure 5.1 *(continued) System operational and analytical data at sampling dates*

Sampling Date		4/13/2017		4/18/2017		4/20/2017		4/24/2017		4/25/2017		4/26/2017		4/27/2017	
Sampling Location		In	G	In	G	In	G	In	G	In	G	In	G	In	G
Parameters	Unites														
Flowrate	L/min	20.0	20.0	20.7	20.7	20.5	20.5	17.5	17.5	16.7	16.7	16.6	16.6	16.3	16.3
Throughput	m^3	-	40.67	-	45.89	-	53.68	-	59.51	-	62.82	-	64.82	-	67.12
Bed volumes		-	-	-	-	-	-	-	-	-	-	-	-	-	-
Filtration rate	m/h	-	12.05	-	12.47	-	12.35	-	10.54	-	10.06	-	10.00	-	9.82
Pressure drop	psi	-	5.5	-	5.8	-	6	-	6.4	-	7	-	7	-	7
pH		8.13	8.08	8.18	7.99	7.45	7.40	8.21	8.03	8.37	8.28	8.26	8.16	8.38	8.15
Temperature	°C	10.7	10.4	10.9	11	10.6	11	11.2	11.3	10.5	10.7	11.3	11.1	10.8	11
Ozone	mg/L	0.5	0	0.5	0	0.5	0	1	0	1	0	1	0	1	0
As (Total)	mg/L	0.0088	0.0080	0.0086	0.0084	0.0094	0.0092	0.0094	0.0086	0.0094	0.0091	0.0094	0.0090	0.0094	0.0091
Mn (Total)	mg/L	0.13	0.003	0.130	0.001	0.135	0.003	0.135	0.005	0.132	0.002	0.133	0.001	0.132	0.001
Fe (Total)	mg/L	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Fluoride	mg/L	0.21	0.21	0.21	0.21	0.20	0.21	0.21	0.22	0.20	0.21	0.20	0.22	0.2097	0.2125
Chloride	mg/L	15.45	15.40	15.27	15.22	15.00	15.06	15.38	15.50	15.41	15.45	15.48	15.52	15.45	15.44
Nitrite	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Nitrate	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Bromide	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Phosphate	mg/L	1.14	1.14	1.14	1.15	1.15	1.14	1.18	1.18	1.21	1.18	1.19	1.19	1.19	1.19
Sulfate	mg/L	20.09	20.11	20.10	20 .11	20.09	20.11	18.10	19.11	19.09	20.05	20.10	20.11	17.09	17.11
Turbidity	NTU	0.04	0.08	0.04	0.07	0.04	0.06	0.04	0.06	0.04	0.07	0.04	0.09	0.04	0.07

Figure 5.1 *(continued) System operational and analytical data at sampling dates*

Sampling Date		6/1/2017		6/2/2017		6/3/2017	
Sampling Location		In	G	In	G	In	G
Parameters	Unites						
Flowrate	L/min	18.0	18.0	18.0	18.0	18.1	18.1
Throughput	m^3	-	23.79	-	48.29	-	71.69
Bed volumes		-	-	-	-	-	-
Filtration rate	m/h	-	10.84	-	10.84	-	10.9
Pressure drop	psi	-	4.2	-	6.2	-	7.9
pH		6.86	6.84	6.82	6.85	7.37	7.30
Temperature	°C			11.5	11.9	11.3	11.5
Free chlorine	mg/L	-	0.13	-	0.15	-	0.12
Total chlorine	mg/L	-	0.9	-	0.95	-	0.9
As (Total)	mg/L	0.0097	0.0044	0.0097	0.0064	0.0090	0.0072
Mn (Total)	mg/L	0.141	0.001	0.141	0.004	0.130	0.005
Fe (Total)	mg/L	0.001	0.061	0.001	0.389	0.001	0.524
Fluoride	mg/L	0.20	0.21	0.20	0.19	0.21	0.19
Chloride	mg/L	15.67	19.26	15.69	19.37	15.64	19.13
Nitrite	mg/L	BDL	BDL	BDL	BDL	BDL	BDL
Nitrate	mg/L	BDL	BDL	BDL	BDL	BDL	BDL
Bromide	mg/L	BDL	BDL	BDL	BDL	BDL	BDL
Phosphate	mg/L	1.14	1.14	1.14	1.15	1.15	1.14
Sulfate	mg/L	20.09	20.11	20.10	20 .11	20.09	20.11
Turbidity	NTU	0.04	0.11	0.04	0.29	0.05	0.30