



Pilot Testing Project Report:

Evaluation of Greensand Filtration Operation for the Reduction of Manganese

Walkerton Clean Water Centre

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Executive Summary

Background

Manganese is normally not considered to be a health concern (MOECC, 2006). However, there are a number of problems which can occur if too much manganese is present in the water, such as generating a metallic taste and coloured water, staining of laundry and plumbing fixtures, formation of deposits in the distribution system and plumbing, and interference with the disinfection process (Ellis *et al.*, 2000). The Ontario drinking water quality standard for manganese is an aesthetic objective of 0.05 mg/L (MOE, 2006); however, due to increased evidence of potential health effects, Health Canada has proposed a maximum acceptable concentration (MAC) of 0.1 mg/L, and an aesthetic objective of 0.02 mg/L for total manganese in drinking water (Health Canada, 2016). Several techniques are available for removing manganese from drinking water sources, including adsorption/oxidation method, oxidation/filtration method and biological method.

The Township of Hamilton, located in Central Ontario, has a drinking water treatment plant (WTP) that uses greensand filtration for the reduction of turbidity, iron and manganese from groundwater. Two catalytic greensand filters are operated in parallel and are continuously regenerated with the injection of liquid potassium permanganate (KMnO_4) ahead of each filter. The Township of Hamilton agreed to allow the Centre to perform bench-scale and pilot-scale tests on-site with the aim of optimizing the greensand filter performance at their WTP.

Objectives

The objectives of this pilot testing project were to assist the operators at the WTP by providing information on the optimal potassium permanganate dose for effective iron and manganese reduction in the finished water and to evaluate two different operation and maintenance approaches for the greensand filters; continuous regeneration and intermittent regeneration.

Approach

The Centre initially conducted bench-scale jar tests to determine the optimal permanganate dosage. Following bench-scale testing, two pilot-scale greensand filters were installed in parallel at the WTP for testing. The pilot system was installed to use the WTP's raw source water as influent. The greensand filters were then operated in both continuous regeneration mode and intermittent regeneration mode to compare the reduction capabilities for manganese.

During the pilot testing experiments, the Centre also compared the performance of aged filter media with that of new filter media. One filter was filled with aged greensand and anthracite that was collected from one of the full-scale greensand filters at the WTP while the second filter was filled with new greensand and anthracite media from the Centre.

Key Findings

The key findings of the bench-scale jar testing were as follows:

- The optimal permanganate dosage for manganese oxidation can be determined using a simple equation. This was calculated using iron and manganese concentrations measured in the raw water and then confirmed through a jar test to be optimal for the source water.
- Under dosing of permanganate was found to cause incomplete oxidation of soluble manganese to insoluble forms and therefore increased the level of manganese remaining in the finished water.

The key findings of the pilot-scale testing were as follows:

- Continuous regeneration of the greensand filters using permanganate can remove the majority of the insoluble manganese and >70% of the remaining soluble manganese; it is important to note however that operating in this mode would most likely increase chemical costs.

- Intermittent regeneration of the greensand filters with no oxidant can remove the majority of the insoluble manganese and adsorb >86% of the soluble manganese; it is important to note however that operating in this mode would most likely increase the amount of plant operation and maintenance conducted by operators.
- The older greensand media showed to not be as effective at adsorbing soluble manganese and had shorter run times when operated in intermittent regeneration mode. No difference in soluble manganese reduction performance was observed when operating in continuous regeneration mode.

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1. Introduction

Manganese is commonly found together with iron in groundwater and is normally not considered to be a health concern (MOE, 2006). However, there are a number of problems which can occur if too much manganese is present in the water, such as generating a metallic taste and coloured water, staining of laundry and plumbing fixtures, formation of deposits in the distribution system and plumbing, and interference with the disinfection process (Ellis *et al.*, 2000). The Ontario drinking water quality standards for manganese indicate an aesthetic objective of 0.05 mg/L (MOE, 2006); however, due to increased evidence of potential health effects, Health Canada has proposed a maximum acceptable concentration (MAC) of 0.1 mg/L, and an aesthetic objective of 0.02 mg/L for total manganese in drinking water (Health Canada, 2016).

Manganese (Mn) is present in natural waters as different species and valence states, but predominantly in dissolved (Mn II) form. Most literature considers the portion of Mn passing through a 0.45 µm filter as soluble, and the part that does not pass through the filter as insoluble. Several techniques are available for removing manganese from drinking water sources, including the adsorption/oxidation method, oxidation/filtration method and biological method. The adsorption/oxidation process involves using a filter media (e.g. manganese oxide coated greensand) that has the capacity to adsorb the soluble manganese and then it is oxidized into insoluble manganese by subsequent oxidation (Tobiason *et al.*, 2008). The oxidation/filtration method applies a strong oxidant to oxidize soluble manganese into insoluble manganese, and then the insoluble manganese is removed by a physical particle removal process (such as filtration or membrane filtration) (Tobiason *et al.*, 2008). The biological method using bio-filtration processes utilizes manganese-oxidizing bacteria (Burger *et al.*, 2008) to remove soluble manganese.

A town located in Central Ontario has a drinking water treatment plant (WTP) that uses greensand filtration for removal of iron and manganese from groundwater as well as for turbidity control. Two catalytic greensand filters are operated in parallel. Both filters are continuously regenerated with an injection of liquid potassium permanganate (KMnO₄)

ahead of each filter. UV disinfection and chlorination are then applied to disinfect the filtered water. The raw groundwater contains high levels of manganese (0.17 mg/L) and iron (0.40 mg/L). In addition, dissolved organic carbon (2.0 mg/L) and ammonia (2.0 mg/L) levels are also at levels that may cause treatment concerns. Filter 1 was able to consistently reduce Mn concentrations to below 0.05 mg/L from 2003 to 2006. However, both filters started to show unstable performance after Filter 2 was installed in 2006.

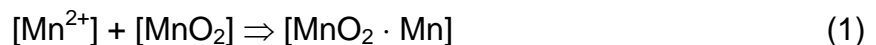
1.1 Objectives

The objectives of this pilot testing project are to identify the optimal permanganate dose for iron and manganese removal, and to evaluate operation and maintenance approaches to improve the Mn removal by the greensand filters.

2. Literature Review

2.1 Adsorption/Oxidation Method

Manganese greensand is made from a glauconitic mineral that is chemical treated to form a manganese oxide coating on the grain of sand; manganese oxide (MnO_2) is capable of adsorbing dissolved Mn (Morgan and Stumm, 1964). Manganese greensand has been used effectively for iron (Fe) and manganese removal for several decades (Knocke *et al.*, 1990). A greensand filter usually consists of three different layers. The top layer usually consists of anthracite, followed by manganese greensand, with graded gravel on the bottom. The greensand has an effective size of 0.30 – 0.35 mm and a uniformity coefficient of 1.6 or less (Knocke *et al.*, 1988). The removal of soluble Mn is achieved by adsorption followed by oxidation processes. Adsorption of soluble manganese on the oxide surface and its subsequent oxidation by an oxidant processes are shown below (Van Benschoten, 1992).



When a manganese oxide coated greensand filter is used in water treatment, soluble manganese is adsorbed on the sand grain and associated with manganese oxide

coating (Equation 1) but not oxidized. The oxidant then oxidizes the associated soluble manganese to manganese oxide (Equation 2), which is removed by filter backwashing.

The filter media is regenerated either continuously or intermittently to restore the oxidation capacity (Merkle, 1997a). Continuous regeneration is best suited to water with a high iron concentration and low manganese concentration, where iron removal is the main objective. In continuous regeneration, a strong oxidant such as potassium permanganate or free chlorine is fed into the water prior to entering the filter. As a result, iron and some of the manganese are oxidized into insoluble forms before reaching the filter. The remaining soluble manganese is then adsorbed on the surface of the sand grains (Merkle, 1997a). On the other hand, intermittent regeneration is suitable to water with a high manganese concentration and low iron concentration. In intermittent regeneration mode, no oxidant is added pre-filter. Instead, the adsorption and oxidation of manganese occurs directly on the greensand grains. After treating a specific volume of water, the adsorption/oxidation capacity of the media will be exhausted and regeneration is required. This process is normally accomplished by soaking the media for several hours in a 2 – 3% solution of potassium permanganate (Sommerfeld, 1999). The excess permanganate from regeneration can be recycled for the next regeneration to minimize the chemical cost (Merkle, 1997b).

2.2 Oxidation/Filtration Method

The oxidation of manganese is commonly accomplished by free chlorine, chlorine dioxide, ozone and potassium permanganate. Free chlorine is often used because it is economical and easy to feed. Sufficient chlorine dosage and contact time must be available for effective oxidation of soluble Mn. In addition, this oxidation process is not efficient at $\text{pH} < 9$ (Knocke *et al.*, 1988). Other compounds that add to the water's chlorine demand such as the presence of natural organic matter and ammonia will require a much higher chlorine dose to completely oxidize the soluble manganese. Formation of disinfection by-products is a concern when chlorine is used in waters with high levels of natural organic matter.

Potassium permanganate (KMnO₄) is widely used in water treatment plants for the oxidation of soluble iron and manganese. The theoretical stoichiometric dose for soluble iron (Fe²⁺) and manganese (Mn²⁺) oxidation is 0.94 and 1.92, respectively (Knocke *et al.*, 1991a). Therefore, the calculation for determining the required dose of permanganate to oxidize iron and manganese ahead of the filter is given by equation 3 (Sommerfeld, 1999). It is important to optimize the permanganate dose as excessive permanganate in water produces a pink colour which will lead to customer complaints, and insufficient permanganate will not be able to oxidize the soluble Mn to a suitable level (e.g. <0.01 mg/L). However, low temperature and the presence of natural organic matter can increase the amount of time it takes for effective oxidation to occur (Gregory and Carlson, 2003), making the process difficult to optimize.

$$\text{KMnO}_4 \text{ Dose (mg/L)} = 1 \times [\text{Fe Concentration}] + 2 \times [\text{Mn Concentration}] \quad (3)$$

Media filtration is commonly used to remove insoluble Mn after the oxidation process. Therefore, it is important to monitor whether all the soluble Mn in the water has been converted to the insoluble state. When not all the soluble Mn is converted into insoluble state, some Mn will be left in a colloidal size range. It has been found that colloidal Mn present in filter influent may not be removed efficiently by media filtration (Knocke *et al.*, 1991b, Carlson *et al.*, 1997). Membrane filtration can also be applied to remove manganese, and soluble manganese cannot be effectively removed by membrane without being oxidized to the insoluble form. For example, microfiltration with pre-oxidation by permanganate as well as advanced oxidation process (Teng *et al.*, 2001; Ellis *et al.*, 2000), and ultrafiltration with in-line pre-chlorination have been successfully applied to remove manganese and/or iron from groundwater (Choo *et al.*, 2005).

2.3 Biological Method

Biological methods have been tested to treat Mn containing groundwater in recent years, and particularly by bio-filtration processes utilizing manganese-oxidizing bacteria (Burger *et al.*, 2008). This technology is a low-cost alternative treatment method and has shown much promise in removing dissolved Mn as well as other contaminants (Han *et al.*, 2013). Tekerlekopoulou *et al.* (2013) reviewed a variety of full and pilot-scale

biological filters that have been used for combined or simultaneous removal of manganese, iron, and ammonia, as well as factors and conditions that were found to affect the process. The bio-filtration can achieve manganese removal without using chemical oxidants and under natural pH conditions (Pacini *et al.*, 2005), in which over 95% manganese removals were achieved. The advantages of biological treatments compared to physical and chemical treatment methods are: no use of chemicals, higher filtration rates, and lower operation and maintenance costs.

3. Methods

3.1 Jar Test and Water Quality Analysis

Jar tests were conducted first to determine the optimal permanganate dosage. The jar test was carried out using 2L square jars with paddle stirrers. Water samples were mixed at 100 rpm for 1 min after permanganate addition to provide rapid mixing, and then the speed was reduced to 20 rpm for 30 min. Jar tests were conducted using different permanganate dosages and different contact times.

Water quality parameters including pH, turbidity, total and soluble iron, and total and soluble manganese were analyzed (Table 1).

Table 1. Water quality parameters and their determination methods

Parameters	Method	Instruments
pH		Hach HQ40D portable pH meter
Turbidity		Hach 2100P portable turbidity meter
UV ₂₅₄		Real UV254 Meter
DOC	APHA 5310	Sievers 5310C Laboratory TOC Analyzer
KMnO ₄	DPD method	Hach DR1900 portable spectrophotometer
Manganese	PAN method (#8149)	Hach DR1900 portable spectrophotometer
Iron	FerroVer method (#8008)	Hach DR1900 portable spectrophotometer

3.2 Comparison of Analytical Methods

The Centre compared two methods for the determination of permanganate: the N, N-diethyl-p-phenylenediamine (DPD) method and the 1-(2-Pyridylazo)-2-Naphthol (PAN) method (Method #8149). The purpose of this comparison is to identify the best method for the analysis of permanganate with the presence of a high concentration of manganese. The DPD method is designed for the measurement of free chlorine but it can also be used to measure permanganate, especially when other forms of manganese are present. Strong oxidants such as free chlorine and permanganate react with the DPD reagent to generate a color for the spectrophotometer to read. The PAN method can be used to measure permanganate although it is designed to measure manganese, but is not ideal due to the hazardous reagents involved. The PAN method uses a reducing reagent to convert all forms of manganese (including permanganate) to soluble manganese (Mn^{2+}) and then a color is produced with an indicator. The molecular weight of $KMnO_4$ is 158, and the molecular weight of Mn^{2+} is 55, so the ratio is $158/55 = 2.87$. Therefore, the spectrophotometer reading can be multiplied by 2.87 to determine the concentration of permanganate. This method is only applicable when $KMnO_4$ is predominant in the water sample. According to the results of this project, when a relatively high concentration of manganese is present, the PAN method will overestimate the permanganate concentration. The DPD method was determined to be the better method to measure permanganate during this project. It was found that both methods generated very similar results for samples in which $KMnO_4$ was predominant (e.g., $KMnO_4$ stock solution).

For the analysis of total and soluble Mn, the Centre also selected a number of samples to compare the accuracy of the PAN method with the standard, inductively coupled plasma mass spectrometry (ICP-MS) method, used in certified laboratories. For the measurement of manganese, both the PAN method and the standard ICP-MS method are applicable. The PAN method involves using hazardous reagents and requires a well-vented fume hood for the analysis; however, it is easy to use and fast, providing timely data for users to adjust treatment processes. A few water samples were collected from the raw water and filter effluent. These were analyzed using the PAN method first,

and then forwarded to a laboratory for ICP-MS analysis. It was found that the results from the two methods were very close (as shown in Figure 2), maybe because of the relatively low hardness of water samples (~174 mg/L as CaCO₃). High hardness (e.g. >300 mg/L as CaCO₃) is known to have an impact on the accuracy of the PAN method.

Sample filtration using a 0.45 µm filter was used for the measurement of soluble manganese. The filter paper is able to separate the soluble manganese from the insoluble manganese. Therefore, the results reported from a filtered sample are referred to as soluble manganese, and the results from unfiltered samples are referred to as total manganese.

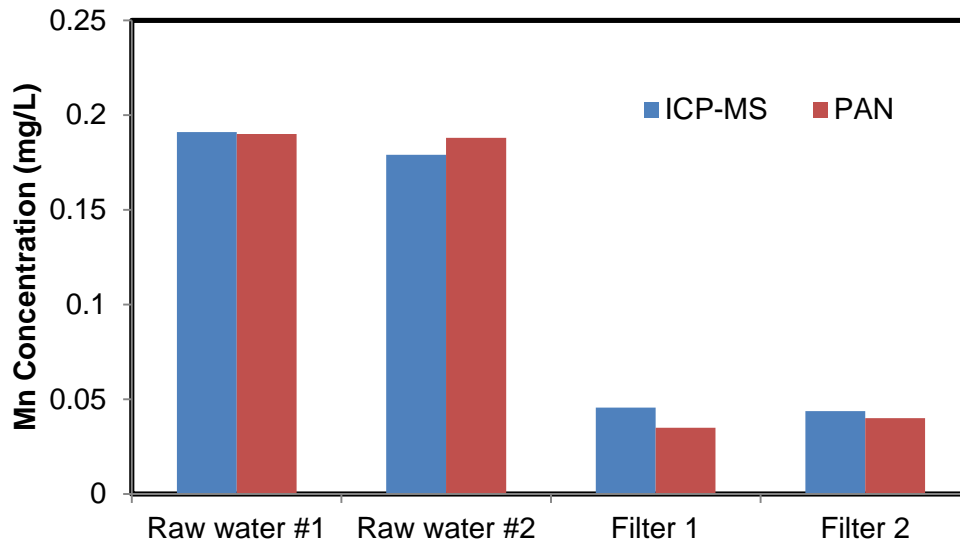


Figure 1. Manganese measurements using Hach’s PAN method and standard ICP-MS method (by a licensed laboratory).

3.3 Pilot Greensand Filters

The Centre installed two pilot-scale greensand filters in parallel at the WTP plant in November 2017 for testing. To compare the performance of media, Filter 1 was filled with used greensand and anthracite that was collected from a full-scale greensand filter at the DWT plant. Filter 2 was filled with new greensand and anthracite media. The performance of Filter 2 was verified in a previous pilot testing project. Both filters were

0.254 m in diameter (10 inches). The flow rate was 7.5 L/min and filtration rate was 8.9 m/h, which was very similar to the full-scale WTP filters.

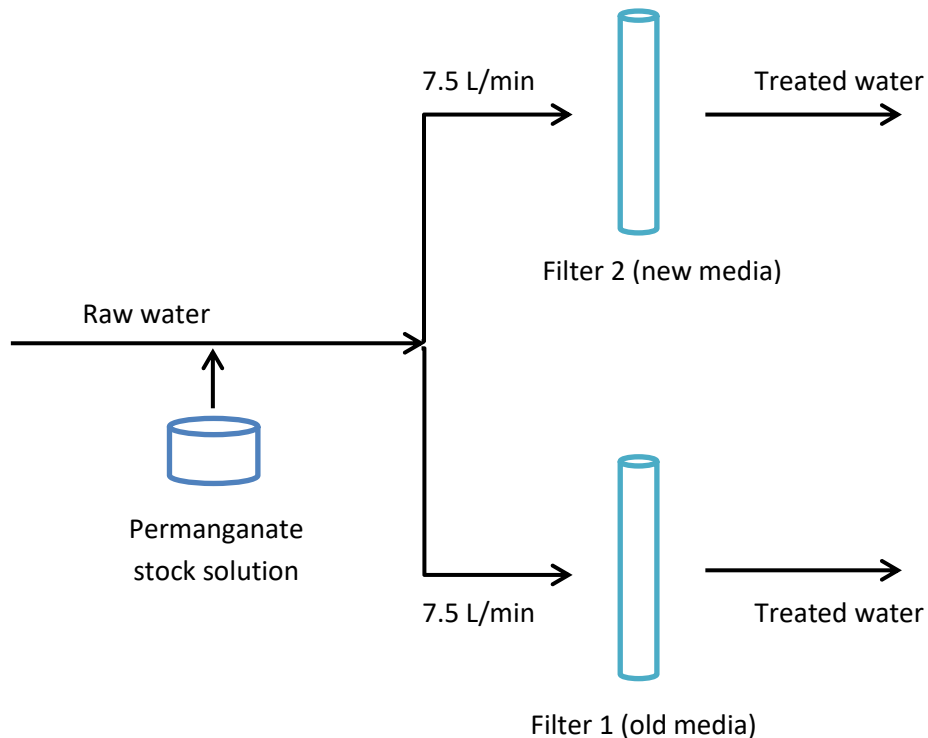


Figure 2. The pilot-scale setup

4. Results and Discussion

4.1 Raw Water Quality

Raw water samples were collected and a number of water quality parameters were measured. As shown in Table 2, the total Mn concentrations ranged from 0.188 – 0.196 mg/L in which the soluble Mn was predominant. Similarly, the total Fe concentrations ranged from 0.34 – 0.39 mg/L and the soluble Fe was predominant. Relatively high levels of organics were present indicated by the UV absorbance measurements ($>0.12 \text{ cm}^{-1}$). Turbidity was low but varied from 0.35 – 1.1 NTU. In addition, both pH (~8) and hardness (~174 mg/L as CaCO_3) readings were very stable.

Table 2. Raw water quality

Date	Manganese (mg/L)		Iron (mg/L)		UVA (cm ⁻¹)	Turbidity (NTU)	pH	Hardness (mg/L as CaCO ₃)
	Total	Soluble	Total	Soluble				
Nov. 22	0.188	0.182	0.35	0.35	0.127	0.35	8.01	174
Nov. 23	0.196	0.195	0.34	0.33	0.149	1.1	8.09	175
Nov. 24	0.185	0.176	0.38	0.38	0.125	0.78	8.06	175
Nov. 27	0.19	0.188	0.39	0.39	0.142	0.37	8.04	176

4.2 Jar Test

The average concentrations of iron and manganese in raw water were 0.35 mg/L and 0.19 mg/L, respectively. Therefore, the calculated permanganate dosage was 0.73 mg/L using equation 3 ($0.35 + 0.19 \times 2 = 0.73$). A jar test was performed using raw water to identify the optimal dosage of potassium permanganate. As shown in Figure 3, when no permanganate was added (0 mg/L), total Mn (0.190 mg/L) and soluble Mn (0.184 mg/L) were almost the same due to the fact that soluble Mn was predominant in raw water. The total Mn concentrations increased with the increased permanganate dosage, and the soluble Mn concentrations decreased due to the oxidation reaction. The soluble Mn concentration reached the plateau (0.034 mg/L) when 0.7 mg/L of permanganate was added into the jar. Therefore the optimal permanganate dosage identified was 0.7 mg/L which is very close to the calculated permanganate dosage (0.73 mg/L).

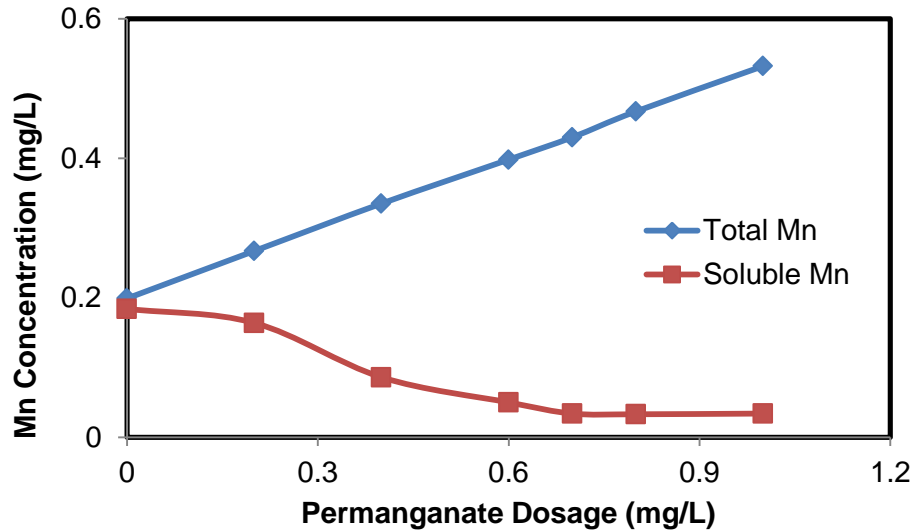


Figure 3. Jar test to identify the optimal permanganate dosage

4.3 Effect of Continuous Regeneration on the Reduction of Manganese

For the first 8 days, both pilot greensand filters were tested in the continuous regeneration mode with a permanganate dosage of 0.75 mg/L. Water samples were taken after both filters were run in parallel for 12 hours. As shown in Figure 4, the total Mn concentrations in raw water were stable (0.18 – 0.19 mg/L). Due to the continuous addition of permanganate and the oxidation between permanganate and manganese, the total Mn concentrations in the pre-filter increased to about 0.4 mg/L. Total Mn in Filter 1 effluent was high (0.24 mg/L) initially, but quickly decreased to the same level as Filter 2 after backwashing (regeneration cycle). Both filters were able to remove most of the total Mn and keep the total Mn concentrations low (0.03 – 0.04 mg/L) in the filter effluent.

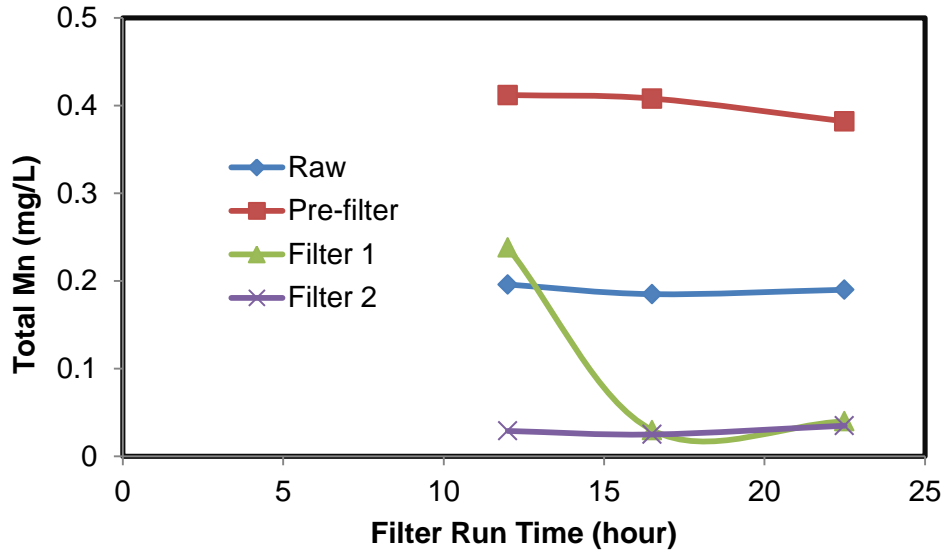


Figure 4. Total Mn concentrations in raw water, pre-filter, and filter effluent using continuous regeneration mode

The reductions of soluble and insoluble manganese are shown in Figure 5. It was found that in the raw water most of the Mn was in the soluble form (0.18 mg/L). As a result of the oxidation process after the permanganate was added to raw water, most of the soluble Mn was oxidized to insoluble Mn with about 0.07 mg/L soluble Mn remaining. The insoluble Mn was greatly increased because of the formed Mn oxides as well as the remaining permanganate. Then most of the insoluble Mn (92.5%) and a significant portion of the remaining soluble Mn (71.4%) were adsorbed and removed by the greensand filters. Both filters performed similarly showing that the impact by media aging was minimal.

The effective removal of insoluble Mn by the greensand filter was expected; it was expected whether the manganese oxide coated greensand or any other media filtration was used as the insoluble Mn is in particulate form. However, it was found that the removal of soluble Mn depends on the adsorption process within the greensand grains. Greensand filters are designed so that soluble Mn adsorbs on the sand grains and is then oxidized. It is important that the manganese does not oxidize before arriving at the filter (Merkle *et al.*, 1997b). Therefore, a relatively weak oxidant such as free chlorine (Knocke *et al.*, 1990) is often selected rather than permanganate in the continuous

regeneration mode. In this pilot test, permanganate oxidized soluble Mn before it arrived at the filter (as shown in Figure 5), then the insoluble Mn interfered with the adsorption of the soluble Mn on the sand grains. This reduced the removal of soluble Mn. Knocke *et al.* (1991b) found that during pre-filter treatment with a strong oxidant, all the Mn might not be converted into a particulate state, leaving some Mn in a colloidal size range, and therefore may not be removed efficiently by media filtration.

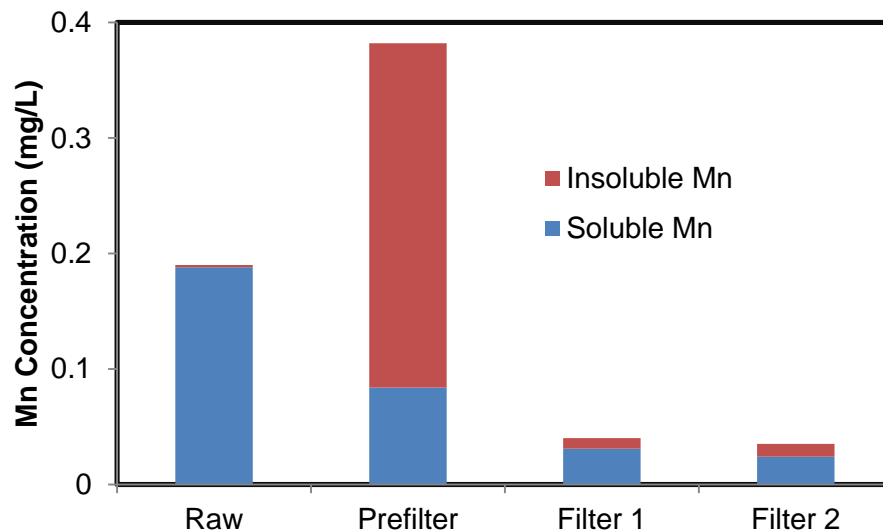


Figure 5. The removal of insoluble and soluble Mn in continuous regeneration

Thus, continuous regeneration with permanganate may not efficiently remove soluble Mn, especially when the manganese concentration in raw water is high or the permanganate dosage is not optimized. A few potential approaches may be used to improve the removal efficiency of the soluble manganese.

Firstly, the permanganate dosage should be optimized so that most of the soluble Mn is oxidized before entering the filter. Although the optimized permanganate dosage can be determined by the jar test (as shown in section 4.2), it can be difficult since ammonia (~2 mg/L) and natural organic matter (DOC ~2 mg/L) are also commonly present in raw water and are reactive to permanganate. Under dosing the permanganate will lead to inefficient oxidation of soluble manganese, and over dosing will increase the chemical cost. However, under dosing should be avoided since the greensand filter is not able to

efficiently remove the remaining soluble Mn as a colloidal state is created when permanganate is added prior to the filter (Knocke *et al.*, 1991b).

Secondly, a switch to a relatively weaker oxidant such as free chlorine may improve the removal efficiency (Knocke *et al.*, 1990). Such oxidants cannot oxidize manganese before entering the filter but can regenerate the media continuously, so the manganese remains in soluble form and will be adsorbed by the greensand grain. Chlorine has proven to be effective in full-scale plants. However, in this study if chlorine was used, a significant amount of chlorine would need to be injected to generate free chlorine because of the presence of high levels of ammonia in the raw water, which may lead to the formation of a significant amount of trihalomethanes. Adding an additional treatment unit such as an ion exchange or activated carbon prior to the greensand filtration could help to reduce the organics and ammonia. In addition, aeration or activated carbon adsorption following greensand filtration could reduce the level of disinfection by-products formed.

Thirdly, applying no oxidants prior to the filter would switch the continuous regeneration mode of the greensand filter to intermittent regeneration mode. This was conducted in a later experiment and a detailed discussion can be found in section 4.4.

4.4 Effect of Intermittent Regeneration on the Reduction of Manganese

Both Filters 1 and 2 were switched to intermittent regeneration mode at day 9, in which no oxidant was added prior to the filter. As shown in Figure 6, Filter 2 had better performance as a longer filter run time was obtained. Filter 2 (with new media) was able to consistently reduce the total Mn from 0.18 mg/L in raw water to below 0.03 mg/L in filter effluent. However, Filter 1 (with old media) was not able to keep the total Mn in the filter effluent lower than 0.05 mg/L consistently. A regeneration followed by a backwash cycle was performed on Filter 1 after 12.5 hours of filter run time when the total Mn went up to 0.75 mg/L, and a second regeneration was performed after 50 hours of filter run time. The results indicated that the old media was not performing as well as the new media in terms of adsorption of soluble Mn.

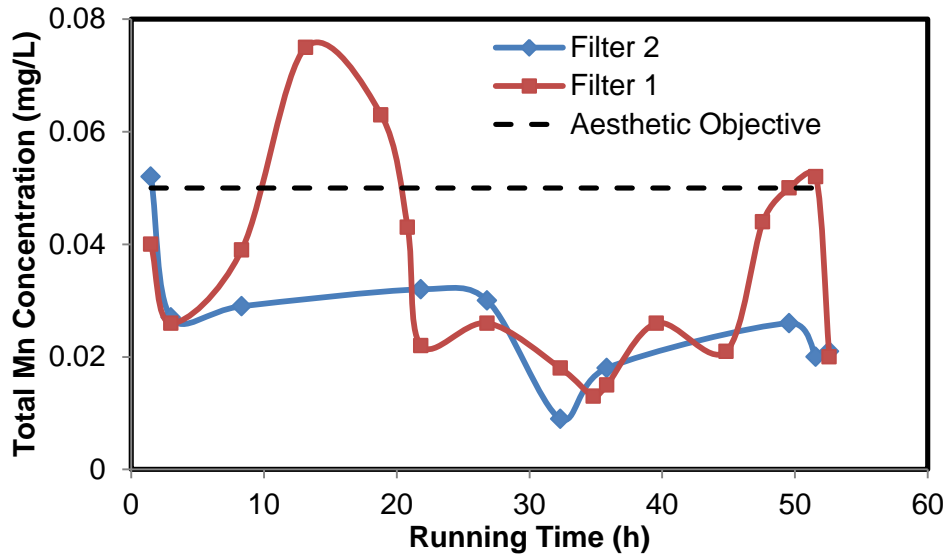


Figure 6. Total Mn concentrations in Filter 1 and Filter 2 using the intermittent regeneration method.

The reductions of soluble and insoluble manganese were shown in Figure 7. The raw water sample was almost identical to the pre-filter sample as no oxidant was added. Manganese remained in soluble form when entering the filter. It was found that both Filter 1 and Filter 2 could reach >86% removal of soluble Mn due to the adsorption by the greensand grains. Intermittent regeneration showed better removal of soluble Mn than the continuous regeneration method and significant savings on chemical cost. However, filters have to be regenerated and backwashed more often than the continuous regeneration mode, which results in increased operation and maintenance.

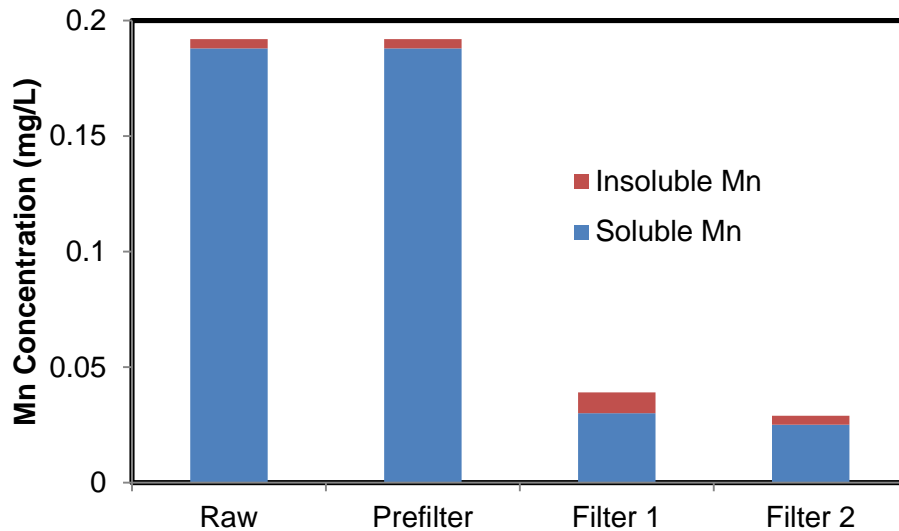


Figure 7. The reduction of insoluble and soluble Mn in intermittent regeneration mode

4.5 Optimization of Permanganate Dosage

Greensand filtration is designed to remove soluble Mn using an adsorption/oxidation process, however, when permanganate is added continuously prior to the greensand filter, the removal mechanism is switched to an oxidation/filtration process. Chemical oxidation (e.g. using permanganate) provides a rapid and convenient way for Mn removal. However, when Mn is present in relatively high concentrations, and/or in an organically complexed form, large dosages of permanganate may be required which may lead to residual Mn concentrations that exceed the aesthetic objective in treated water. Sometimes Mn is in a form that is bound to organics, which makes it difficult to remove. It is very difficult to optimize permanganate dosage in continuous regeneration mode. If the dosage is too high, a permanganate break-through may happen, which will contribute to the total Mn in the filter effluent. If the dosage is too low, the pre-filter oxidation reaction is not completed resulting in a higher remainder of soluble Mn.

Yu *et al.* (2015) investigated the combination of chlorine and permanganate for Mn removal in organic-rich surface water. The results have shown that the combination of the two chemicals is beneficial and synergistic. The addition of chlorine appears to enhance the release of bound Mn and the subsequent conversion of soluble Mn to

insoluble Mn. This finding may be useful to study in a future project as both chlorine dosages and permanganate dosages could be reduced and would therefore reduce the formation of disinfection by-products as well as the overall chemical cost.

5. Conclusions

In this study, both greensand filtration with continuous regeneration using permanganate and intermittent regeneration were tested for their effect on manganese reduction in the filter effluent. The principal conclusions are as follows:

- The jar test indicated that the optimal permanganate dosage for manganese oxidation can be determined by Equation 3, and under dosing will lead to incomplete oxidation of soluble manganese to insoluble forms.
- Continuous regeneration of the greensand filters using permanganate can remove the majority of the insoluble manganese and >70% of the remaining soluble manganese; it is important to note however that operating in this mode would most likely increase chemical costs.
- Intermittent regeneration of the greensand filters with no oxidant can remove the majority of the insoluble manganese and adsorb >86% of the soluble manganese; it is important to note however that operating in this mode would most likely increase the amount of plant operation and maintenance conducted by operators.
- The older greensand media showed to not be as effective at adsorbing soluble manganese and had shorter run times when operated in intermittent regeneration mode. No difference in soluble manganese reduction performance was observed when operating in continuous regeneration mode.

Other options identified that could improve the removal of manganese using greensand systems may include the following:

- Continuous regeneration with permanganate is very difficult to optimize. Permanganate dosage is required to be optimized to improve the removal of soluble permanganate. Weaker oxidants such as free chlorine which will not oxidize manganese before entering the filter may improve the greensand

adsorption capability. Alternatively, studies have shown a combination of chlorine and permanganate may also be able to improve the greensand adsorption.

- Removing natural organic matter and ammonia from the source water would decrease the permanganate demand in continuous regeneration operation and will minimize the formation potential of disinfection by-products in the finished water.
- Flow rate, pH, and the amount of manganese oxide coating on the greensand grains had significant impact on the adsorption capacity. It could be studied how lowering the water flow rate to increase the retention time, adjusting the pH, and increasing the amount of manganese coating in the regeneration process may improve the greensand filter performance.

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