SUMMARY

This report details the methods and results of a pilot study for iron and manganese removal at the Oakdale Well in West Boylston, MA operated by the West Boylston Water District. The field component of the pilot study was conducted from March 28 to July 14, 2019.

The pilot study evaluated two alternative iron and manganese removal treatment processes: Greensand Filtration and Biological Filtration. The raw water concentrations of manganese during the study at the Oakdale Well had a median concentration of 0.764 mg/L, exceeding the Secondary Maximum Contaminant Level (SMCL) of 0.05 mg/L Mn. The raw water concentration of iron at the Oakdale Well had a media concentration of 0.05 mg/L, and did not exceed the SMCL of 0.10 mg/L Fe. Raw iron and manganese concentrations measured during the study were similar to the concentrations reported by the West Boylston Water District.

GREENSAND FILTRATION

The Greensand Filtration pilot process operated from April 30 to May 10, 2019.

The pilot study evaluated pressure filtration using four individual filters with GreensandPlus™ adsorptive media, with an anthracite coal filter cap, operating in parallel in side-by-side testing. The study used the four filters to evaluate pretreatment using NaOCl and KOH (target filter influent pH = 6.8 s.u.) at different loading rates (4.0, 5.0, 6.0, and 7.0 gpm/sf).

A total of 16 individual filter runs were completed using the Greensand filters. All pilot filters effectively removed metal contaminants to meet the project goals for iron (Fe <0.10 mg/L) and manganese (Mn <0.05 mg/L) at both well sites. Effective operating conditions included chlorine doses of 50.6 – 81.1 ppm as 6% sodium hypochlorite and FSLRs between 4 and 7 gpm/sf.

Differential pressure (DP) across the filters increased over time as a function of filter loading rate and raw water quality. Filter run times are expected to exceed 72 hours at all filter surface loading rates between 4 and 7 gpm/sf. Trials 1 – 3 were terminated based on pilot schedule while Trial 4, the supernatant recycle trial, operated to 10 psi of headloss.

The recycle trial was conducted using backwash water collected from previous trials and allowed to settle for at least four hours. Recycling the settled supernatant into filter influent at a rate of 10% of the total influent flow did not have a significant negative impact on filter effluent water quality or filter performance.

BIOLOGICAL FILTRATION

The Biological Filtration pilot process operated from March 28 to July 14, 2019. The pilot study evaluated biological filtration using two individual filters with sand media fully acclimated for manganese treatment at a full-scale biological water treatment plant located in Putnam, CT.

The study evaluated pretreatment using KOH for pH adjustment and air for dissolved oxygen (DO) addition. The pilot filters were operated at different loading rates (5.0, 10.0 and 15.0 gpm/sf). A total of 17 individual biological filter trials were completed.

The biological removal Filter M1 did not immediately start treatment manganese despite being fully acclimated at another site. M1 required re-acclimation at a low loading rate (5 gpm/sf) which took approximately 673 hours (28.0 days). After increasing the loading rate (10 gpm/sf) another period of acclimation was required to achieve acceptable manganese removal, this period lasted approximately 747 hours (31.1 days).

The biological removal Filter M2 did not immediately start treatment manganese despite being full acclimated at another site. M2 required re-acclimation at a low loading rate (5 gpm/sf) which took approximately 864 hours (36.0 days). After increasing the loading rate (15 gpm/sf) another period of acclimation was required to achieve acceptable manganese removal, this period lasted approximately 747 hours (31.1 days).

During representative biological filter operations, both M1 and M2 met the goals for iron and manganese removal at all evaluated loading rates. Biological treatment was inconsistent during most periods of operation. Though the average manganese concentration met the goal at this site, biological filtration is not recommended due to the issues with long acclimation times and inconsistent treatment. Tables 3.14 and 3.15 on Page 53 show that many of the trials had occurrences of high manganese.

Run times were limited by terminal headloss at 10 psi of differential pressure. Runtimes for Filter M1 was 308.3 hours operating at 5 gpm/sf and 41.2 - 117.0 hours operating at 10 gpm/sf. Runtimes for Filter M2 was 289.5 hours operating at 5 gpm/sf and 32.3 - 106.5 hours at 15 gpm/sf.

REPORT OVERVIEW

The Pilot Study Report has been organized to provide the reader with the methods, results, and interpretation of the data in separate sections. Section 2 "Methods" describes the equipment and methods used during the field testing. Section 3 "Results" contains data that was developed without interpretation, thus allowing the reader to form their own opinion of the data. Section 4 "Data Analysis" is included to provide interpretation of results and to combine disparate pieces of information into a comprehensive evaluation.

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LIMITATIONS

This pilot test report was prepared for Comprehensive Environmental Inc. and the West Boylston Water District, for the purpose of evaluating treatment of iron and manganese in water supplied from the Oakdale Well in West Boylston, MA. The findings provided in this report are based solely on the information contained and referenced herein. All field operations, field analyses, data compilation, data analysis and reporting were completed in a fair and impartial manner and are intended to be an accurate representation of treatment performance. Additional quantitative information regarding the raw water, or other treatment goals and concerns that were not available to Blueleaf, Inc. at the time of the pilot study may result in modification of the stated findings. Note that bench and/or pilot scale studies may not identify issues arising from long-term changes to source water quality, nor predict long-term performance of the treatment processes tested.

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ABBREVIATIONS

ANOVA	Analysis of Variance
ATP	Adenosine Triphosphate
BDL	Below Detection Limit
DO	Dissolved Oxygen
FSLR	Filter Surface Loading Rate
gpm	Gallons per Minute
gpm/sf	Gallons per Minute per Square Foot (of surface area)
gpd	Gallons per Day
gr	Gram
HP	Horsepower
L	Liter
mg	Milligram
MG	Million Gallons
MGD	Million Gallons per Day
µg/L	Micrograms per Liter (equivalent to ppb)
mg/L	Milligrams per Liter (equivalent to ppm)
min	Minutes
mV	Millivolt
NTU	nephalometric turbidity units
N/A	Not Available / Not Applicable
ND	Not Detected
ORP	Oxidation Reduction Potential
PID	Proportional Integral Derivative
ppb	Parts per Billion
ppm	Parts per Million
SM	Standard Methods
S.U.	Standard Units
TSS	Total Suspended Solids

1 INTRODUCTION

1.1 BACKGROUND

The West Boylston Water District (WBWD) provides public drinking water to the Town of West Boylston MA. The Oakdale Well historically has had variable iron concentrations ranging from non-detect to 0.107 mg/L, which is less than the Secondary Maximum Contaminant Limit (SMCL) for iron (0.30 mg/L Fe). Historically, manganese concentrations ranged from 0.8463 to 0.9278 mg/L from the Oakdale Well and is significantly over both the SMCL (0.05 mg/L Mn) and the Massachusetts OSRG (0.30 mg/L Mn). There is currently no iron or manganese removal process in use at this source.

WBWD has retained the services of Comprehensive Environmental Inc (Marlborough MA) to assist in the selection, design, permitting and construction of an iron and manganese treatment facility for the source. The two processes under consideration for this site are:

- Manganese Greensand - removal of dissolved iron and manganese from raw water through a combination of processes including chemical oxidation and precipitation, followed by adsorption and filtration onto a media bed of anthracite and GreensandPlus™ (Inversand, Clayton NJ). The removal mechanism for iron is precipitation using an oxidant followed by filtration of precipitated floc particles. The removal mechanism for manganese is adsorption and subsequent adsorption on the GreensandPlus media.
- Biological - biological iron and manganese filtration system is an alternative to physical/chemical processes. Biological filtration is currently being used in Cavendish VT, Shrewsbury MA and Putnam CT and Middleborough MA. Biological filtration uses microorganisms that are present in the ground water to oxidize and adsorb the dissolved iron and manganese onto a bed of sand.

1.2 PILOT STUDY GOALS

The goals of the pilot study were as follows:

1. Demonstrate the ability of GreensandPlus filtration and biological filtration to remove iron and manganese to concentrations below the SMCL (0.3 mg/L Fe and 0.05 mg/L Mn), and pilot goals of 0.10 mg/L Fe and 0.05 mg/L Mn.
2. Quantify the filter runtime to the point of contaminant breakthrough or terminal headloss at various Filter Surface Loading Rates.
3. Quantify the rate at which pressure losses increase at various Filter Surface Loading Rates.
4. Provide chemical dosages for effective treatment conditions.
5. Characterize the backwash water quality and settleability.
6. Confirm the performance of the treatment process when recycling the settled backwash water supernatant into the raw water.

2 METHODS AND MATERIALS

Section 2 - Methods and Materials describes the equipment, procedures, and analytical methods utilized during the pilot testing effort. Results are included in this Section only when discussing the precision and accuracy of field methods used.

2.1 PILOT EQUIPMENT DESCRIPTION

2.1.1 Raw Water Connections

Raw water from the Oakdale Well was supplied from a 2" connection at the base of the vertical turbine pump. The West Boylston Water Department installed a backflow preventer as shown in Figure 2.01. This connection supplied water to both the Greensand Pilot and Biological Pilot and any water not utilized by the pilot systems was used for municipal supply.

Figure 2.01: Oakdale Well Pilot Connection

The Oakdale Well does not operate continuously, so a 4,900-gallon tank was used to store raw water while the well was on and provided continuous raw water for the pilot when the well was off. The storage tank was equipped with a sight tube to check the water level, an overflow, and a float to turn off raw water flow to both the pilot systems in the event the tank level was too low. The tank is shown in Figure 2.02.

Figure 2.02: Raw Water Storage Tank

Raw water was conveyed from the well pump to the storage tank via 1-1/2” nylonbraid hose. The hose was equipped with a rotameter and flow control valve to control the flow of raw water to the tank. When the Oakdale Well was active, raw water flowed through the rotameter and was conveyed to one of the two pilot systems with any excess water filling the storage tank from the bottom. When the Oakdale Well was inactive, both pilot systems received raw water from the raw water storage tank. The valves controlling raw water to both pilot systems are shown in Figure 2.03.

Figure 2.03: Raw Water Feed to Pilot Systems

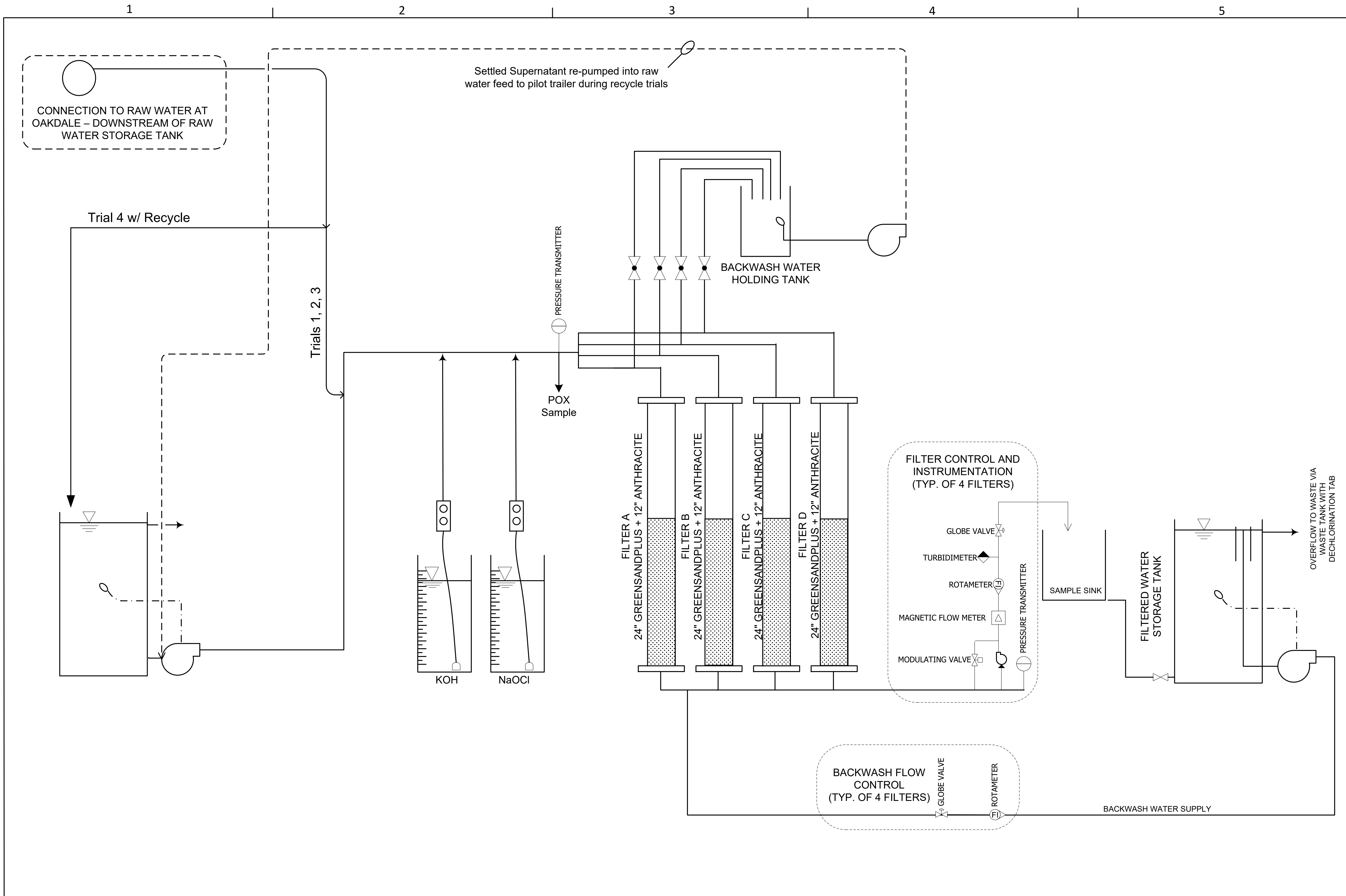
Each pilot system was supplied raw water from the storage tank via ½ horsepower inline booster pump. These booster pumps would also supply adequate pressure for operation of each pilot process.

2.1.2 Greensand Pilot System

The greensand pilot system was delivered to the Oakdale Well Station on April 30, 2019. Formal filter trials began that day and concluded on May 10, 2019. The pilot filtration system and field laboratory were contained in a cargo style trailer. Figure 2.04 shows the pilot trailer set up at the Oakdale Well Station.

Figure 2.04: Exterior of Pilot Trailer at Oakdale Well Station

Figure 2.05 shows a schematic of the pilot filtration system.



PROJECT: IRON AND MANGANESE REMOVAL PILOT STUDY – OAKDALE WELL

BLUELEAF, INC
PILOT TESTING FOR WATER AND WASTEWATER TREATMENT
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(508) 248-7094

FIGURE 2.05: GREENSAND PILOT SYSTEM SCHEMATIC

DRAWN BY E. GROTTON
FILE NAME 03508_015
DATE 05SEP2019
SIZE: 11' X 17"
SCALE: 1" = 2'
DWG NO 2.05

The pilot filtration system included equipment for chemical pretreatment, flow control, four media filters operating in parallel, a data acquisition system, and sample points for all relevant sample streams. Figure 2.06 shows the chemical feed area with 2 Grundfos chemical feed pumps and two day tanks. Each day tank had a capacity of 17 liters and was constructed of clear 6" PVC with 0.1 L graduation intervals.

Figure 2.06: Pilot Trailer Chemical Feed Area

The pilot influent was pretreated using potassium hydroxide (KOH) to adjust the pH followed by sodium hypochlorite (NaOCl) for oxidation. All four pilot filters received the same pretreated water. Pretreated water was sampled via ¼-inch sample lines connected to filter inlets of Filter A and C. Periodically, a composite of the two samples was monitored for various water quality parameters, typically including chlorine (free and total), iron (total and dissolved), manganese (total and dissolved), and pH.

Figure 2.07 shows the flow control for the pilot filters. There were four parallel flow control assemblies, one per filter. Each flow control assembly included separate components for filtration and backwash operations. Forward flow had automated control capability. A flow meter controlled an automatic modulating valve via a PC-based PLC program with a PID loop. The PLC continuously monitored and logged filter flow rates, filter inlet and outlet pressures, filter effluent turbidities, and filter influent pH. The flow rate to the turbidimeters was manually adjusted and periodically measured.

Figure 2.07: Flow Control for Pilot Filters

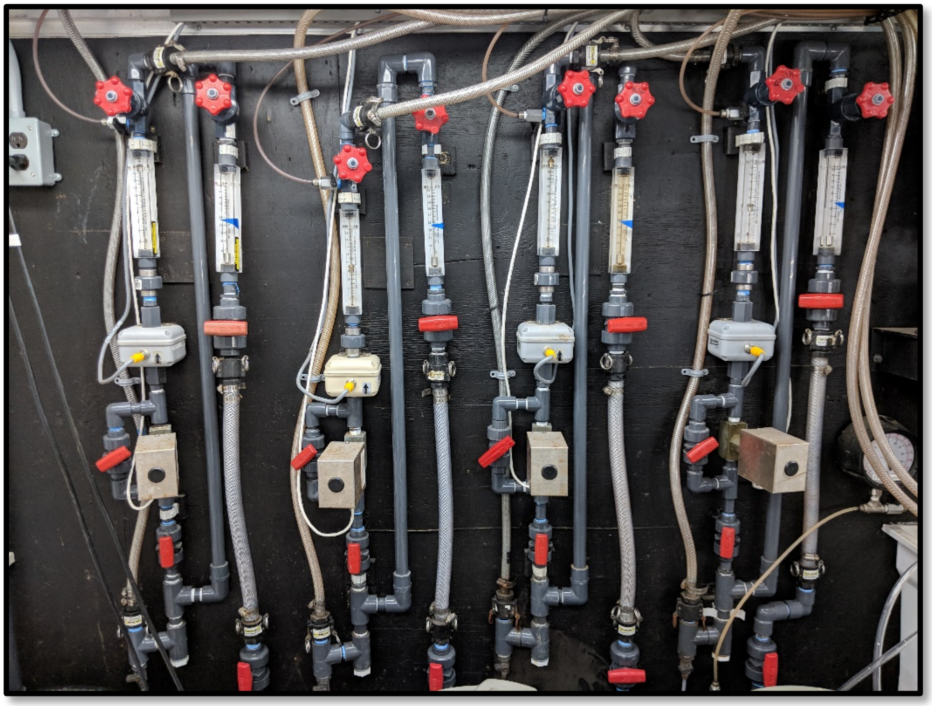


Figure 2.08 shows the sample sink, with ½" hoses for pilot filter effluent, 3/8" lines for discharge from the four Hach 1720e flow-through turbidimeters, and the 1/4" sample lines for untreated raw water, pretreated filter influent from Filter A, and pretreated filter influent from Filter C. The pretreated filter influent sample lines flowed into a common sample cup with two online pH meters, connected to a Hach SC200 controller. The pH controller provided automated control of the potassium hydroxide feed pump to maintain the target filter influent pH. The pH setpoint used throughout the study was 6.8 s.u.

Figure 2.08: Pilot Trailer Sample Sink

Four pilot filters were operated in parallel during all trials. Each pilot filter was 6 inches in diameter by 60 inches high. Pilot filters were constructed from 6-inch clear PVC schedule 40 pipe. Each filter had an underdrain consisting of a 2” stainless steel slotted media-retention nozzle with No. 8-12 garnet surrounding the nozzle. All four filters contained 24 inches of GreensandPlus^{TM} (GSP) filtration media, with a 12” anthracite coal filter cap.

Each filter effluent flow had a dedicated flow-through Hach 1720E low range turbidimeter. The four effluent turbidimeters were connected to two Hach SC100 2-channel controllers. Filter effluent grab samples were collected from the individual filter effluent streams at the points of discharge into the sample sink. Autosamplers were connected to the effluent lines and programmed to collect grab samples at programmed intervals when the pilot system was not staffed.

Water from the sample sink was conveyed into a 150-gallon tank. The filters were backwashed using filter effluent stored in the 150-gallon effluent tank. The effluent tank was equipped with an overflow which was discharged to a infiltration basin located onsite. The effluent tank and discharge are shown in Figure 2.09

Figure 2.09: Pilot Effluent Tank and Waste Discharge

During backwashes a booster pump supplied backwash water from the effluent tank to the trailer. Backwash flows were controlled on the upstream, clean-water side of the filters while in reverse flow mode. Each filter had a dedicated 0-5 gpm rotameter and flow control valve.

All filters were backwashed at a nominal flow rate of 2.4 gpm (12 gpm/sf) for a period of 10 minutes. For each filter, the entire backwash volume was collected in a 30-gallon tank, and backwashing continued until a volume of 24-gallons was collected. The collected bulk backwash sample was typically sampled to characterize the backwash water. After sampling, the backwash water was either discharged to waste or transferred to a 150-gallon tank for eventual use as supernatant recycle.

The spent backwash water from all filters was stored in a 150-gallon tank for settling. The settled supernatant was then recycled into the raw water at a rate of 10% of the total forward feed flow during supernatant recycle trials. A Masterflex peristatic pump fed the supernatant into the raw water at a rate calibrated to equal 10% of the total pilot system influent flow rate. The intake for the supernatant pump was suspended above the sludge layer in the backwash settling tank to avoid the withdrawal of solids. Figure 2.10 shows the supernatant recycle feed pump and the backwash storage tank.

Figure 2.10: Supernatant Recycle Pump and Intake

Table 2.01 summarizes the pilot filter configurations.

Table 2.01: Pilot Filter Configurations

Parameter	Filters A, B, C, D
Adsorptive filtration media	GreensandPlus^{TM} with Anthracite
Adsorptive media depth	24 inches (61 cm)
Anthracite filter cap	12 inches (30 cm)
Total filter bed depth	36 inches (91 cm)
Filtration media volume	0.4 ft^3 (11.3 L)
Anthracite volume	0.2 ft^3 (5.7 L)
Total media volume	0.6 ft^3 (17.0 L)
Freeboard above filter surface	24 inches (61 cm)
Filter vessel diameter	6 inches (15 cm)
Filter surface area	0.20 ft^2 (182 cm^2)
Filter vessel height	60 inches (1.52 m)
Filter vessel empty volume	27.6 gallons (104.5 L)

2.1.2.1 GreensandPlus™ Filtration Media (GSP)

GreensandPlus™ (GSP) is a non-proprietary filtration media with the same adsorptive coating and treatment performance as standard manganese greensand, but the adsorptive coating is fused to a silica core. This allows GreensandPlus™ to withstand higher differential pressures than standard greensand without breakdown of the particles, and without stripping the adsorptive coating from the substrate. GreensandPlus™ can operate at filter loading rates 8 gpm/sf or greater, depending upon water quality, compared to 2 to 5 gpm/sf for standard manganese greensand.

GreensandPlus™ has a manganese oxide coating that both catalyzes the oxidation/reduction of manganese and is adsorptive to manganese. The manganese dioxide coating is maintained by feeding an oxidant, typically either permanganate or chlorine. Pre-oxidation for contaminant removal or disinfection can provide sufficient oxidant to also maintain the adsorptive qualities of the media, but it is sometimes necessary to perform specific media regeneration procedures. Regeneration can be performed continuously by feeding permanganate or chlorine during filter service (continuous regeneration, CR), or intermittently by occasionally backwashing or soaking with permanganate (intermittent regeneration, IR).

GreensandPlus™ filters are typically backwashed at 12 gpm/sf minutes, with or without air scour. A terminal differential pressure (DP) of 10 psi is often used to trigger backwash, but the manufacturer claims GreensandPlus™ is capable of withstanding DPs substantially greater than 10 psi.

2.1.3 Biological Pilot System

The biological pilot equipment was mobilized to the Oakdale Well Station and began operating without the biological filters in place on March 19, 2019. The biological pilot filters had been operating at the Park Street Wellfield in Putnam CT since December 17, 2018 and were reducing the raw water manganese in the raw water from 0.8 mg/L to less than 0.02 mg/L. Two filters were brought to the Oakdale Well site on March 20. On March 28, a third pilot filter was brought from Putnam and replaced one of the pilot filters for the remainder of the study (M1). The second biological pilot filter (M2) remained in operation with the same media from March 20 for the entire duration of the study.

The pilot equipment was located in a 20 ft x 8 ft ground level storage container. The container was situated off the driveway adjacent to the Oakdale Well Station. A process flow diagram of the pilot equipment is included as Figure 2.11.

Sample ID Key	
RAW	Untreated Pilot Influent from Oakdale Well
MPOKA	Biological Manganese Filter Influent
M1	Biological Manganese Filter 1 Effluent
M2	Biological Manganese Filter 1 Effluent

Filter Configurations	Filter M1	Filter M2
Anthracite	0	0
Sand	48	48
Diameter (inches)	6	6
Height (inches)	72	72

Data Logger Trending Parameters

	RAW	MPOKA	M1	M2
pH	X	X	X	X
TEMP	X	X	X	X
DO	X	X	X	X
ORP		X		
FLOW			X	X
DP			X	X

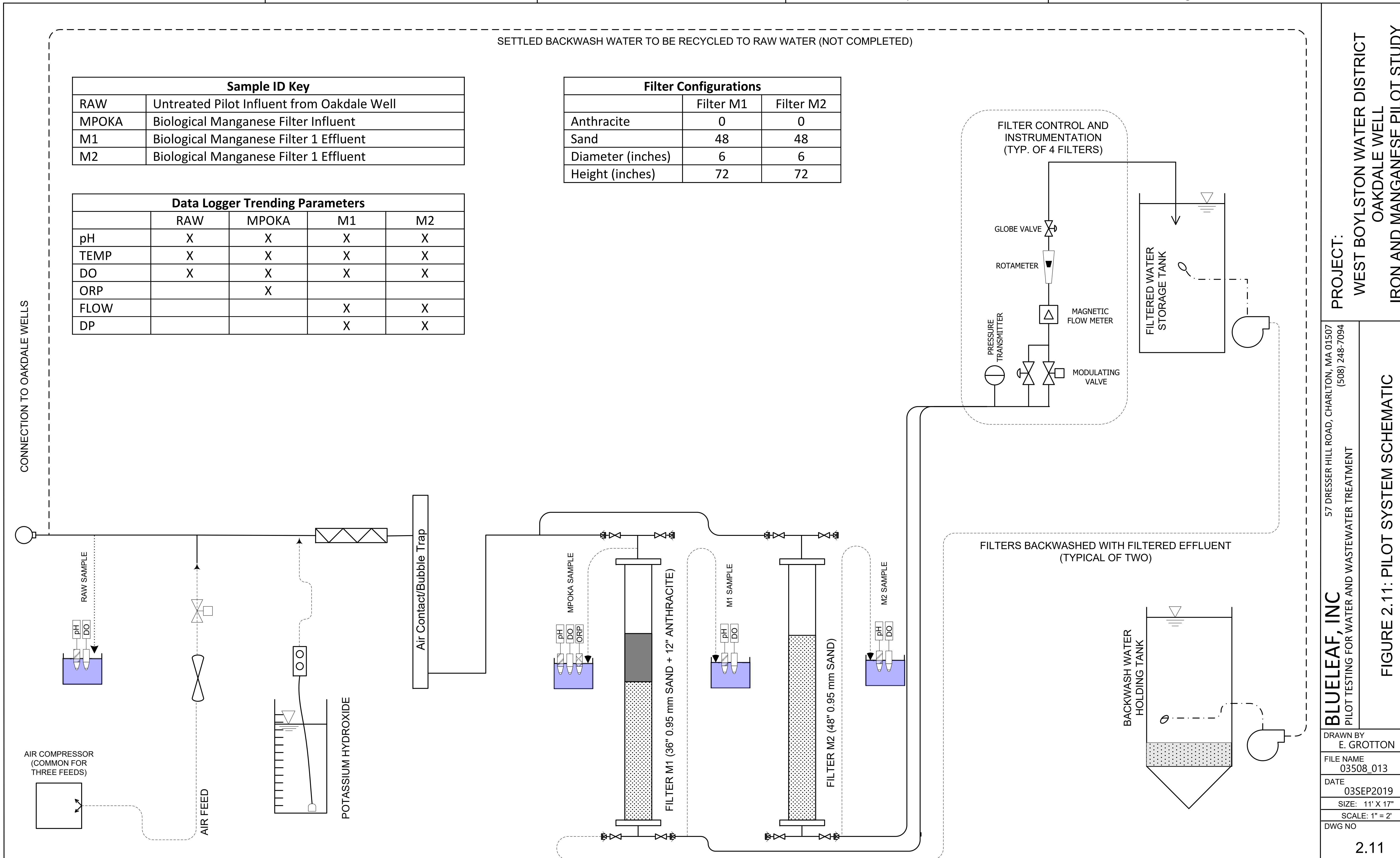


Figure 2.12 shows the ground level storage container.

Figure 2.12: Ground Level Storage Container with Pilot Equipment

The pilot equipment consisted of the following major components:

1. Feed Connections
2. Two Biological Pilot Filters
3. Instrumentation
4. Backwash Water Feed, Pump, and Valves
5. Field Laboratory and Analytical Testing Equipment

2.1.3.1 Feed Connections

Feed connections for the Oakdale Well was described in Section 2.1.1. A sample tap on the feed piping provided a live RAW sample to a sample container in the pilot sample sink.

2.1.3.2 Pretreatment

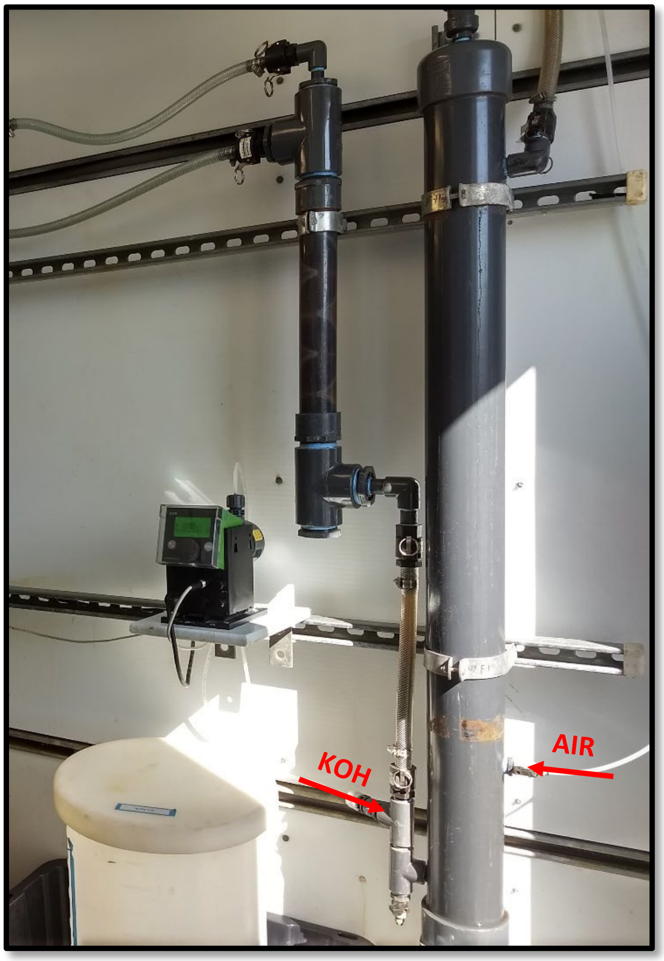
Pretreatment for the biological filters included the addition of potassium hydroxide for pH adjustment and an air feed to adjust the dissolved oxygen concentration. Both pilot filters received the same pretreated water adjusted for specfic pH and DO conditions.

A solution of potassium hydroxide was added to the flow using an electric diaphragm chemical feed pump controlled by a programmabe logic controller (PLC) connected to an online pH meter. The pH target was set by the operator, and the PLC controlled the speed of the pump to maintain the target pH.

An air compressor was used to introduce air and increase dissolved oxygen to filter influent during the Biological pilot. The air flow was regulated using a rotameter. The DO of the aerated water was monitored downstream of the contactor. Excess entrained air was purged from the line through an air release valves located at the top of the air saturator. An air release valve was also located at the top of each filter.

Figure 2.13 shows the air saturation and injection equipment.

Figure 2.13: Air Injection at Cross Current Air Contactor and KOH Injection at Static Mixer



2.1.3.3 Biological Filters

Two biological filters were evaluated during the pilot study:

- M1 consisted of a single filter for the concurrent removal of iron and manganese. Filter media was acclimated in Putnam CT and began receiving water from the Oakdale Well on March 20. M1 removed Mn from the raw water at Oakdale for a few hours, but there was little Mn removal after the first day. M1 was replaced with another biological filter containing media acclimated in Putnam on March 28 and operated for the remainder of the pilot.

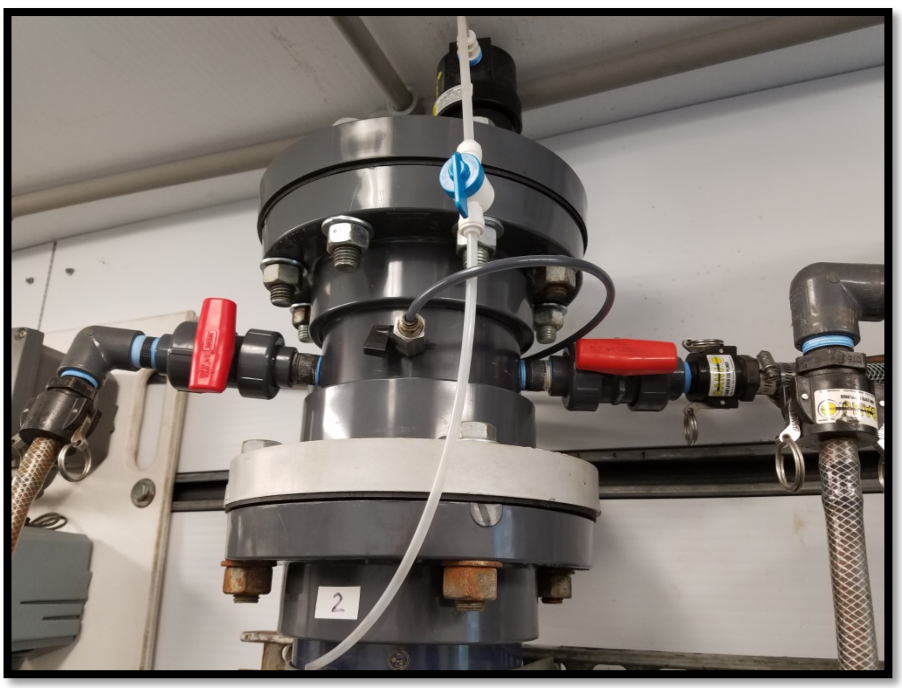
- M2 consisted of a single filter for the concurrent removal of iron and manganese. Media was acclimated at a previous site and began receiving water from the Oakdale Well on March 20.

A sample tap was located at the top of each filter and delivered a sample stream to the Post-Aeration, Post-KOH Addition (MPOKA) sample container. The pretreated, pH-adjusted, aerated water was filtered through each pilot filter.

The filters were 60-inches in height and were constructed from 6" diameter clear PVC schedule 40 pipe. The filter media was supported with a 6" diameter section of Tetra Block "S" underdrain. Filters M1 and M2 had 48 inches of 0.95 mm sand media. Filters M1 and M2 contained acclimated media previously used for biological manganese removal (in Putnam CT).

Figure 2.14 shows the inlet assembly on the top of one of the filters. Influent flow is from the right and backwash outflow is to the left. The air relief valve is on the top, with a ¼" tube and valve to contain any water discharged. The ¼" influent (MPOKA) sample tap is on the front of the assembly, and the sample flowed to the lab sink. There was a second ¼" tube connection on the back side (not seen in the figure) for monitoring the inlet pressure and the differential pressure across the filter.

Figure 2.14: Filter Inlet Assembly

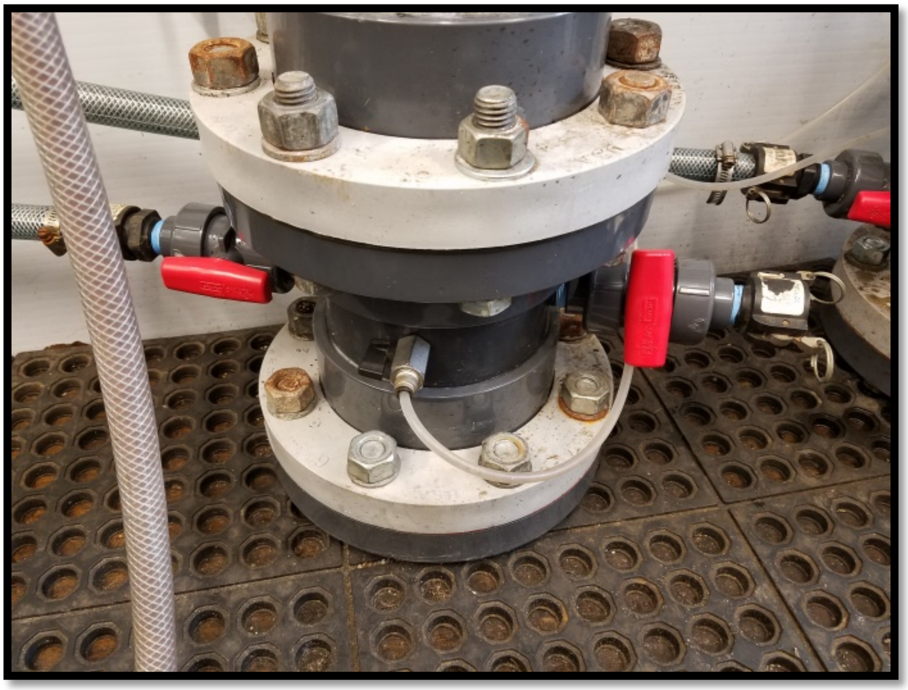


A ¾" hose conveyed final filter effluent from the bottom of the filter, through flow metering and control, and to the filter effluent sample containers located in the lab sink. These filter effluent samples were labelled "MEFF 1" for M1 and "MEFF 2" for M2. Figure 2.15 shows the two biological filters.

Figure 2.15: Filter Vessel M1 and M2

Figure 2.16 shows the filter outlet assembly for one of the two filters. The media retention screen was located in the flange connection between the outlet assembly and the filter vessel. There was no media in the outlet assembly. The connection on the left side of the outlet assembly is the effluent hose, and the connection on the right side is for backwash supply. The backwash supply hose was attached by a quick-connect fitting only when backwashing was performed. The ¼" tube connection on the front of the assembly was the compressed air supply for backwashing with air scour. There was a second ¼" tube connection on the back side (not seen in the figure) for monitoring the outlet pressure and the differential pressure across the filter.

Figure 2.16: Filter Outlet Assembly



Taps were installed in a tee immediately upstream and downstream of each filter and were connected to 0-100 psi pressure gauges for manual measurement of filter headloss, and to a pressure transmitter for online monitoring of differential pressure.

The flow rate through each filter was monitored and controlled on the effluent side of the filter. Flow rate was measured using both a rotameter scaled from 0-10 gpm, and an ultrasonic flow meter scaled from 0 to 3 gpm. The ultrasonic flow meter was used to provide continuous monitoring of the flowrate and recording the flow on the data logger when the pilot was not staffed. The accuracy of both flow meters was verified by measuring the actual flow with a calibrated graduated cylinder and stopwatch, at the point where the filter effluent discharged to the lab sink.

For each filter, the flow rate was controlled by a 3/8-inch diameter modulating control valve and PLC controlled PID loop. The PID loop controlled the modulating valve to maintain constant flow per the Signet flow meter. Figure 2.17 shows the pressure gauges, modulating flow control valves, and flow meters (flow is right to left).

Figure 2.17: Flow Controls for Filters

Effluent from the filters was discharged to the sample sink. Filter effluent and the sample sink drained to waste at the exterior of the trailer.

2.1.3.4 Instrumentation

Tubing installed from eight sample taps throughout the process were piped to a sample sink to provide continuously running samples for online and grab analyses. Samples were collected from the following locations during the pilot study:

- *Pilot Influent (RAW)*: Raw water prior to any pretreatment. The sample was obtained before the addition of aeration or chemical injection.
- *Filter Influent - Post-Aeration, Post-KOH Addition (MPOKA)*: Pretreated water into the filters, downstream of aeration and caustic addition. Both filters had a common influent source which was labelled MPOKA. MPOKA was sampled from a composite of both sample taps at the top of each of the filter columns.
- *Filter Effluents (MEFF1 and MEFF2)*: Effluent from the filters, sampled immediately downstream of the online flow meter and rotameter on the effluent side of the filters.

The pH meters were HACH pHd differential pH (HACH #DRC1R5N) sensors and an SC200 controller. Online sensors for DO were HACH LDO Probes with HACH SC200 controllers.

Online sensors were placed into 1,000 mL sample containers in the sample sink. Each sample container was continuously filled by the appropriate sample line, and sensors were placed into the cups for continuous monitoring. The sample containers were continuously overflowing with sample, and the flow rate was controlled to limit the surface agitation to prevent air entrainment at the sample containers.

All online instrumentation was connected to a digital recorder for data logging capability. Online measurements included:

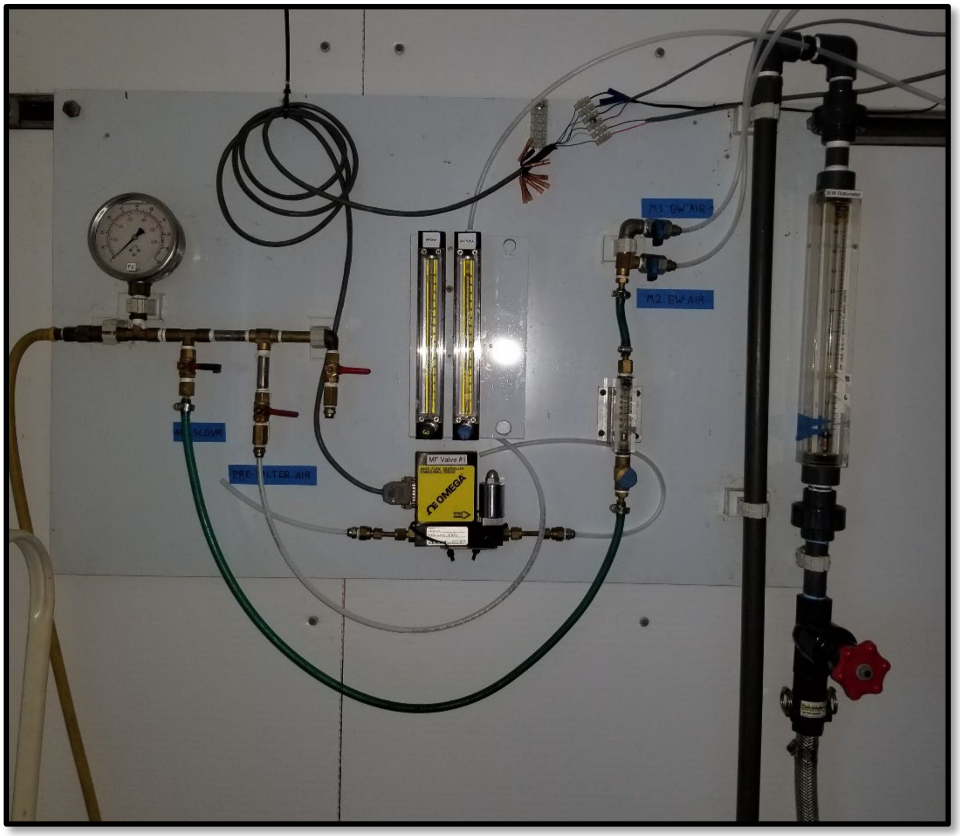
1. Raw Influent pH
2. Raw Influent DO
3. MPOKA pH
4. M1POKA DO
5. MEFF1 flow rate
6. MEFF1 differential pressure
7. MEFF1 pH
8. MEFF1 DO
9. MEFF2 flow rate
10. MEFF2 differential pressure
11. MEFF2 pH
12. MEFF2 DO

2.1.3.5 Backwash Water Feed Tank, Pump, and connections

A 1/5 HP sump pump was used to pump water into the filters for backwashing. The backwash supply water was filter effluent collected in a 30 gallon drum. Four valves were installed on each filter to allow air and water to enter the bottom of the filter and exit the top of the filter. Two of the valves that were designated for forward flow were manually closed for a backwash and the other two valves were then manually opened. All backwash water was discharged to a 15 gallon plastic tank.

Flow rates for the air scour and backwash rinse were controlled by a series of rotameters. Figure 2.18 shows the backwash control panel. The rotameter and globe valve in the center were used to control the flow rate from the backwash supply sump pump to the filter. The air connection for the air compressor can be seen on the far left. The small rotameters and needle valves were for controlling air flow rates during air scour. The compressed air and backwash supply water were injected into the outlet assembly on the bottom of each filter. Filters were backwashed one-at-a-time, not simultaneously.

Figure 2.18: Backwash Rotameters for Air Scour and Water Rinse



2.1.4 Field Laboratory and Analytical Testing Equipment

Both pilot systems are equipped with a field laboratory built into the pilot container to provide an area to complete the field analyses. Figure 2.19 shows the field laboratory in the Greensand pilot trailer while Figure 2.20 shows the field laboratory in the biological pilot container. Glassware, reagents, and analytical equipment necessary to complete the analyses described in Section 2.3 were included in the field laboratory.

Figure 2.19: Greensand Pilot Trailer Field Laboratory

Figure 2.20: Biological Pilot Container Field Laboratory

The following sample locations were used during the pilot study:

Common Pilot Samples

- RAW – Raw water sample from the Oakdale Well collected from pilot influent tap.

Greensand Pilot Samples

- POX – Pretreated influent to the Greensand filters collected from filter influent tap.
- FILTER A – Filter Effluent from Filter A collected at the point of discharge to the sample sink.
- FILTER B – Filter Effluent from Filter B collected at the point of discharge to the sample sink.
- FILTER C – Filter Effluent from Filter C collected at the point of discharge to the sample sink.
- FILTER D – Filter Effluent from Filter D collected at the point of discharge to the sample sink.
- CBW A – Combined Backwash Filter A collected from homogenized backwash.
- CBW B – Combined Backwash Filter B collected from homogenized backwash.
- CBW C – Combined Backwash Filter C collected from homogenized backwash.
- CBW D – Combined Backwash Filter D collected from homogenized backwash.
- SSN A – Settled Supernatant Filter A collected from top of settled CBW A.
- SSN B – Settled Supernatant Filter B collected from top of settled CBW B.
- SSN C – Settled Supernatant Filter C collected from top of settled CBW C.
- SSN D – Settled Supernatant Filter D collected from top of settled CBW D.

Biological Pilot Sample Locations

- MPOKA - Pretreated influent Post-Aeration, Post-KOH addition to Filter M1 and M2 collected from a composite of both filter influent sample taps.
- MEFF1 – Filter M1 Effluent sampled at the point of discharge to the sample sink.
- MEFF2 – Filter M2 Effluent sampled at the point of discharge to the sample sink.
- CBW M1 – Combined Backwash Filter M1 collected from homogenized backwash.
- CBW M2 – Combined Backwash Filter M2 collected from homogenized backwash.
- SSN M1 – Settled Supernatant Filter B collected from top of settled CBW M1.
- SSN M2 – Settled Supernatant Filter D collected from top of settled CBW M2.

2.2 PRETREATMENT

Liquid pretreatment chemicals were diluted with filtered water at measured volumetric ratios to produce feed stocks with the desired concentrations. The objective was to maintain chemical feed rates within the mid-range of the feed pumps to allow for dose adjustments as required.

Sodium hypochlorite (NaOCl) was used for oxidation of dissolved iron and manganese for all Greensand Trials. NaOCl was injected into the common raw feed for all four filters. Potassium hydroxide (KOH) was used for pH control of all Greensand and Biological Trials. KOH was dosed to achieve the target pH of each filter. The chemical feed pumps and day tank for the Biological Pilot are shown in Figure 2.21.

The liquid chemicals were added to graduated day tanks, which allowed measurement of daily drawdown rates. The drawdown rates were used to calculate chemical feed rates and doses. Dilutions were as follows:

- KOH was used at a dilution of 33% (1/3). The diluted KOH was placed in a 6" diameter day tank with a volume of 17 L, with graduations at 0.1 L (100 mL) intervals for the Greensand pilot. A 55L day tank with 5L increments (Figure 2.14) was utilized for the Biological pilot.
- NaOCl was used at a dilution of 20% (1/5) and 33% (1/3). The diluted NaOCl was placed in a 6" diameter day tank with a volume of 17 L, with graduations at 0.1 L (100 mL) intervals.

Figure 2.21: Pretreatment Chemicals in the Biological Pilot (Left) and the Greensand Pilot (Right)

2.2.1 Dose Calculation for NaOCl

NaOCl doses were calculated based on the stock concentration of the product, the dilution of the stock product with make-up water, the chemical feed rate, and the flow rate of the process water. The NaOCl dose based on volume was determined using the following formula:

$$Cl_2\ Dose\ (\text{ppm}) = \left[\frac{(R)(D)(10^6\ ppm)}{(Q)(3{,}785\ mL/gal)(60\ min/hr)}\right]$$

Where: *R* = chemical feed rate (mL/hour) per day tank drawdown measurements
Q = process water flow rate (gpm)
D = dilution factor of chemical in day dank (dimensionless ratio)

The concentration of free available chlorine in sodium hypochlorite stock solution was not determined during the pilot study. Typical store-bough sodium hypochlorite stock solution is assumed to have an available chlorine concentration of 6%. For determining the mass based NaOCl dose, the sock solution is assumed to have a free chlorine concentration of 6% by weight and a specific gravity of 1.2. The NaOCl dose based on mass was determined using the following formula:

$$Cl_2\ Dose\ (mg/L) = \left[\frac{(R)(D)(1.20)(6\%)(10^6\ mg/L)}{(Q)(3{,}785\ mL/gal)(60\ min/hr)}\right]$$

Where: *R* = chemical feed rate (mL/hour) per day tank drawdown measurements
Q = process water flow rate (gpm)
1.20 = specific gravity of the product (dimensionless)
6% = weight percentage of the product (% NaOCl)
D = dilution factor of chemical in day dank (dimensionless ratio)

2.2.2 Dose Calculation for KOH

KOH doses were calculated based on the specific gravity and stock concentration of the product, the dilution of the stock product with make-up water, the chemical feed rate, and the flow rate of the process water. The doses were calculated in terms of mg/L as KOH. The product had a weight percentage of 45%, a specific gravity of 1.45, and a normality of 11.7 N. Doses were calculated as:

$$KOH\ Dose\ (mg/L) = \left[\frac{(R)(D)(1.45)(45\%)(10^6\ mg/L)}{(Q)(3{,}785\ mL/gal)(60\ min/hr)}\right]$$

Where: *R* = chemical feed rate (mL/hour) per day tank drawdown measurements
Q = process water flow rate (gpm)
1.45 = specific gravity of the product (dimensionless)
45% = weight percentage of the product (% KOH)
D = dilution factor of chemical in day dank (dimensionless ratio)

2.3 FIELD ANALYTICAL METHODS

2.3.1 Iron - FerroVer

Iron samples for raw water, pilot influent and intermediate filtrations steps were analyzed in accordance with Hach (Loveland CO) FerroVer® method #8008. Samples with iron concentrations above 3.3 mg/L were diluted with distilled water by a ratio appropriate to bring them into a measureable range. Samples were distributed to 25 ml sample vials. FerroVer iron reagent was added to each sample vial and mixed, and 3 minutes were allowed for reaction. The samples were read using a Hach DR 5000, or DR 890 colorimeter. The colorimeter was zeroed with each set of readings using a blank from the appropriate sample site. The estimated detection limit for the method was 0.04 mg/L.

2.3.2 Manganese – PAN Method (Field Method)

Manganese samples were analyzed using the PAN (1-(2 Pyridylazo)-2 Napthol) method in accordance with Hach method #8149. 10 mL samples were measured into 25 ml sample vials. Ascorbic acid, alkaline cyanide and 0.1% PAN indicator solution were added using autoburettes set to dispense 0.5 mLs of ascorbic acid, 0.4 mLs of alkaline cyanide, and 0.4 mLs of PAN reagent. The vials were mixed and 2 minutes were allowed for reaction. The samples were read using a Hach DR 5000 or DR 890 colorimeter. The colorimeter was zeroed with each set of readings with a blank of DI water, prepared identically to the samples according to the PAN method. A new blank was prepared with each set of manganese samples that were analyzed. The results were displayed in mg/L of total manganese.

2.3.3 Manganese - Graphite Furnace Analysis

Manganese samples were collected during the pilot study to be analyzed using Blueleaf's Perkin Elmer 900Z graphite furnace. The analyses were completed in accordance with EPA Method 200.9 using a wavelength of 279.5, a sample volume of 20 µL and a calibration range of 0 to 50 µg/L.

The method detection limit for the graphite furnace method was calculated in accordance to Method 200.9 by measuring 7 replicate analyses of a single biological filter effluent sample collected during the study. Results are shown in Table 2.XX.

Table 2.02: Estimation of Method Detection Limit for GF Method

	Manganese, Total (ug/L)
Replicate 1	35.5
Replicate 2	33.9
Replicate 3	34.1
Replicate 4	34.2
Replicate 5	35.9
Replicate 6	34.0
Replicate 7	34.0
Standard Deviation	0.81
t-statistic for 6 degrees of freedom, α=0.01	3.14
MDL (ug/L)	**2.55**

The estimated detection limit for the method was 0.00255 mg/L.

2.3.4 Carbon Dioxide

Carbon dioxide was determined in accordance with Standard Method 4500-CO_2 and an Orion 3-star pH meter. A titration was performed on 100 mL samples using 0.02 N NaOH while pH was continously monitored. The titration was complete when the pH reached approximately 8.3. The volume of titrant added was then used to calculate the concentration of carbon dioxide using the following formula:

$$\frac{mg\ CO_2}{L} = \frac{Volume\ of\ Titrant\ (mL)\ x\ 0.02\ N\ NaOH\ x\ 44{,}000}{100\ mL}$$

2.3.5 pH Measurements

Manual pH measurements were made in accordance with Standard Methods 4500-H+B using an Orion glass pH Triode with temperature compensation, and an Orion 3-Star pH meter. A two-point calibration was performed using standard buffer solutions of pH 4.00 SU and pH 7.00 SU, or pH 7.00 SU and pH 10.00 SU.

Online pH was monitored continuously by placing the probe in a sample container in the sample sink; the sample container was continuously filling with fresh sample and overflowing at a constant level.

2.3.6 Dissolved Oxygen

DO measurements were made using an HACH LDO® Process Dissolved Oxygen Probe with a Hach SC200 controller. A calibration was performed by sampling the oxygen in air (typically 20.9%). Calibration was performed periodically during the pilot study. DO was monitored continuously by placing the probe in a sample container in the sample sink; the sample container was continuously filling with fresh sample, and overflowing at a constant level.

2.4 LABORATORY METHODS

Alpha Analytical (Westborough MA) was utilized as the certified laboratory for off-site analyses. Samples were collected by Blueleaf personnel by filling laboratory-prepared bottles, which were delivered to the lab on the day of sampling.

2.4.1 SDS Setup and Sampling Procedure

Blueleaf personnel collected two liters of sample in one-liter amber bottles. The samples were submitted to Alpha under chain of custody. The two samples were collected from Filters A and C and incubated at a target chlorine residual of 1.0 mg/L for 167 hours at 15°C. Prior to incubation, Alpha adjusted the Cl2 residual to the target chlorine residual. The pH remained at the ambient pH of the sample during incubation. At the end of the incubation period TTHM and HAA5 samples were collected from the incubated sample volume.

Table 2.02 provides an example of the SDS setup and sampling procedure utilized during the greensand pilot.

Table 2.02: SDS Setup and Sampling Procedure

Filter A	**Filter C**
2 Liters Unpreserved Sample Collected by Blueleaf and Submitted to Alpha Cl2 Near 0.81 mg/l and 6.8 pH	2 Liters Unpreserved Sample Collected by Blueleaf and Submitted to Alpha Cl2 Near 0.91 mg/l and 6.8 pH
Alpha Splits Sample for Cl2 Adjustment	Alpha Splits Sample for Cl2 Adjustment
Adjust Cl2 to 1.0	Adjust Cl2 to 1.0
Incubate for 167 hours at 20 C and ambient pH	
Collect TTHM Sample	Collect TTHM Sample
Collect HAA Sample	Collect HAA Sample

2.5 STATISTICAL METHODS

2.5.1 Paired t-test

The paired t-test procedure is used to analyze the differences between paired observations. The procedures are used to determine if the mean difference for the population is likely to be different from zero. The paired t-procedure is used to compare two opposing hypotheses:

H_o (the null hypothesis): That the mean of the differences in the population is equal to zero
- or -
H_1 (the alternative hypothesis): That the mean of the differences in the population is not equal to zero.

The paired t test results are normally displayed as a confidence interval, which is a range of likely values for the difference between the two sample sets. Confidence intervals that contain zero normally indicate that the null hypothesis has not been disproven, i.e. that there was not a significant difference in paired values.

The t-test results also provide two statistics to test of the mean difference: a t-value and a p-value. The t-value is not very informative by itself, but it is used to determine the p-value. The p-value indicates how likely it is that H_o is true. High p-values suggest that there is no difference between paired values, while low p-values suggest that there is a statistically significant difference between paired values.

2.5.2 Analysis Of Variance (ANOVA)

When appropriate, Minitab software was used to perform an Analysis Of Variance (ANOVA) to compare the effects of two or more factors upon a specific response. For example, an ANOVA might be used to compare effluent iron concentrations (the response) at different surface loading rates (the factor). The following explanation was adapted from the software documentation.

An ANOVA tests the hypothesis that the means of two or more populations are equal. The procedure uses variances to determine whether the means are different, by comparing the variance between group means versus the variance within groups. In this way the ANOVA determines whether the different groups are all part of one larger population, or can be statistically distinguished as separate populations with different characteristics. An ANOVA requires data from normally distributed populations with roughly equal variances between factor levels.

An example of the output from an ANOVA is shown below. The ANOVA tested a data set to determine whether the Factor had a statistically significant affect upon the Response. The Factor had two levels. Level 1 included 22 data points, and Level 2 included 10 data points.

Table 2.03: Example of One-Way ANOVA Response versus Factor with Two Levels

```
Source  DF        SS        MS       F      P
Trial    1  0.071783  0.071783  234.91  0.000
Error   30  0.009167  0.000306
Total   31  0.080950

S = 0.01748   R-Sq = 88.68%   R-Sq(adj) = 88.30%

                             Individual 90% CIs For Mean Based on
                             Pooled StDev
Level   N     Mean    StDev  ------+---------+---------+---------+---
1      22  0.12318  0.02009                                     (-*-)
2      10  0.02100  0.00876  (--*--)
                             ------+---------+---------+---------+---
                                 0.030     0.060     0.090     0.120

Pooled StDev = 0.01748
```

The most important aspects of the ANOVA are described below.

2.5.2.1 Null Hypothesis

The ANOVA determines whether the null hypothesis should be accepted or rejected. For all ANOVAs herein, the null hypothesis and its alternative hypothesis were as follows:

- The Null Hypothesis (Ho) states that all population means are equal.
- The Alternative Hypothesis (H_1) states that at least one population mean is different.

If the null hypothesis is rejected, it indicates that the population means were different, and it follows that the Factor had a statistically significant affect upon the Response. If the null hypothesis is accepted, then it follows that the factor did not have a significant effect upon the response.

2.5.2.2 Probability Value

The probability value (p-value) reports the probability that the null hypothesis can be accepted. The p-value is tested against an alpha value (α), often called the level of significance. Alpha was chosen to be 0.100 (10%) for all ANOVAs herein. If the p-value is greater than alpha ($p>0.01$) then there was greater than 10% probability that the population means were the same (or alternatively less than 90% probability that the means were different) and the null hypothesis cannot be rejected. If the p-value is less than alpha ($p<\alpha$), then the null hypothesis can be rejected, and it can be concluded that at least one mean is different than the others to a certainty of >90%.

In the example above, the p-value was 0.000, which indicates <0.1% probability that the null hypothesis is correct, or conversely >99.9% probability that the null hypothesis can confidently be rejected.

2.5.2.3 Confidence Intervals

A confidence level of 90% was chosen for all ANOVAs herein. The ANOVA output includes a plot of the 90% confidence intervals. For each data set (Levels 1 and 2) the asterisk (*) indicates the mean value, and 9 out of 10 data fall within the 90% confidence interval indicated between the parentheses.

In the example above, there is no overlap of the confidence intervals. The data sets corresponding to Level 1 and Level 2 are clearly different. This indicates that the Factor at Levels 1 and 2 had a significant effect upon the response.

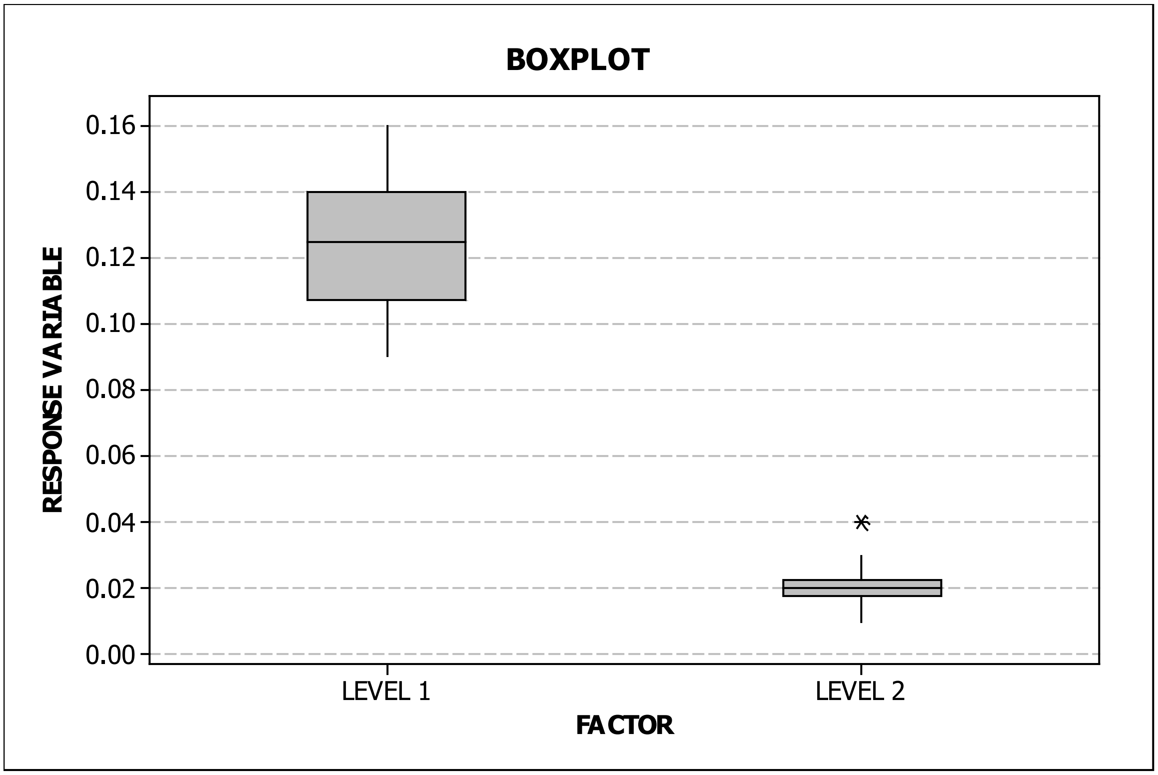
2.5.2.4 Mean and Standard Deviation

The ANOVA reports the mean, standard deviation, and sample count (N) for each data set. In the example above, Level 1 had a mean of 0.123 and a standard deviation of 0.020, while Level 2 had a mean of 0.021 and a standard deviation of 0.009. Level 2 had a lower mean and a smaller standard deviation than Level 1.

2.5.3 Boxplots

Boxplots are used to provide a graphical summary of the distribution of a sample. Minitab can include a boxplot as part of the output of an ANOVA. A boxplot shows the shape, central tendency, and variability of the sample. Figure 2.22 was from the same data used for the ANOVA example, above. One factor was tested at two levels. The boxplot shown here suggests that Level 2 resulted in a lower median response than Level 1, and also had a narrower range of variation than Level 1.

Figure 2.22: Boxplot Example



The important aspects of the boxplot are described below:

1. The upper whisker extends to the maximum data point within 1.5 box heights from the top of the box.
2. The interquartile range box contains the middle 50% of the data.
    a. The top line indicates the third quartile (Q3). 75% of the data are less than or equal to this value.
    b. The middle line indicates the median (Q2). 50% of the data are less than or equal to this value, and 50% of the data are greater than this value.
    c. The bottom line indicates the first quartile (Q1). 25% of the data are less than or equal to this value.
3. The lower whisker extends to the minimum data point within 1.5 box heights from the bottom of the box.
4. An asterisk (*) denotes an outlier, an observation that is beyond the upper or lower

2.6 EXPERIMENTAL PLAN AND SCHEDULE

Table 2.04 shows the trials conducted during the Greensand Filtration portion of the study. A total of 4 experimental trials were completed on four pilot filters (Filters A – D) for a total of 16 individual filter runs. Trials 1 – 3 operated the filters with the same pretreatment conditions (chlorine dose and pH) at different filter surface loading rates. Trial 4 tested supernatant recycle. The trial began without supernatant addition to confirm initial treatment, then settled supernatant was added to raw water at a rate of 10% of the total pilot influent. The recycle period lasted 4 hours and the supernatant recycle addition concluded once supernatant volume was low. The filter trial then continued to its conclusion without supernatant addition.

Table 2.05 lists the trials conducted during the Biological Filtration portion of the study. This part of the study has been organized into four "Phases" which include 9 experimental trials using M1 and 8 experimental trials using M2 for a total of 17 individual filter runs. The Phases of the biological pilot study are the following:

- Phase 1: Acclimation at Low Rate – Both filters operated at the same low loading rate (5 gpm/sf) for one continuous filter run that lasted approximately 673 and 863 hours for M1 and M2, respectively. Phase 1 lasted until both filters successfully reduced manganese below the SMCL (SMCL Mn < 0.050 mg/L) with relative consistency while operating at the low loading rate. Note that this acclimation phase was required even though both pilot filters contained media that had been acclimated to remove manganese at a site containing high concentration of manganese in Putnam CT.
- Phase 2: Filter Performance at Low Rate – This phase was to evaluate the hydraulic performance and effluent water quality of biological filtration when operating at a low loading rate (5 gpm/sf). This phase included one continuous filter run that was considered representative of an acclimated biofilter operating at 5 gpm/sf.
- Phase 3: Acclimation at High Rate – During this phase, the loading rates of both filters were increased, M1 to 10 gpm/sf and M2 to 15 gpm/sf, which caused an increase in effluent manganese concentrations. It was hypothesized that the increase in loading rate disrupted the biomass and a period of re-acclimation was required. Both filters were backwashed four times during this phase and lasted approximately 747 and 609 hours for M1 and M2, respectively. Phase 3 lasted until both filters successfully reduced manganese below the SMCL with relative consistency while operating at the high loading rate.
- Phase 4: Filter Performance at High Rate – This phase was to evaluate the hydraulic performance and effluent water quality of biological filtration when operating at high loading rates (M1 at 10 gpm/sf and M2 at 15 gpm/sf). During this phase, M1 completed 6 filter trials and M2 completed 5 filters trials, for a total of 11 individual filter runs.

Table 2.04: Experimental Plan and Schedule for Greensand Pilot

Trial	Start	End	Duration (hrs)	Filter	Target FSLR (gpm/sf)	Average FSLR (gpm/sf)	Termination Criteria
1	4/30/19 16:21	5/1/19 8:45	16.4	A	5	5.05	Time Constraint
				B	5	5.40	Time Constraint
				C	5	5.76	Time Constraint
				D	5	5.31	Time Constraint
2	5/1/19 9:39	5/3/19 9:06	47.4	A	4	3.88	Time Constraint
				B	4	3.92	Time Constraint
				C	6	5.69	Time Constraint
				D	6	5.63	Time Constraint
3	5/3/19 9:36	5/6/19 7:57	70.3	A	7	6.76	Time Constraint
				B	7	6.69	Time Constraint
				C	5	5.31	Time Constraint
				D	5	5.19	Time Constraint
4[1]	5/6/19 8:39	5/10/19 12:24	99.8	A	5	5.05	Differential Pressure > 10 psi
				B	5	5.27	Differential Pressure > 10 psi
				C	7	6.96	Differential Pressure > 10 psi
				D	7	6.91	Differential Pressure > 10 psi

[1]Highlighted trials indicate a period of supernatant recycle took place.

Table 2.05: Experimental Plan and Schedule for Biological Pilot

Phase	Trial	Filter	Start	End	Duration (hours)	Target Filter Influent		Target FSLR (gpm/sf)	Average FSLR (gpm/sf)	Termination Criteria
						pH (s.u.)	DO (ppm)			
1	1	M1	3/28/19 14:24	4/25/19 15:03	672.6	8.50	7.70	5.00	5.01	Differential Pressure > 10 psi
		M2	3/20/19 15:36	4/25/19 15:03	863.5	8.50	7.70	5.00	4.94	Differential Pressure > 10 psi
2	1	M1	4/25/19 15:30	5/10/19 6:21	350.9	8.50	7.50	5.00	4.94	Differential Pressure > 10 psi
		M2	4/25/19 15:30	5/10/19 6:21	350.9	8.50	7.50	5.00	4.94	Differential Pressure > 10 psi
3	1	M1	5/10/19 7:27	6/10/19 10:03	746.6	8.30	7.50	10.00	9.93	Differential Pressure > 10 psi
		M2	5/10/19 7:27	6/10/19 10:12	746.7	8.30	7.50	15.00	14.3	Differential Pressure > 10 psi
4	1	M1	6/10/19 10:15	6/17/19 16:42	174.4	8.30	> 9.00	10.00	9.93	Differential Pressure > 10 psi
		M2	6/10/19 10:24	6/17/19 16:42	174.3	8.30	> 9.00	15.00	14.0	Differential Pressure > 10 psi
	2	M1	6/17/19 17:15	6/23/19 10:42	137.4	8.30	> 9.00	10.00	9.88	Differential Pressure > 10 psi
		M2	6/17/19 17:06	6/23/19 10:27	137.3	8.30	> 9.00	15.00	13.5	Differential Pressure > 10 psi
	3	M1	6/23/19 11:06	6/28/19 13:03	122.0	8.30	> 9.00	10.00	10.0	Differential Pressure > 10 psi
		M2	6/23/19 11:15	7/6/19 8:36	309.4	8.30	> 9.00	15.00	13.5	Differential Pressure > 10 psi
	4	M1	6/28/19 13:15	7/6/19 8:24	187.1	8.30	> 9.00	10.00	10.0	Differential Pressure > 10 psi
		M2	7/6/19 8:45	7/9/19 12:57	76.2	8.30	> 9.00	15.00	12.3	Differential Pressure > 10 psi
	5	M1	7/6/19 8:39	7/9/19 13:09	76.5	8.30	> 9.00	10.00	10.0	Differential Pressure > 10 psi
		M2	7/9/19 13:12	7/14/19 22:21	129.2	8.30	> 9.00	15.00	12.6	Time Constraint
	6	M1	7/9/19 13:36	7/14/19 22:21	128.7	8.30	> 9.00	10.00	9.89	Differential Pressure > 10 psi

3 RESULTS

Section 3 – Results, presents the data and results collected during the pilot testing effort.

3.1 RAW WATER QUALITY

3.1.1 Raw Water Quality

Table 3.01 summarizes the results from field and lab analyses as well as historic raw water data from the Oakdale Well. Historical represents raw water quality data from the Oakdale Well between April 2011 and February 2018. Table 3.02 summaries the results of additional lab analyses conducted on raw water from the Oakdale Well.

Table 3.01: Raw Water Quality from Field, Laboratory, and Historical Analyses

Parameter	Units	Field Analysis	Laboratory Analysis	Historical Data
Total Fe	mg/L	**0.05** (0.00-0.49) [43]	**BDL** (<0.050-0.107) [3]	**0.00** (0.00-1.30) [7]
Dissolved Fe	mg/L	**0.04** (0.00-0.11) [36]	**BDL** (<0.050) [3]	-
Total Mn	mg/L	**0.76** (0.59-1.00) [59]	**0.900** (0.846-0.923) [3]	**0.63** (0.15-2.1) [92]
Dissolved Mn	mg/L	**0.75** (0.54-0.97) [50]	**0.863** (0.801-0.933) [3]	-
pH (Handheld)	s.u.	**6.50** (5.65-6.98) [39]	**6.30** (6.20-6.30) [3]	-
pH (Online)	s.u.	**6.13** (4.35-7.46) [56995]	-	-
Temperature	°C	**10.2** (9.1-11.9) [37]	-	-
Dissolved Oxygen (Online)	mg/L	**7.15** (4.95-10.63) [56935]	-	-

BDL = Below Detection Limit

Table 3.02: Additional Raw Water Quality from Laboratory Analysis – May 8, 2019

Parameter	Units	Laboratory Results	Reporting Limit
Metals			
Aluminum, Total	mg/L	ND	0.100
Antimony, Total	mg/L	ND	0.0040
Arsenic, Total	mg/L	0.0023	0.0010
Barium, Total	mg/L	0.0213	0.0010
Beryllium, Total	mg/L	ND	0.0010
Cadmium, Total	mg/L	ND	0.0002
Calcium, Total	mg/L	21.4	0.100
Chromium, Total	mg/L	ND	0.0010
Copper, Total	mg/L	ND	0.010
Hardness	mg/L	64.4	0.660
Magnesium, Total	mg/L	2.68	0.100
Mercury, Total	mg/L	ND	0.0002
Nickel, Total	mg/L	ND	0.0020
Potassium, Total	mg/L	3.68	2.50
Selenium, Total	mg/L	ND	0.0050
Silver, Total	mg/L	ND	0.007
Sodium, Total	mg/L	48.5	2.00
Thallium, Total	mg/L	ND	0.0010
Zinc, Total	mg/L	ND	0.050
Inorganics & Miscellaneous			
Alkalinity, Total	mg CaCO3/L	25.3	2.00
Carbon Dioxide	mg/L	230	2.0
Chloride	mg/L	104	5.00
Color, Apparent	A.P.C.U.	ND	5.0
Color, True	A.P.C.U.	ND	5.0
Coliform, Total	col/100mL	Negative	-
Cyanide, Total	ND		0.005
Dissolved Solids, Total	mg/L	260	10
Escherichia Coli	col/100mL	Negative	-
Fluoride	mg/L	ND	0.20
Odor @ 60 C	TON	NO ODOR	1
Organic Carbon, Dissolved	mg/L	1.0	1.0
Organic Carbon, Total	mg/L	0.800	0.500
Sulfate	mg/L	10.1	1.00
Surfactants, MBAS	mg/L	ND	0.050
Turbidity	NTU	0.59	0.20
Volatiles			
Chloroform[1]	ug/L	0.63	0.50

[1]Chloroform was the only analysis for volatiles that was detectable. The full laboratory report is presented in Appendix B.

3.2 PRETREATMENT CONDITIONS

3.2.1 Pilot Doses

3.2.1.1 NaOCl Doses

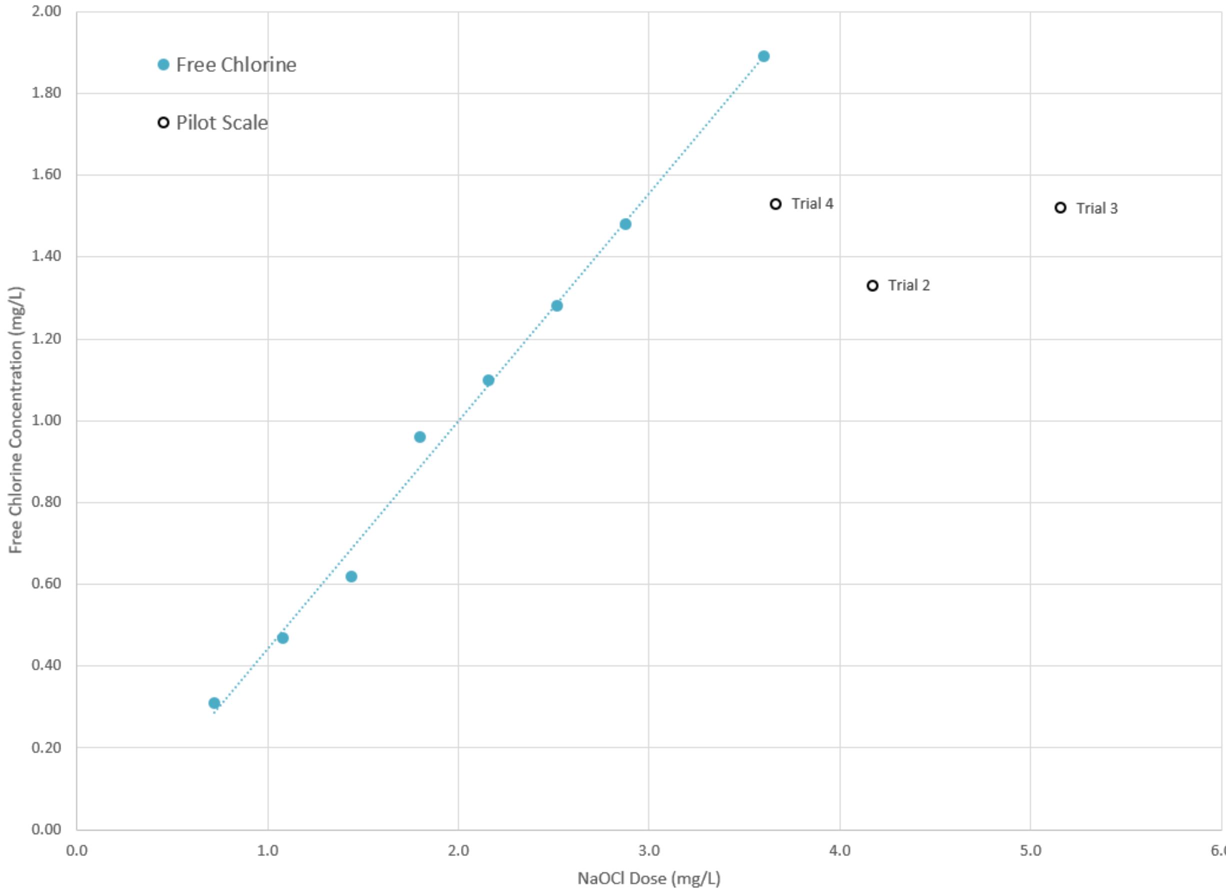
Sodium hypochlorite doses were calculated as described in Section 2.2.1. The doses utilized during the greensand pilot are summarized in Table 3.03.

Table 3.03: Pretreatment Sodium Hypochlorite Doses

Trial No.	Approximate Chlorine Dose (ppm as 6% NaOCl)	Approximate Chlorine Dose (mg/L)
1	81.1	5.8
2	57.9	4.2
3	71.6	5.2
4	50.6	3.7

A bench scale dose response test was conducted to determine the NaOCl dose required to achieve a target free chlorine residual in filter influent to the greensand filters. The test was conducted using nine 100 mL samples of raw water from the Oakdale Well. An increasing amount of NaOCl (assumed stock strength = 6%; Dilution = 1/1000) was added to each sample and was then analyzed for free and total chlorine. Figure 3.01 plots the results of the bench scale testing as well as the doses used during pilot testing.

Figure 3.01: Results from Bench Scale NaOCl Dose Testing using Raw Water from Oakdale Well



3.2.1.2 KOH Doses

A bench scale dose response test was conducted to determine the KOH dose required to adjust raw water pH to the respective target pH for influent to the greensand or giological filters. The test was conducted using 1 L of raw water from the Oakdale Well. KOH (Stock Strength = 45%; Dilution = 1/500) was titrated into the raw water sample while pH was monitored with a handheld pH meter. The dose response curves are plotted in Figure 3.03 and are specific to the adjustment of raw water pH. Doses used in greensand and biological pilot studies are plotted in the figure and summarized in Table 3.04 and 3.05, respectively. KOH doses were calculated using chemical usage data.

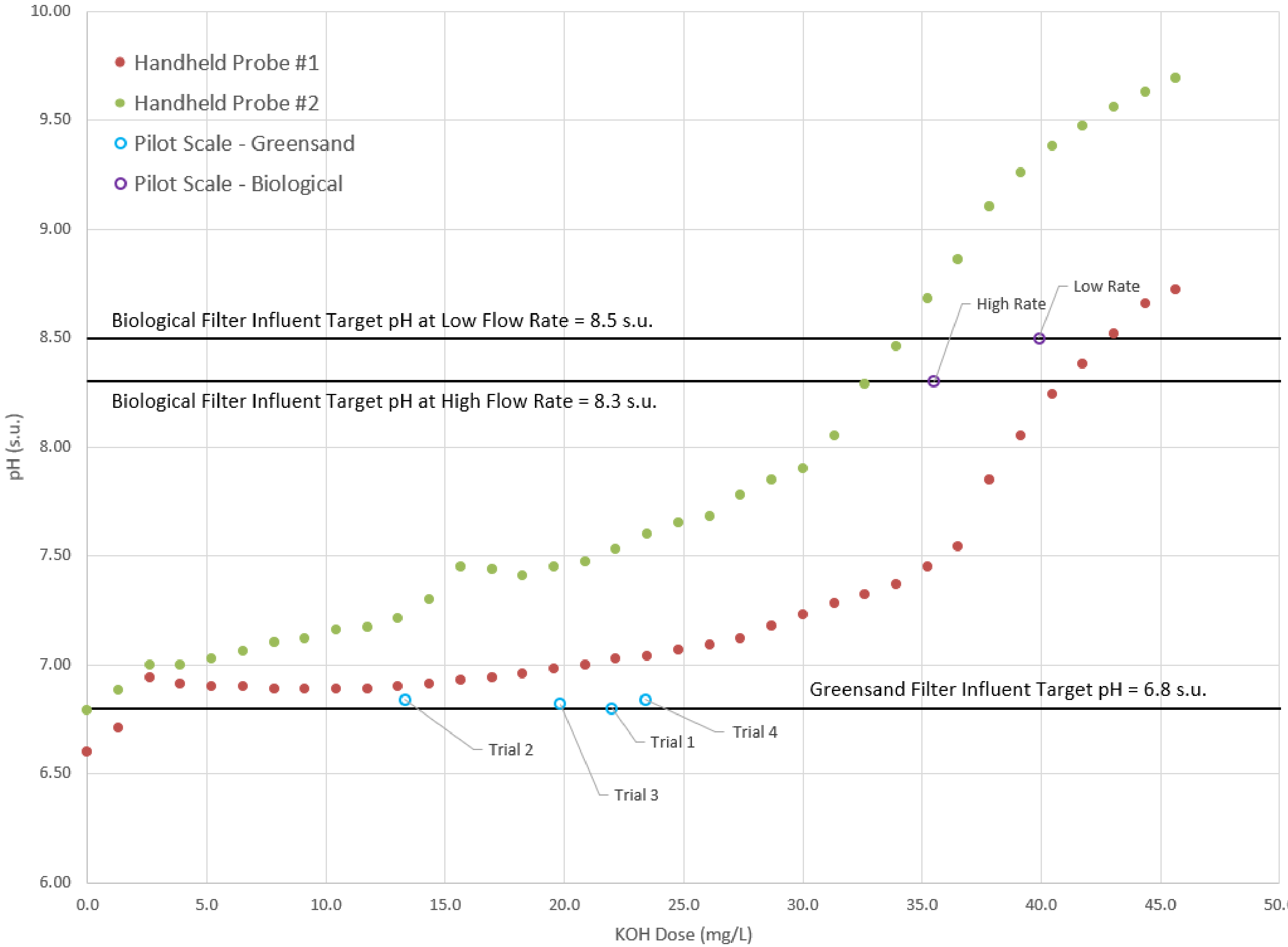
Table 3.04: Pretreatment KOH Doses – Greensand Filtration

Trial No.	Approximate KOH Doses (mg/L)
Target Influent pH = 6.8 s.u.	
1	22.0
2	13.3
3	19.8
4	23.4

Table 3.05: Pretreatment KOH Doses – Biological Filtration

Phase No.	Approximate KOH Doses (mg/L)
Target Influent pH = 8.5 s.u.	
1	39.4
2	39.9
Target Influent pH = 8.3 s.u.	
3	30.7
4	40.3

Figure 3.02: Bench Scale KOH Dose Test with Raw Water from the Oakdale Well



3.2.2 GreesandPlus Pilot – Pretreatment Conditions

Pretreatment during the greensand pilot included pH adjustment with KOH to increase raw pH from approximately 6.8. Sodium hypochlorite was added to oxidize dissolved iron and manganese such that they could be adsorbed and/or removed as precipitated particles. The pretreated water quality for the greensand pilot is summarized by trial in Table 3.06.

Table 3.06: Greensand Pilot - Pretreated Water Quality Data from Field Analyses

Trial	Free Cl (mg/L)	Total Cl (mg/L)	Dissolved Fe (mg/L)	Dissolved Mn (mg/L)	Handheld pH (s.u.)
1	**0.60** (0.38-0.72) [4]	**0.92** [1]	**0.02** [1]	**0.720** [1]	**No Data** [0]
2	**1.33** (0.62-2.20) [17]	**2.16** (1.25-2.20) [7]	**0.01** (0.00-0.06) [7]	**0.686** (0.673-0.707) [7]	**6.84** (6.41-7.15) [14]
3	**1.52** (1.09-1.76) [4]	**2.19** (2.05-2.20) [3]	**0.02** (0.00-0.06) [3]	**0.684** (0.682-0.690) [3]	**6.82** (6.67-7.00) [6]
4	**1.53** (1.10-2.14) [12]	**2.11** (1.98-2.20) [10]	**0.02** (0.00-0.04) [10]	**0.743** (0.697-0.919) [10]	**6.84** (6.45-7.25) [21]

3.2.3 Biological Pilot – Pretreatment Conditions

Tables 3.07 and 3.08 summarize the pretreated water quality data for the biological pilot by Trial. Pretreatment included control and modification of two factors: DO and pH. Pretreatment was intended to produce an environment conducive to the biological treatment of manganese in Filters M1 and M2. Unlike the greensand pilot where treatment relies on the effective oxidation of iron and manganese biological filtration treats iron and manganese in their dissolved state.

Actual filter trial operating conditions and durations are detailed in Section 3.3.2 Biological Filter Performance. Data are presented in one of two formats:

(i) median (minimum – maximum) [number of samples]

(ii) average ± standard deviation [number of samples]

The data included in the tables are as follows:

- Trial Number - Filter trial numbers are unique to each filter. Filters have a differing number of trials based on runtimes and backwash frequency. Filter trials are defined in Section 2.6.2 (Experimental Plan and Schedule), including the date, time and duration of each trial.
- Influent to Filter Continuous Online pH - Online pH @ 3-minute intervals.
- Influent to Filter DO - Dissolved oxygen from online instrumentation @ at 3-minute intervals.
- Iron, Dissolved - Dissolved iron concentration by field analyses.
- Manganese, Dissolved - Dissolved manganese by field analyses.

Pretreatment conditions and effectiveness are evaluated in Section 4.4.1.

Table 3.07: Biological Pilot - Pretreated Water Quality Data by Trial for Filter M1

Trial	Influent Filter pH (s.u.)	Influent Filter DO (ppm)	Iron, Dissolved (mg/L)	Manganese, Dissolved (mg/L)
1-1	**8.50** ± 0.06 [13454]	**7.73** ± 1.37 [13454]	**0.07** (0.05-0.08) [4]	**0.737** (0.625-0.766) [11]
2-1	**8.50** ± 0.18 [6863]	**7.55** ± 0.33 [6955]	**0.02** (0.01-0.08) [7]	**0.682** (0.650-0.966) [7]
3-1	**8.30** ± 0.09 [14933]	**7.52** ± 0.27 [14933]	**0.05** (0.03-0.06) [5]	**0.872** (0.740-1.034) [7]
4-1	**8.29** ± 0.15 [3490]	**11.95** ± 0.97 [3490]	No Data [0]	0.663-0.700 [2]
4-2	**8.28** ± 0.10 [2750]	**11.33** ± 0.30 [2750]	0.00-0.05 [2]	0.656-0.718 [2]
4-3	**8.30** ± 0.12 [2440]	**10.50** ± 0.29 [2440]	**0.05** [1]	**0.552** [1]
4-4	**8.30** ± 0.07 [3744]	**10.20** ± 0.30 [3744]	**0.02** [1]	**0.539** [1]
4-5	**8.30** ± 0.06 [1531]	**9.92** ± 0.33 [1531]	No Data [0]	No Data [0]
4-6	**8.30** ± 0.12 [2576]	**10.12** ± 0.50 [2576]	**0.04** [1]	**0.570** [1]

Table 3.08: Biological Pilot – Pretreated Water Quality Data by Trial for Filter M2

Trial	Influent Filter pH (s.u.)	Influent Filter DO (ppm)	Iron, Dissolved (mg/L)	Manganese, Dissolved (mg/L)
1-1	**8.49** ± 0.35 [17270]	**7.70** ± 1.58 [17270]	**0.07** (0.05-0.08) [4]	**0.737** (0.625-0.766) [11]
2-1	**8.50** ± 0.18 [6863]	**7.55** ± 0.33 [6955]	**0.02** (0.01-0.08) [7]	**0.682** (0.650-0.966) [7]
3-1	**8.30** ± 0.09 [14936]	**7.52** ± 0.28 [14936]	**0.05** (0.03-0.06) [5]	**0.872** (0.740-1.034) [7]
4-1	**8.29** ± 0.15 [3487]	**11.95** ± 0.97 [3487]	No Data [0]	0.663-0.700 [2]
4-2	**8.28** ± 0.08 [2748]	**11.33** ± 0.30 [2748]	0.00-0.05 [2]	0.656-0.718 [2]
4-3	**8.30** ± 0.09 [6188]	**10.31** ± 0.33 [6188]	0.02-0.05 [2]	0.539-0.552 [2]
4-4	**8.30** ± 0.05 [1525]	**9.92** ± 0.33 [1525]	No Data [0]	No Data [0]
4-5	**8.30** ± 0.13 [2584]	**10.12** ± 0.50 [2584]	**0.04** [1]	**0.570** [1]

3.3 FILTER PERFORMANCE

3.3.1 GreensandPlus Filter Performance

3.3.1.1 GreensandPlus Filter Effluent Water Quality

Water quality results from field analyses are shown in Table 3.09. The table summarizes water quality based on the source water, trial number, and filter surface loading rate. For 3 or more data, the data are presented in the format:

median (minimum – maximum) [number of samples]

For two data, the data are presented in the format:

(minimum – maximum) [2]

For one data, the data is presented in the format:

value [1]

A “filter run” refers to operation of a single filter in forward flow filtration mode, from startup to shutdown, followed by backwashing. A total of 16 individual filter runs were completed during the greensand pilot study. Supernatant recycling occurred during Trial 4 for Filter A – D.

The Supernatant recycle trials began without supernatant addition to confirm initial treatment. Settled supernatant from prior backwashes was then injected into the raw water influent at a feed rate of 10% of the total pilot flow rate. The recycle period lasted 3-4 hours and was dependent on the pilot flow rate and the available volume of supernatant. Supernatant recycle addition concluded once supernatant volume was low. The filter trial then continued to its conclusion without supernatant addition.

Laboratory data from two rounds of sampling are reported in Table 3.10 – 3.12.

Table 3.09: Greensand Pilot - Filtered Water Quality from Field Analysis

Trial		Filter	Target FSLR (gpm/sf)	Chlorine, Free (mg/L)	Chlorine, Total (mg/L)	Iron, Total (mg/L)	Manganese, Total – Field Analysis, PAN (mg/L)	Manganese, Total Graphite Furnace (mg/L)	pH (s.u.)	Temperature (°C)
1		A	5	**0.29** [1]	**0.31** [1]	**0.00** [1]	**0.003** [1]	No Data [0]	No Data [0]	No Data [0]
		B	5	**0.28** [1]	**0.51** [1]	**0.00** [1]	**0.001** [1]	No Data [0]	No Data [0]	No Data [0]
		C	5	**0.27** [1]	**0.53** [1]	**0.00** [1]	**0.010** [1]	No Data [0]	No Data [0]	No Data [0]
		D	5	**0.35** [1]	**0.58** [1]	**0.00** [1]	**0.013** [1]	No Data [0]	No Data [0]	No Data [0]
2		A	4	**0.80** (0.41-0.94) [9]	**1.06** (0.72-1.14) [7]	**0.00** (0.00-0.06) [15]	**0.010** (0.000-0.026) [15]	**BDL** (<0.003-0.031) [15]	**6.85** (6.46-7.16) [14]	**10.1** (10.0-10.5) [14]
		B	4	**0.63** (0.37-0.87) [7]	**1.03** (0.71-1.25) [7]	**0.00** (0.00-0.02) [7]	**0.010** (0.000-0.023) [7]	**BDL** (<0.003-0.008) [7]	**6.86** (6.50-7.16) [14]	**10.1** (10.0-10.5) [14]
		C	6	**0.87** (0.41-0.97) [7]	**1.36** (0.78-1.40) [7]	**0.00** (0.00-0.05) [15]	**0.012** (0.000-0.027) [15]	**BDL** (<0.003-0.004) [15]	**6.79** (6.47-7.16) [14]	**10.0** (9.9-10.4) [14]
		D	6	**0.82** (0.50-1.05) [7]	**1.40** (0.75-1.47) [7]	**0.04** (0.00-0.05) [7]	**0.014** (0.002-0.024) [7]	**BDL** (<0.003) [7]	**6.77** (6.51-7.16) [14]	**10.0** (9.9-10.5) [14]
3		A	7	**1.10** (0.69-1.28) [5]	**1.25** (0.92-1.79) [3]	**0.02** (0.00-0.04) [10]	**0.009** (0.007-0.019) [10]	**BDL** (<0.003-0.004) [14]	**6.80** (6.67-7.02) [6]	**10.2** (10.2-10.4) [6]
		B	7	**1.04** (0.65-1.26) [4]	**1.46** (1.32-1.78) [3]	**0.02** (0.00-0.04) [4]	**0.007** (0.003-0.010) [4]	**BDL** (<0.003) [3]	**6.78** (6.20-6.83) [6]	**10.2** (10.2-10.4) [6]
		C	5	**0.98** (0.68-1.36) [5]	**1.35** (1.07-1.77) [3]	**0.02** (0.00-0.05) [11]	**0.010** (0.004-0.021) [11]	**BDL** (<0.003) [16]	**6.82** (6.56-7.01) [6]	**10.2** (10.2-10.4) [6]
		D	5	**1.07** (0.67-1.29) [4]	**1.30** (1.26-1.34) [3]	**0.02** (0.00-0.04) [4]	**0.011** (0.000-0.014) [4]	**BDL** (<0.003-0.005) [3]	**6.91** (6.65-7.01) [6]	**10.4** (10.2-10.4) [6]
4	Pre -Recycle	A	5	**0.81** (0.78-1.24) [7]	**1.29** (1.24-1.37) [6]	**0.01** (0.00-0.09) [17]	**0.012** (0.008-0.030) [17]	**BDL** (<0.003) [14]	**6.87** (6.64-7.15) [12]	**10.6** (10.1-12.4) [12]
		B	5	**0.88** (0.83-0.95) [6]	**1.34** (1.29-1.38) [6]	**0.05** (0.03-0.06) [6]	**0.011** (0.001-0.020) [6]	**BDL** (<0.003-0.004) [6]	**6.90** (6.63-7.10) [12]	**10.7** (10.1-12.1) [12]
		C	7	**1.06** (0.84-1.53) [9]	**1.50** (1.35-1.52) [6]	**0.01** (0.00-0.08) [12]	**0.009** (0.000-0.020) [12]	**BDL** (<0.003-0.004) [9]	**6.86** (6.62-7.14) [12]	**10.6** (10.0-12.1) [12]
		D	7	**1.04** (0.91-1.07) [6]	**1.51** (1.20-1.60) [6]	**0.03** (0.00-0.07) [6]	**0.012** (0.006-0.025) [6]	**BDL** (<0.003) [6]	**6.90** (6.63-7.10) [12]	**10.6** (10.0-12.0) [12]
	During Recycle[1]	A	5	**0.79** [1]	**1.26** [1]	**0.02** (0.00-0.08) [10]	**0.013** (0.005-0.028) [10]	**BDL** (<0.003) [10]	7.18-7.27 [2]	11.5-11.5 [2]
		B	5	**1.02** [1]	**1.33** [1]	0.06-0.08 [2]	0.016-0.019 [2]	**BDL** (<0.003) [2]	7.17-7.28 [2]	11.5-11.5 [2]
		C	7	**0.96** [1]	**1.38** [1]	**0.02** (0.00-0.03) [10]	**0.004** (0.000-0.024) [10]	**BDL** (<0.003) [10]	7.17-7.27 [2]	11.4-11.4 [2]
		D	7	**1.07** [1]	**1.56** [1]	0.04-0.08 [2]	0.019-0.024 [2]	**BDL** (<0.003) [2]	7.17-7.30 [2]	10.4-10.4 [2]
	Post Recycle	A	5	**0.65** (0.29-0.86) [4]	**1.29** (1.21-1.38) [4]	**0.01** (0.00-0.05) [13]	**0.013** (0.000-0.030) [19]	**BDL** (<0.003) [10]	**6.89** (6.51-7.22) [8]	**10.7** (9.9-11.7) [6]
		B	5	**0.80** (0.64-0.87) [4]	**1.43** (1.24-1.51) [4]	**0.01** (0.00-0.07) [5]	**0.018** (0.013-0.064) [5]	**BDL** (<0.003-0.007) [4]	**6.93** (6.55-7.21) [8]	**10.7** (9.9-10.7) [6]
		C	7	**0.86** (0.60-0.90) [4]	**1.40** (1.39-1.48) [4]	**0.01** (0.00-0.03) [13]	**0.011** (0.001-0.057) [19]	**BDL** (<0.003) [10]	**6.82** (6.51-7.19) [8]	**10.6** (9.8-11.5) [6]
		D	7	**0.93** (0.55-0.94) [4]	**1.44** (1.40-1.48) [4]	**0.01** (0.00-0.06) [5]	**0.092** (0.012-0.191) [8]	**0.005** (<0.003-0.033) [4]	**6.85** (6.55-7.21) [8]	**10.6** (9.8-10.7) [6]

BDL = Below Detection Limit

[1]Collected during period of supernatant recycle

Table 3.10: Greensand Pilot - Filtered Water Quality from Laboratory Analysis

		May 8 8:30		May 8[1] 11:00		May 8 14:30		Reporting Limit
Parameter	**Units**	**A**	**C**	**A**	**C**	**A**	**C**	
Total Fe	mg/L	ND	ND	ND	ND	ND	ND	*0.050*
Dissolved Fe	mg/L	ND	ND					*0.050*
Total Mn	mg/L	ND	ND	ND	ND	ND	0.0010	*0.00100*
Dissolved Mn	mg/L	ND	ND					*0.0010*
pH	s.u.	6.6	6.7					*N/A*
Alkalinity	mg/L as $CaCO_3$	40.3	40.1					*2.00*
Carbon Dioxide	mg/L	210	200					*2.0*
Odor @ 60 c	TON	NO ODOR	NO ODOR					*1*
Color, True	A.P.C.U.	ND	ND					*5.0*
Color, Apparent	A.P.C.U	5.0	6.0					*5.0*
Turbidity	NTU	0.37	0.22					*0.20*
Solids, Total Dissolved	mg/L	270	280					*10*
Cyanide, Total	mg/L	ND	ND					*0.005*
Fluoride	mg/L	ND	ND					*0.20*
Total Organic Carbon	mg/L	0.800	0.800					*0.500*
Dissolved Organic Carbon	mg/L	1.0	ND					*1.0*
Surfactants, MBAS	mg/L	ND	ND					*0.050*
Coliform, Total	col/100 mL	Neg	Neg					*N/A*
E. Coli	col/100 mL	Neg	Neg					*N/A*
Chloride	mg/L	106	106					*5.00*
Sulfate	mg/L	10.0	10.0					*1.00*
Chloroform	ug/L	0.89	0.92					*0.50*

[1]Collected during the period of supernatant recycle

Table 3.11: Greensand Pilot - Filtered Water Quality from Laboratory Analysis (Total Metals)

		May 8, 2019 8:30		
Parameter	**Units**	**Filter A**	**Filter C**	**Reporting Limit**
Aluminum, Total	mg/L	ND	ND	*0.100*
Antimony, Total	mg/L	ND	ND	*0.0040*
Arsenic, Total	mg/L	0.0015	0.0014	*0.0010*
Barium, Total	mg/L	0.0182	0.0198	*0.0010*
Beryllium, Total	mg/L	ND	ND	*0.0010*
Cadmium, Total	mg/L	ND	ND	*0.0002*
Calcium, Total	mg/L	20.8	20.8	*0.100*
Chromium, Total	mg/L	ND	ND	*0.00010*
Copper, Total	mg/L	ND	ND	*0.010*
Hardness	mg/L	62.9	62.7	*0.660*
Magnesium, Total	mg/L	2.63	2.60	*0.100*
Mercury, Total	mg/L	ND	ND	*0.0002*
Nickel, Total	mg/L	ND	0.0020	*0.0020*
Potassium, Total	mg/L	16.7	17.2	*2.50*
Selenium, Total	mg/L	ND	ND	*0.0050*
Silver, Total	mg/L	ND	ND	*0.007*
Sodium, Total	mg/L	50.5	51.2	*2.00*
Thallium, Total	mg/L	ND	ND	*0.0010*
Zinc, Total	mg/L	ND	ND	*0.050*

Table 3.12: Greensand Pilot - Simulated Distribution System Results

May 8, 2019 8:30		**Filter A**	**Filter C**
Incubation Time	hours	167	167
Chlorine Dose	mg/L	1.0	1.0
pH, Initial	SU	6.33	6.39
pH, Final	SU	7.23	7.52
Residual Chlorine, Initial	mg/L	1.27	1.39
Residual Total Chlorine, Final	mg/L	0.740	0.680
Residual Free Chlorine, Final	mg/L	0.700	0.660
Chloroform	µg/l	6.5	6.3
Bromodichloromethane	µg/l	3.8	3.5
Dibromochloromethane	µg/l	2.5	2.3
Bromoform	µg/l	ND	ND
THMs, Total	**µg/l**	**13**	**12**

3.3.1.2 GreensandPlus Filter Performance

For each filter run, online data was logged every 3 minutes by the PLC, and grab samples were collected and analyzed periodically throughout the day. In addition, autosamplers collected samples from Filters A and C periodically when the pilot site was not staffed.

Figures C.01 to C.16 in Appendix C show important operating conditions and effluent iron and manganese concentrations for each filter run. Figure 3.03 (Also in Appendix as Figure C.13: Filter A – Trial 4) is representative of the figures included and is described below:

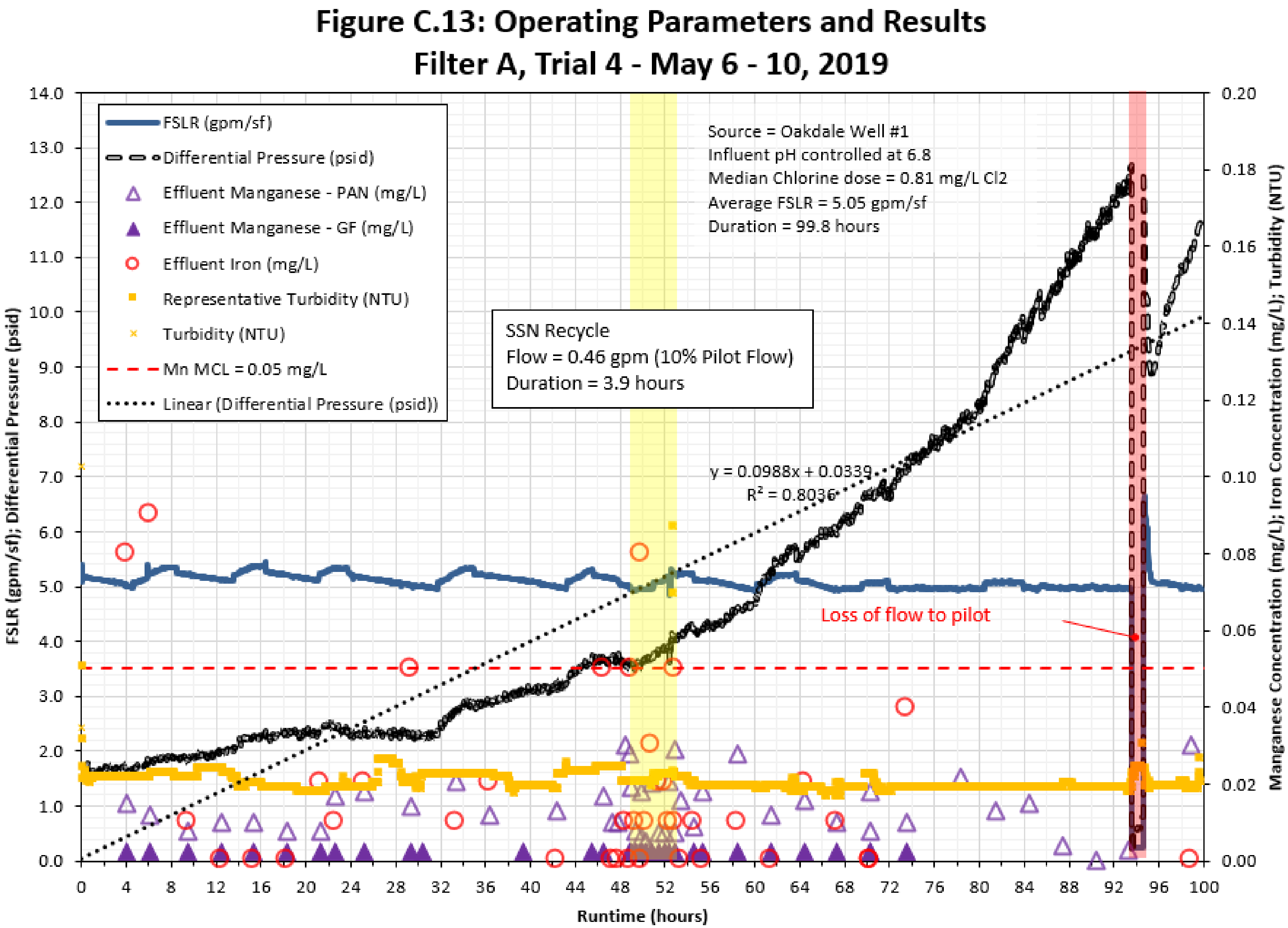
1. X-axis is presented in units of hours of filter run time, with 0 hours set at the time the filter was placed online.
2. Field data for effluent iron concentrations are presented as red circles in units of mg/L and represent results of field analyses of grab samples. The data are plotted using the right y-axis.
3. Field data for effluent manganese concentrations are presented as hollow purple triangles in units of mg/L and represent results of field analyses of grab samples. Grab samples collected from filter effluent and later analyzed by Blueleaf's graphite furnace for manganese concentrations are presented as solid purple triangles in units of mg/L. The data are plotted using the right y-axis.
4. All recorded filter effluent turbidity data are presented as orange "x". These are all the turbidity data logged by the PLC during the filter trial in units of NTUs. The data are plotted using the right y-axis.
5. Representative filter effluent turbidity data are presented as orange squares. These are the turbidity recorded after the filter-to-waste period, and prior to breakthrough in units of NTUs. The data are plotted using the right y-axis.
6. The filter surface loading rate (FSLR) is shown as a blue line. Loading rate was calculated from the effluent flow rate and the surface area of the filters (0.2 ft^2). The FSLR is included in the figures to show when flow rates were stable, when flow rate adjustments were made, and when the filter experienced declining rate conditions. The FLSR is presented in gpm/sf and is plotted using the left y-axis.
7. Differential pressure (DP) is shown as a dashed black line in units of psid and is plotted using the left y-axis. DP was calculated from the differential pressure transducer connected to the inlet and outlet of the filter. A linear regression was performed on the DP versus time data, and the regression line is shown as a thin black line. The equation of the regression line and the R^2 value are shown. The equation of the line is:

$$y = mx + b$$

Where: y = DP in psi differential (psid)
m = the slope of DP development (psi/hr)
b = y-intercept of DP curve, or initial clean bed DP (psi)
x = runtime in hours

8. Periods of supernatant recycle are identified by a yellow transparent square, where applicable. The presented example figure depicts a supernatant recycle trial which is shown with the flow rate of supernatant to the pilot system along with the duration of the recycle period.

Figure 3.03: Example Figure – Greensand Filter A Operational Data, Trial 4, May 6 – 10, 2019



3.3.1.3 GreensandPlus Filter Performance Summary Tables

Table 3.13 summarizes the operating conditions, and performance of each filter trial. The following information is included for each filter trial:

A. “Source” which identifies the well(s) that were active during the trial
B. “Trial” is the Trial number (1-4).
C. “Target FSLR” is the target FSLR for the trial.
D. “Start” and “End” represent the start and end date and time of the filter trial.
E. “Duration” is the total length of the filter trial in hours.
F. “FSLR” is the actual filter loading rate processed through the filters, in gallons per minute per square foot (gpm/sf). The FSLR was calculated using recorded online flowrate (gpm) and dividing by the surface area of the pilot filter (0.2 ft^2).
G. “Slope” is the slope of the regression equation for DP versus runtime (coefficient “m” in the equation y = mx + b). Slope is reported in psid/hour.
H. “Intercept” is the y-intercept of the line of the regression equation for DP versus runtime (“b” in the equation y = mx + b). The intercept is reported in psid.
I. “R^2“ is the coefficient of multiple determination for multiple regression of the line of the regression equation for DP versus runtime.
J. “Runtime to 10 psi (hrs)” – The estimated runtime (in hours) to develop a DP of 10 psi based on the regression equation. Data are indicated as “greater than” (>) if terminal DP was not exceeded before the filter run ended. Data are indicated with a strikethrough (example: ~~48.1~~) if terminal DP was preceded by contaminant breakthrough, in which case DP was not the limiting factor for filter runtime.
K. “Runtime to Contaminant Breakthrough” – The runtime (in hours) until contaminant breakthrough was observed, if it was observed during the trial. Contaminant breakthrough could be observed by consistent high metal concentrations above the project goals (Fe > 0.10 mg/L, Mn > 0.050 mg/L) or an inflection in the trend of turbidity data indicating a rapid increase in effluent turbidity.
L. “Projected UFRV at Termination Criterion” – The unit filter run volume (UFRV) is the volume of water treated per unit filter surface area at termination (gal/sf). UFRV was calculated based on the projected runtime until 10 psi or contaminant breakthrough, whichever came first. If contaminant breakthrough was not observed and the trial ended prior to the projected runtime to 10 psi, the trial duration was used. Data are indicated as “greater than” (>) because the projected runtime to a differential pressure of 10 psi was greater than the runtime of the trial.
M. “All Turbidity Data” includes all the logged turbidity data, including non-representative data from post-breakthrough operation, turbidity spikes, etc. Turbidity data are presented as Mean ± standard deviation [sample count] in units of NTU.
N. “Representative Turbidity Data” includes only representative turbidity data, excluding non-representative data from post-breakthrough operations, short-term turbidity spikes caused by operational upsets, the presumed filter-to-waste period following backwashing, etc. Turbidity data are presented as Mean ± standard deviation [sample count] in units of NTU.

Table 3.13: Greensand Pilot - Filter Performance Summary

Trial	Start Time	End Time	Duration (hrs)	Filter	Target FSLR (gpm/sf)	FSLR (gpm/sf)	Headloss v. Runtime – Linear Regression			Runtime to 10 psi Differential Pressure		Theoretical UFRV (gal/sf)	All Turbidity Data (NTU)	Representative Turbidity Data (NTU)
							Slope (psi/hr)	Intercept (psi)	R-SQ	Projected Runtime (hours)	Observed Runtime (hours)			
1	4/30/19 16:21	5/1/19 8:45	16.4	A	5	**5.05** ± 0.08 [329]	0.02	2.32	0.76	331.0	-	99,289	**0.048** ± 0.083 [329]	**0.030** ± 0.006 [309]
				B	5	**5.40** ± 0.18 [329]	0.01	1.43	0.22	870.3	-	281,961	**0.045** ± 0.062 [329]	**0.033** ± 0.007 [314]
				C	5	**5.76** ± 0.12 [329]	0.01	1.48	0.54	683.5	-	233,767	**0.059** ± 0.124 [329]	**0.033** ± 0.007 [314]
				D	5	**5.31** ± 0.10 [329]	0.02	1.05	0.65	477.2	-	151,747	**0.043** ± 0.061 [329]	**0.031** ± 0.004 [315]
2	5/1/19 9:39	5/3/19 9:06	47.4	A	4	**3.88** ± 1.01 [950]	0.01	1.78	0.11	645.8	-	147,239	**0.031** ± 0.043 [950]	**0.029** ± 0.029 [945]
				B	4	**3.92** ± 1.10 [950]	0.01	1.05	0.07	1320.0	-	308,871	**0.036** ± 0.030 [950]	**0.035** ± 0.017 [947]
				C	6	**5.69** ± 1.57 [950]	0.02	1.54	0.17	474.2	-	159,330	**0.034** ± 0.055 [950]	**0.035** ± 0.017 [947]
				D	6	**5.63** ± 1.55 [950]	0.01	1.07	0.17	631.1	-	212,061	**0.039** ± 0.017 [950]	**0.039** ± 0.013 [948]
3	5/3/19 9:36	5/6/19 7:57	70.3	A	7	**6.76** ± 1.51 [1408]	0.02	2.45	0.21	434.9	-	174,836	**0.026** ± 0.048 [1408]	**0.026** ± 0.047 [1405]
				B	7	**6.69** ± 1.56 [1408]	0.02	1.68	0.27	443.4	-	175,571	**0.004** ± 0.037 [1408]	**0.004** ± 0.035 [1404]
				C	5	**5.31** ± 1.24 [1408]	0.02	0.61	0.45	521.8	-	165,941	**0.030** ± 0.038 [1408]	**0.004** ± 0.035 [1404]
				D	5	**5.19** ± 1.22 [1408]	0.02	0.03	0.65	477.1	-	146,002	**0.042** ± 0.037 [1408]	**0.041** ± 0.035 [1405]
4[1]	5/6/19 8:39	5/10/19 12:24	99.8	A	5	**5.05** ± 0.50 [1996]	0.10	0.03	0.80	-	84.7	25,410	**0.021** ± 0.003 [1996]	**0.021** ± 0.003 [1994]
				B	5	**5.27** ± 0.59 [1996]	0.08	0.19	0.70	-	87.1	27,160	**0.008** ± 0.009 [1996]	**0.008** ± 0.009 [1996]
				C	7	**6.96** ± 0.76 [1996]	0.18	-1.55	0.82	-	67.1	27,759	**0.030** ± 0.002 [1996]	**0.008** ± 0.009 [1996]
				D	7	**6.91** ± 0.82 [1996]	0.17	-2.20	0.80	-	72.7	30,118	**0.044** ± 0.027 [1996]	**0.044** ± 0.027 [1994]

[1]Highlighted Trials indicate a period of supernatant recycle

3.3.2 Biological Filter Performance

3.3.2.1 Biological Filter Effluent Water Quality

Water quality results from samples analyzed in the field are shown in Tables 3.14 and 3.15. The tables summarize water quality by trial. For 3 or more data, the data are presented in the format:

median (minimum – maximum) [number of samples]

For two data, the data are presented in the format:

(minimum – maximum) [2]

For one data, the data is presented in the format:

value [1]

Laboratory data from four rounds of lab sampling are reported in Table 3.16.

Table 3.14: Biological Pilot - Effluent Water Quality Data by Trial for Filter M1 by Field Analyses

Trial	pH (s.u.)	Dissolved Oxygen (ppm)	Iron, Total (mg/L)	Manganese, Total – PAN (mg/L)	Manganese, Total – GF (mg/L)
1-1[1]	**8.08** ± 0.17 [13454]	**7.43** ± 1.60 [13454]	**0.03** (0.01-0.06) [7]	**0.328** (0.006-0.685) [74]	No Data [0]
2-1	**7.92** ± 0.20 [6984]	**7.15** ± 0.45 [6984]	**0.01** (0.00-0.13) [8]	**0.023** (0.004-0.112) [43]	**0.012** (0.003-0.115) [56]
3-1	**7.78** ± 0.34 [14933]	**7.15** ± 0.36 [14933]	**0.02** (0.01-0.03) [5]	**0.051** (0.024-0.197) [77]	**0.031** [1]
4-1	**7.91** ± 0.21 [3490]	**11.70** ± 3.65 [3490]	No Data [0]	**0.060** (0.023-0.127) [14]	**0.024** (0.015-0.040) [5]
4-2	**8.16** ± 0.25 [2750]	**10.81** ± 0.29 [2750]	**0.04** (0.00-0.10) [3]	**0.023** (0.008-0.033) [17]	**0.015** (0.003-0.037) [14]
4-3	**7.38** ± 0.09 [2440]	**10.14** ± 0.34 [2440]	**0.04** [1]	**0.025** (0.010-0.548) [18]	**0.014** (0.003-0.029) [10]
4-4	**7.66** ± 0.19 [3744]	**9.63** ± 0.34 [3744]	**0.02** [1]	**0.028** (0.011-0.056) [25]	**0.011** (0.004-0.017) [8]
4-5	**7.92** ± 0.13 [1531]	**9.74** ± 0.33 [1531]	No Data [0]	**0.034** (0.000-0.058) [10]	**0.012** (0.008-0.025) [9]
4-6	**7.93** ± 0.23 [2576]	**9.76** ± 1.19 [2576]	**0.01** [1]	**0.029** (0.000-0.060) [13]	**0.010** (0.003-0.017) [13]

[1]Highlighted rows indicate the biological filter was still acclimating during the trial

Table 3.15: Biological Pilot - Effluent Water Quality Data by Trial for Filter M2 by Field Analyses

Trial	pH (s.u.)	Dissolved Oxygen (ppm)	Iron, Total (mg/L)	Manganese, Total – PAN (mg/L)	Manganese, Total – GF (mg/L)
1-1	**7.88** ± 0.30 [17270]	**7.65** ± 1.22 [17270]	**0.02** (0.01-0.05) [7]	**0.100** (0.011-0.664) [64]	No Data [0]
2-1	**7.96** ± 0.25 [6682]	**7.51** ± 0.26 [6963]	**0.03** (0.00-0.09) [8]	**0.030** (0.000-0.180) [43]	**0.014** (0.003-0.102) [56]
3-1	**7.92** ± 0.23 [14936]	**7.53** ± 0.32 [14936]	**0.02** (0.00-0.04) [5]	**0.099** (0.019-0.264) [80]	No Data [0]
4-1	**7.22** ± 0.18 [3487]	**12.16** ± 3.68 [3487]	No Data [0]	**0.062** (0.025-0.163) [20]	**0.020** (0.009-0.024) [5]
4-2	**7.58** ± 0.21 [2748]	**11.24** ± 0.34 [2748]	**0.02** (0.00-0.07) [3]	**0.050** (0.018-0.108) [17]	0.022-0.031 [2]
4-3	**8.01** ± 0.28 [6188]	**10.23** ± 0.44 [6188]	0.01-0.04 [2]	**0.039** (0.003-0.096) [43]	**0.016** (0.005-0.032) [29]
4-4	**8.52** ± 0.06 [1525]	**10.09** ± 0.31 [1525]	No Data [0]	**0.021** (0.000-0.055) [10]	**0.012** (0.003-0.029) [10]
4-5	**8.45** ± 0.20 [2584]	**10.09** ± 1.75 [2584]	**0.00** [1]	**0.027** (0.000-0.091) [13]	**0.016** (0.008-0.034) [13]

Table 3.16: Biological Pilot - Effluent Water Quality Data by Laboratory Analyses

Parameter	Units	May 9, 2019 9:00		July 2, 2019 8:00		Reporting Limit
		M1	M2	M1	M2	
Iron, Total	mg/L	ND	ND	ND	ND	*0.050*
Manganese, Total	mg/L	0.0032	0.0029	0.01497	0.03466	*0.00100*

3.3.2.2 Biological Filter Performance

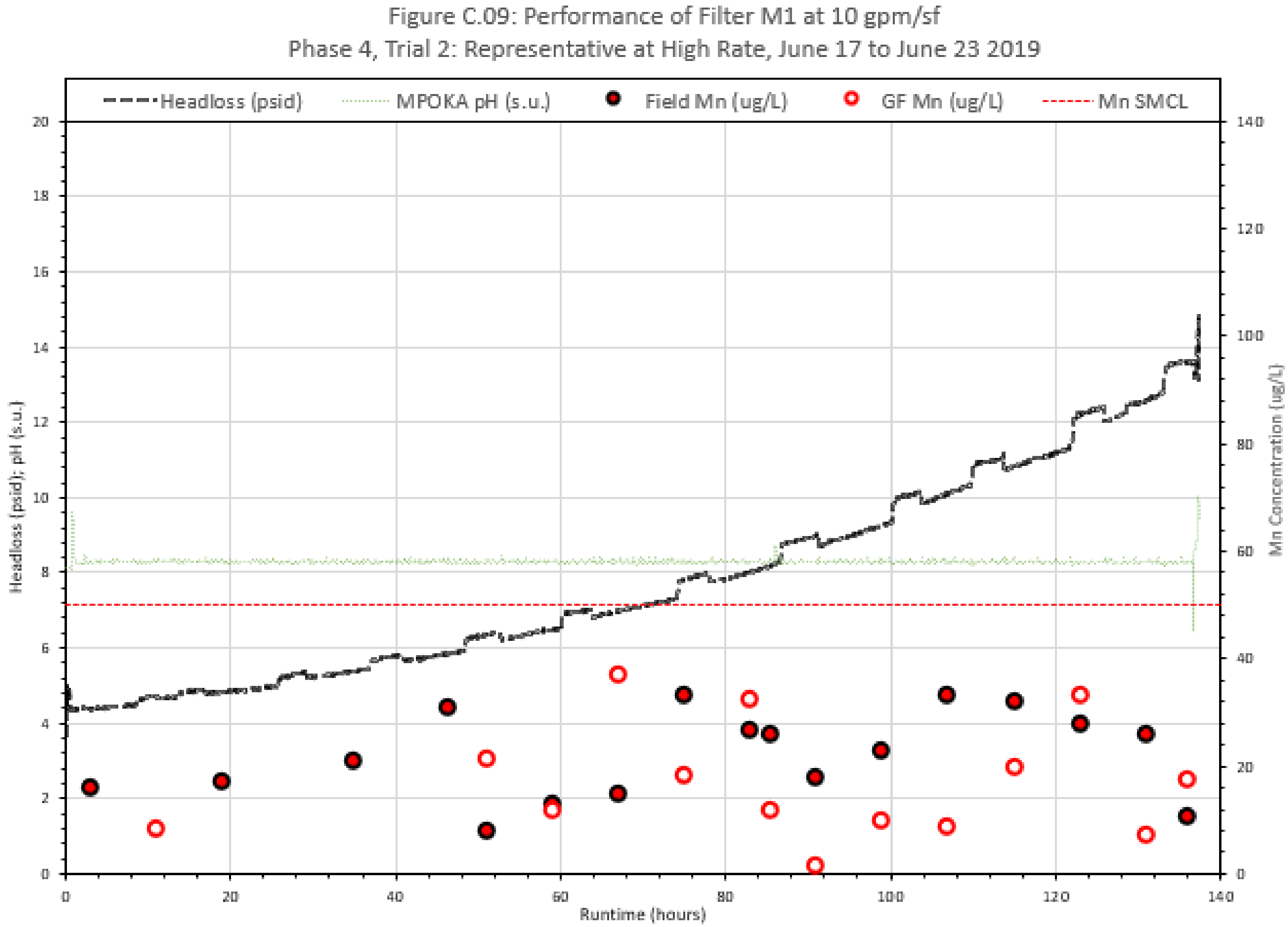
Figure 3.04 is an example figure showing important operating conditions and performance data for the filter trials. Filter M1 Trial 4-2 operated from June 17 through 23, 2019. Individual figures for every filter trial are included in Appendix E.

The figure numbers are also indicated in the other tables throughout this section to allow comparison of the figures to the operational, water quality, and filter performance data. Filters have a differing number of trials based on runtimes and backwash frequency.

The parameters of the figures are described below:

1. The title of the figure identifies the filter (F1, M1, FM2 or FM3) and the trial number. The figure includes operational parameters, influent water quality parameters, and filter effluent water quality parameters.
2. The horizontal axis (x-axis) shows the filter run time. The units are hours. Timing began when the filter began forward flow, following backwash. Start and end times are shown in Tables 3.29 through 3.32.
3. The primary y-axis (left vertical) scales the following parameters: differential pressure (DP) and pH.
4. The secondary y-axis (right vertical) scales total iron and manganese in mg/L.
5. Inlet pH data are presented in standard units (SU) and were measured from the online pH meter. The sample stream was MPOKA. The KOH feed pump control was automated to maintain a setpoint pH level.
6. Differential Pressure was calculated from the differential pressure transducer connected to the inlet and outlet of the filter. The units are PSID.
7. Field Mn indicates the total manganese concentration in filter effluent samples, from field analyses. The units are ug/L and are displayed as red circles with a black outline. GF Mn indicates the total manganese concentration in filter effluent samples from grab samples later analyzed by Blueleaf’s graphite furnace. The units are ug/L and are displayed as hollow red circles. Manganese concentrations are scaled to the right vertical axis.

Figure 3.04: Example Figure – Biological Filter M1 Operational Data, Trial 4-2, June 17 to 23, 2019



3.3.2.3 Biological Filter Performance Tables

A total of 9 trials were completed on Filter M1 and 8 trials on Filter M2. Filters have a differing number of trials based on runtimes and backwash frequency. Each filter trial was preceded by a backwash or an air scour.

For each filter run, the online data listed in Section 2.1.3.4 (Instrumentation) were collected every 3 minutes. Grab samples were collected in accordance with the Protocol. Individual observations and results from field analyses of grab samples are included in the Daily Data Sheets in Appendix B. The results of laboratory analyses are included in Appendices C.

Tables 3.17 and 3.18 present the operating conditions for the filter trials conducted. Data are presented in two formats:

(i) median (minimum – maximum) [number of samples]

(ii) average ± standard deviation [number of samples]

For Tables 3.13 through 3.16 the following information is tabulated for each filter:

- Trial Number - Filter trials were numbered 1 through 26. Some trials had two or more segments with differing operating conditions (example: trials 3a/3b/3c).
- Fig - Indicates the figure number corresponding to the trial. All filter performance figures are provided in Appendix E.
- Start - Indicates the start time of the filter run, i.e. the start of filter forward flow.
- End - Indicates the end time of the filter run.
- Description, Comment - Includes descriptions or comments on the trial or sub-trial.
- Well(s) - Indicates the well or wells that provided raw water for the trial.
- Duration of Trial (hours) - The length of the trial (or sub-trial) in hours.
- Filter Surface Loading Rate (gpm/sf) - The filter surface loading rate, calculated by dividing the flowrate by the surface area of the pilot filter (0.2 sf).
- Slope - is the slope of the regression equation for DP versus runtime (coefficient “m” in the equation $y = mx + b$). Slope is reported in psid/hour.
- Intercept - is the y-intercept of the line of the regression equation for DP versus runtime (“b” in the equation $y = mx + b$). The intercept is reported in psid.
- R^2 - is the coefficient of multiple determination for multiple regression of the line of the regression equation for DP versus runtime.
- Runtime to 10 psid headloss (hours) – This is the projected or observed runtime to a differential pressure of 10 psid. Projected runtimes are determined using the “Slope” and “Intercept” to determine when the differential pressure would be expected to equal 10 psid.
- Extrapolated/Observed – Identified whether the runtime to 10 psid headloss was extrapolated “E” or observed “O”.
- Projected UFRV (gallons/sf) - This is the predicted UFRV (unit filter run volume) calculated based on the predicted run time to 10 psi of headloss, and the filter loading rate.

Table 3.17: Summary of Operating Conditions by Trial for Filter M1

Trial	Fig	Start	End	Description	Duration of Trial (hours)	Filter Surface Loading Rate (gpm/sf)	Headloss v. Runtime – Linear Regression			Runtime to 10 psi (hours)	Extrapolated/ Observed	UFRV (gal/sf)
							Slope (psi/hr)	Intercept (psi)	R-sq			
1-1	C.01	3/28/19 14:24	4/25/19 15:03	Acclimation at Low Rate	672.6	**5.01** ± 0.53 [13454]	-	-	-	-	-	-
2-1	C.03	4/25/19 15:30	5/10/19 6:21	Representative of Low Rate	350.9	**4.94** ± 0.85 [7018]	0.03	0.54	0.65	308.3	O	90,626
3-1	C.05	5/10/19 7:27	6/10/19 10:03	Acclimation at High Rate	746.6	**9.93** ± 1.29 [14933]	-	-	-	-	-	-
4-1	C.07	6/10/19 10:15	6/17/19 16:42	Representative of High Rate	174.4	**9.93** ± 1.94 [3490]	0.03	5.79	0.45	41.2	O	24,473
4-2	C.09	6/17/19 17:15	6/23/19 10:42		137.4	**9.88** ± 0.22 [2750]	0.07	3.28	0.95	100.8	O	59,270
4-3	C.11	6/23/19 11:06	6/28/19 13:03		122.0	**10.05** ± 1.28 [2440]	0.07	3.58	0.86	90.0	O	54,000
4-4	C.13	6/28/19 13:15	7/6/19 8:24		187.1	**10.08** ± 1.52 [3744]	0.08	1.77	0.85	117.0	O	70,230
4-5	C.15	7/6/19 8:39	7/9/19 13:09		76.5	**10.01** ± 1.03 [1531]	0.06	4.67	0.91	76.4	O	45,840
4-6	C.17	7/9/19 13:36	7/14/19 22:21		128.7	**9.89** ± 3.28 [2576]	0.02	4.74	0.33	247.9	E	145,783

Table 3.18: Summary of Operating Conditions by Trial for Filter M2

Trial	Fig	Start	End	Description	Duration of Trial (hours)	Filter Surface Loading Rate (gpm/sf)	Headloss v. Runtime – Linear Regression			Runtime to 10 psi (hours)	Extrapolated/ Observed	UFRV (gal/sf)
							Slope (psi/hr)	Intercept (psi)	R-sq			
1-1	C.02	3/20/19 15:36	4/25/19 15:03	Acclimation at Low Rate	863.5	**4.94** ± 1.04 [17270]	-	-	-	-	-	-
2-1	C.04	4/25/19 15:30	5/10/19 6:21	Representative of Low Rate	350.9	**4.94** ± 0.82 [7018]	0.04	-2.15	0.86	289.5	O	85,113
3-1	C.06	05/10/19 07:27	06/10/19 10:12	Acclimation at High Rate	746.6	**14.34** ± 2.03 [14936]	-	-	-	-	-	-
4-1	C.08	06/10/19 10:24	06/17/19 16:42	Representative of High Rate	174.4	**14.25** ± 2.83 [3487]	0.05	6.26	0.53	32.3	O	27,132
4-2	C.10	6/17/19 17:06	6/23/19 10:27		137.3	**13.57** ± 1.29 [2748]	0.13	4.59	0.98	37.6	O	29,328
4-3	C.12	6/23/19 11:15	7/6/19 8:36		309.4	**13.55** ± 2.13 [6188]	0.03	2.10	0.42	105.6	O	82,407
4-4	C.14	7/6/19 8:45	7/9/19 12:57		76.2	**12.37** ± 1.23 [1525]	0.10	4.57	0.85	58.7	O	42,300
4-5	C.16	7/9/19 13:12	7/14/19 22:21		129.2	**12.60** ± 4.12 [2584]	0.02	3.19	0.12	296.2	E	213,292

3.4 SPENT BACKWASH WATER ANALYSES

3.4.1 GreensandPlus Filter Backwash Water Quality

Table 3.19 shows filter composite backwash (CBW) and settled supernatant (SSN) concentrations from field analyses. Field samples were diluted with distilled water to obtain readings that were in the range of the field methods: 2.2 mg/L instrument limit for iron, and 0.8 mg/L instrument limit for manganese. Table 3.20 shows the results of laboratory analyses conducted on a sample of composite backwash and settled supernatant.

Table 3.19: Backwash Water Quality from Field Analysis

FSLR (gpm/sf)	Trial	Total Fe (mg/L)		Total Mn (mg/L)	
		CBW	SSN	CBW	SSN
5	A-2	0.85	0.33	1.40	1.23
	B-2	0.85	0.38	1.30	1.22
	C-2	1.35	0.56	1.20	1.15
	D-2	1.61	1.02	0.60	1.51
7	A-3	0.90	0.22	4.25	1.34
	B-3	1.16	0.45	5.15	1.70
5	C-3	1.03	0.37	4.60	1.16
	D-3	0.95	0.29	4.90	1.14
5[1]	A-4	1.00	0.03	2.50	0.37
7	C-4	3.00	0.01	1.30	0.54

[1]Highlighted Trials indicate a period of supernatant recycle

Table 3.20: Backwash Water Quality Data by Laboratory Analysis

Parameter	Trial 4			
	5/10/2019			
	Filter A		Filter C	
	CBW	SSN	CBW	SSN
Total Iron (mg/L)	1.38	0.076	1.12	ND
Dissolved Iron (mg/L)	ND	ND	ND	ND
Total Manganese (mg/L)	6.34	0.7208	5.192	0.6064
Dissolved Manganese (mg/L)	0.3374	0.3302	0.5804	0.5518

3.4.2 Biological Filter Backwash Water Analyses

Combined backwash water (CBW) samples and suspended supernatant (SSN) samples were collected for laboratory analyses during each of the four biological pilot lab sampling events. For each backwash analysis:

1. The entire volume of backwash was collected from the filter;
2. The composite backwash (CBW) was mixed to homogenize the sample, and to suspend all solids;
3. A sample of the CBW was collected and submitted to the lab for the following analyses:
    a. Total Iron
    b. Dissolved Iron
    c. Total Manganese
    d. Dissolved Manganese
4. A period of at least 4 hours was allowed for the combined backwash to settle. Suspended supernatant (SSN) samples were then collected and submitted to the lab for the same analyses listed above.

The results of the laboratory analyses are presented in Tables 3.21 and 3.22 for CBW and SSN respectively.

Table 3.21: Combined Backwash Water Quality Data by Field Analyses

Trial	Filter	FSLR (gpm/sf)	Total Fe (mg/L)		Total Mn (mg/L)	
			CBW	SSN	CBW	SSN
2-1	M1	10	20.0	0.12	353.0	0.085
	M2	15	20.0	0.13	562.0	0.094

Table 3.22: Combined Backwash Water Quality Data by Laboratory Analyses

Parameter	Trial 2-1				Trial 4-3 (M1) Trial 4-2 (M2)			
	5/10/19				7/02/19			
	M1		M2		M1		M2	
	CBW	SSN	CBW	SSN	CBW	SSN	CBW	SSN
Total Iron (mg/L)	3.24	0.125	3.25	0.190	1.26	0.072	2.10	0.075
Dissolved Iron (mg/L)	ND	ND	ND	ND	ND	ND	ND	ND
Total Manganese (mg/L)	188.7	0.1647	149.0	0.3225	169	0.1904	133	0.2457
Dissolved Manganese (mg/L)	0.0031	0.0034	0.0023	0.0021	0.242	ND	ND	0.0156

4 DATA ANALYSIS

Section 4 – Data Analysis provides analysis and discussion of the data presented in Section 3. This Section contains comparisons of Filter Trials and discussion of data from separate parts of Section 3. Issues and questions that are addressed in this Section were developed by the pilot operators to answer questions that are generally of interest when testing iron and manganese removal in general, or biological treatment specifically.

4.1 RAW WATER QUALITY

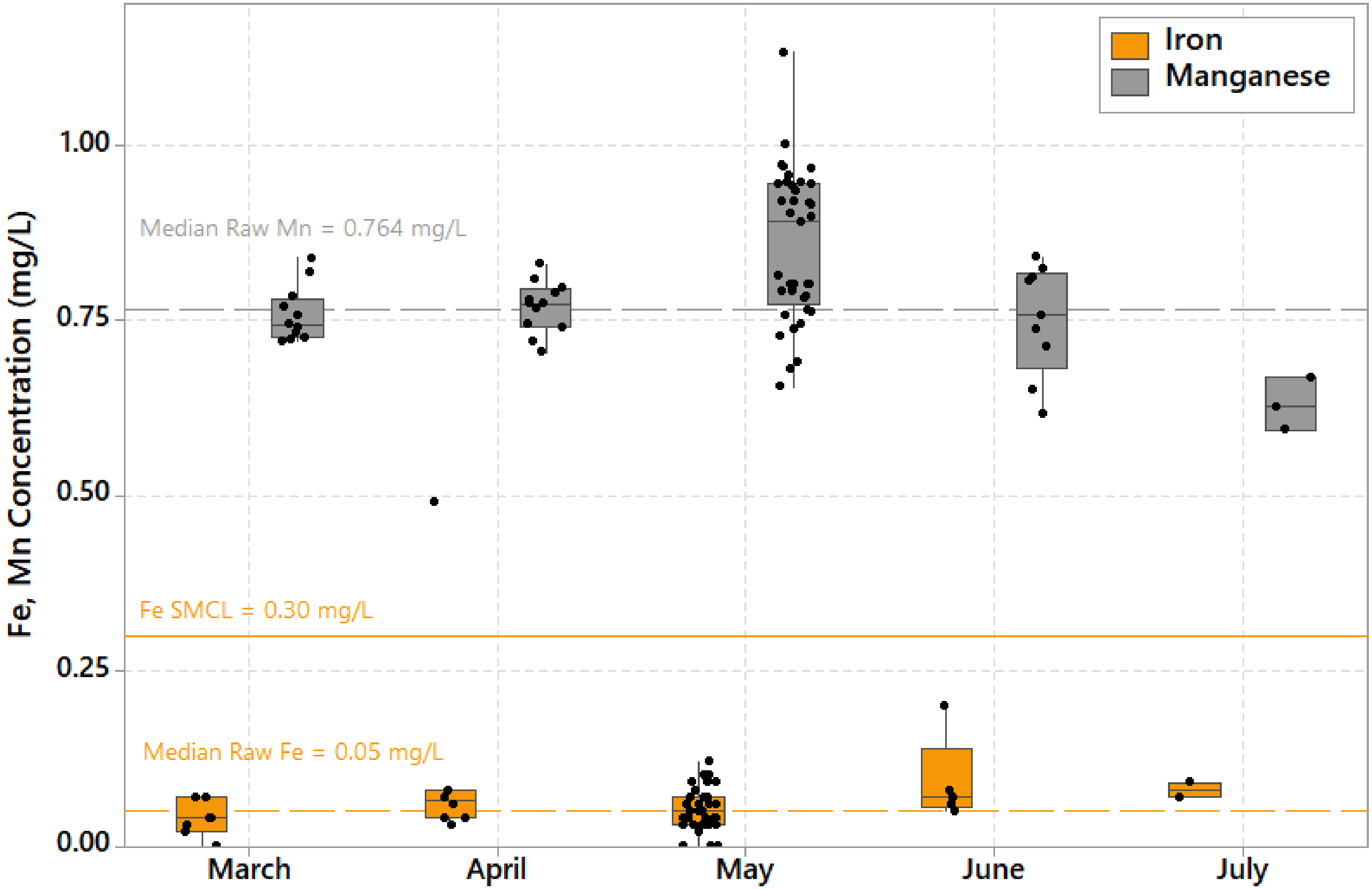
4.1.1 Comparison of Raw Water Quality over Time

To evaluate changes in raw water quality from each well source throughout the study, the raw iron and manganese concentrations were plotted in a time series (Figure 4.01). The time series shows the median iron and manganese concentrations detected in raw water throughout the study in order to assess variability.

Figure 4.01 shows little variability in raw iron concentrations from the Oakdale Well during the test period. The raw iron increased above the median marginally later during the study, but it was a minor increase. It is worth noting that raw iron concentration overall was very low (Median Raw Fe = 0.05 mg/L), far below the secondary limit (Fe SMCL < 0.3 mg/L) and the project goal (Fe Project Goal < 0.10 mg/L).

Figure 4.01 also shows the raw manganese concentrations from the Oakdale Well during the pilot test period remained consistent at the beginning (March, April), increased (May), then began to decline towards the conclusion of the study (June, July). Overall, while there was variability in raw manganese concentrations, these differences were marginal with the exception of during the month of July where raw manganese concentrations were detected noticeably below the median.

Figure 4.01: Times Series of Raw Water Quality at Oakdale Well



4.1.2 Comparison of Raw Water Quality to Historical Data

Historical water quality data were provided by CEI and summarized in Section 3.1.1. The data provided were from periodic raw water sampling for iron and manganese from the Oakdale Well from 2011 – 2018.

The historical data was compared to the raw water quality data generated during the pilot study. Figure 4.02 shows raw water quality data collected during the pilot study plotted next to historical data. The interquartile range of historical raw iron and manganese concentrations is also plotted in the figure. The interquartile range identifies the range of the middle 50% of detected concentrations. Outliers within the historical data set were omitted from the figure.

Figure 4.02: Times Series of Raw Water Quality at Oakdale Well versus Historical Raw Water Quality

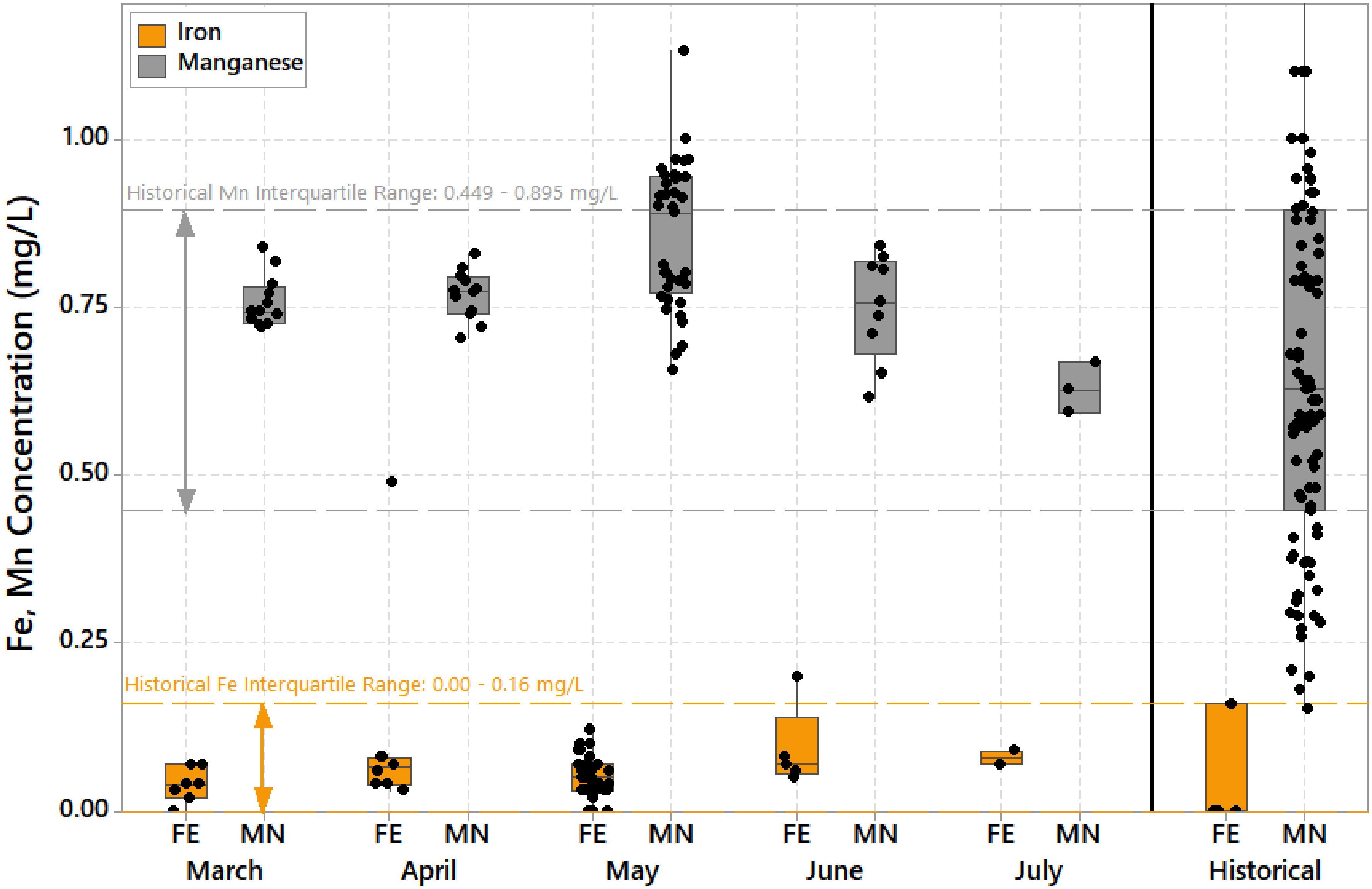


Figure 4.02 shows the raw iron concentrations detected from the Oakdale Well were generally within the interquartile range of historical raw iron concentrations. Figure 4.02 also shows the raw manganese concentrations detected from the Oakdale Well were generally within the interquartile range of historical raw manganese concentrations with the exception of May which showed higher than normal manganese concentrations.

To determine if a statistically significant difference exists between the raw iron and manganese concentrations detected during the pilot study and concentrations observed historically, two ANOVAs were performed. Table 4.01 and 4.02 show the results of the analysis for iron and manganese, respectively.

Table 4.01: ANOVAs of Historical vs Pilot Iron Concentrations

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	0.00	0.00	3.21	0.078
Error	60	0.08	0.00		
Total	61	0.09			

Factor	N	Mean	StDev	95% CI
PILOT	56	0.06	0.03	(0.05, 0.07)
HISTORICAL	6	0.03	0.07	(-0.00, 0.06)

Pooled StDev = 0.0370431

Table 4.02: ANOVAs of Historical vs Pilot Manganese Concentrations

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	0.29	0.29	3.16	0.077
Error	163	14.98	0.09		
Total	164	15.27			

Factor	N	Mean	StDev	95% CI
PILOT	73	0.803	0.102	(0.733, 0.873)
HISTORICAL	92	0.719	0.395	(0.656, 0.781)

Pooled StDev = 0.303191

The results of the ANOVA shown in Table 4.01 concluded a p-value of 0.078 when comparing the raw iron concentrations detected during the pilot study and historical data. This p-value indicates there was not a statistically significant difference between the raw iron concentrations detected during the pilot study and historical data.

The results of the ANOVA shown in Table 4.01 concluded a p-value of 0.077 when comparing the raw manganese concentrations detected during the pilot study and historical data. This p-value indicates there was not a statistically significant difference between the raw manganese concentrations detected during the pilot study and historical data.

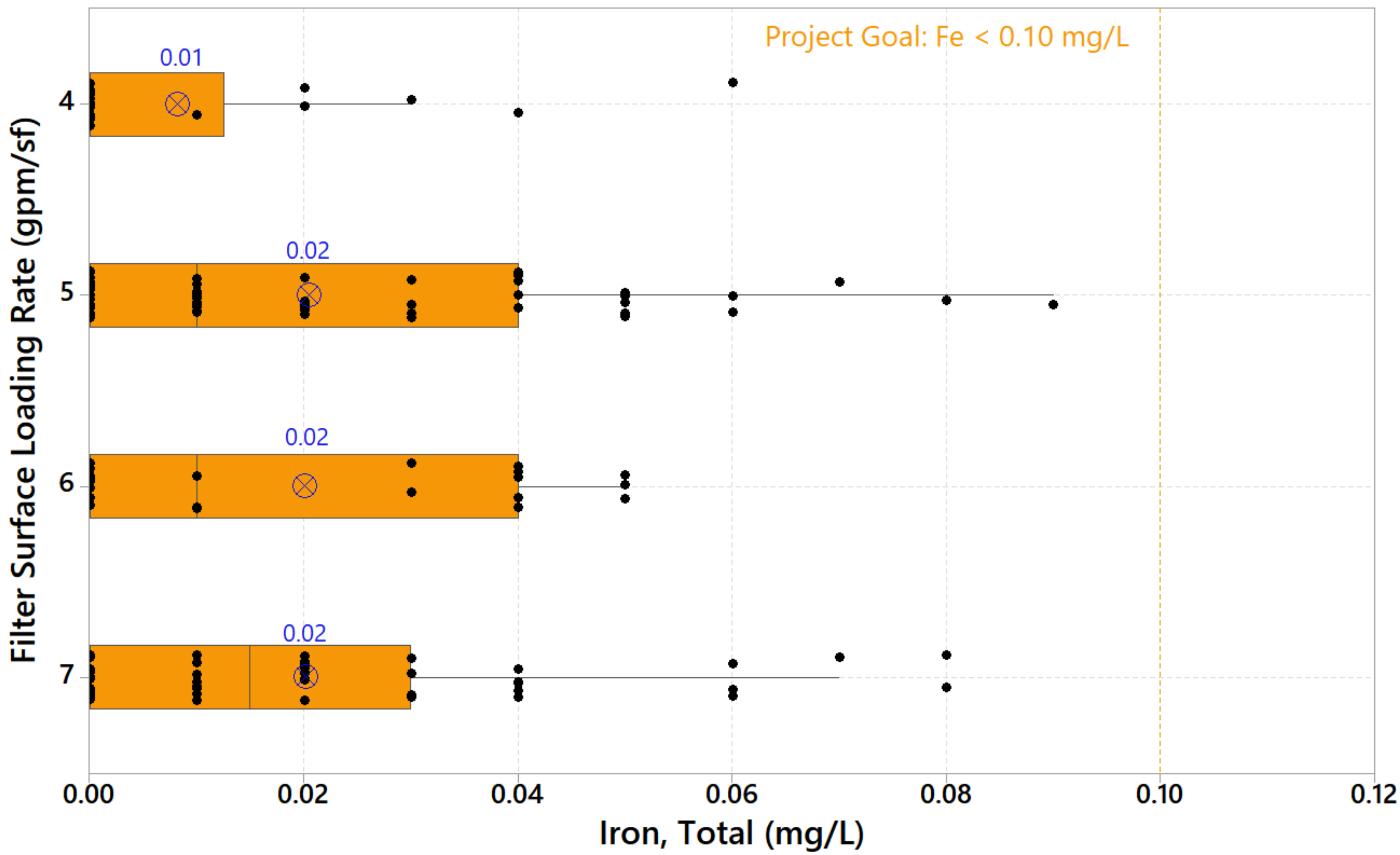
4.2 GREENSANDPLUS PILOT

4.2.1 Greensand Filtration Effectiveness for Fe and Mn Removal

Figure 4.03 shows the iron concentration in filter effluent from field analyses organized by filter surface loading rate. The mean values reported on the figure are rounded because the HACH FerroVer method used in the pilot study reports iron concentration only to the nearest 0.01 mg/L. Figure 4.04 plots the manganese concentration detected in filter effluent from analyses on samples collected and later analyzed by the graphite furnace method.

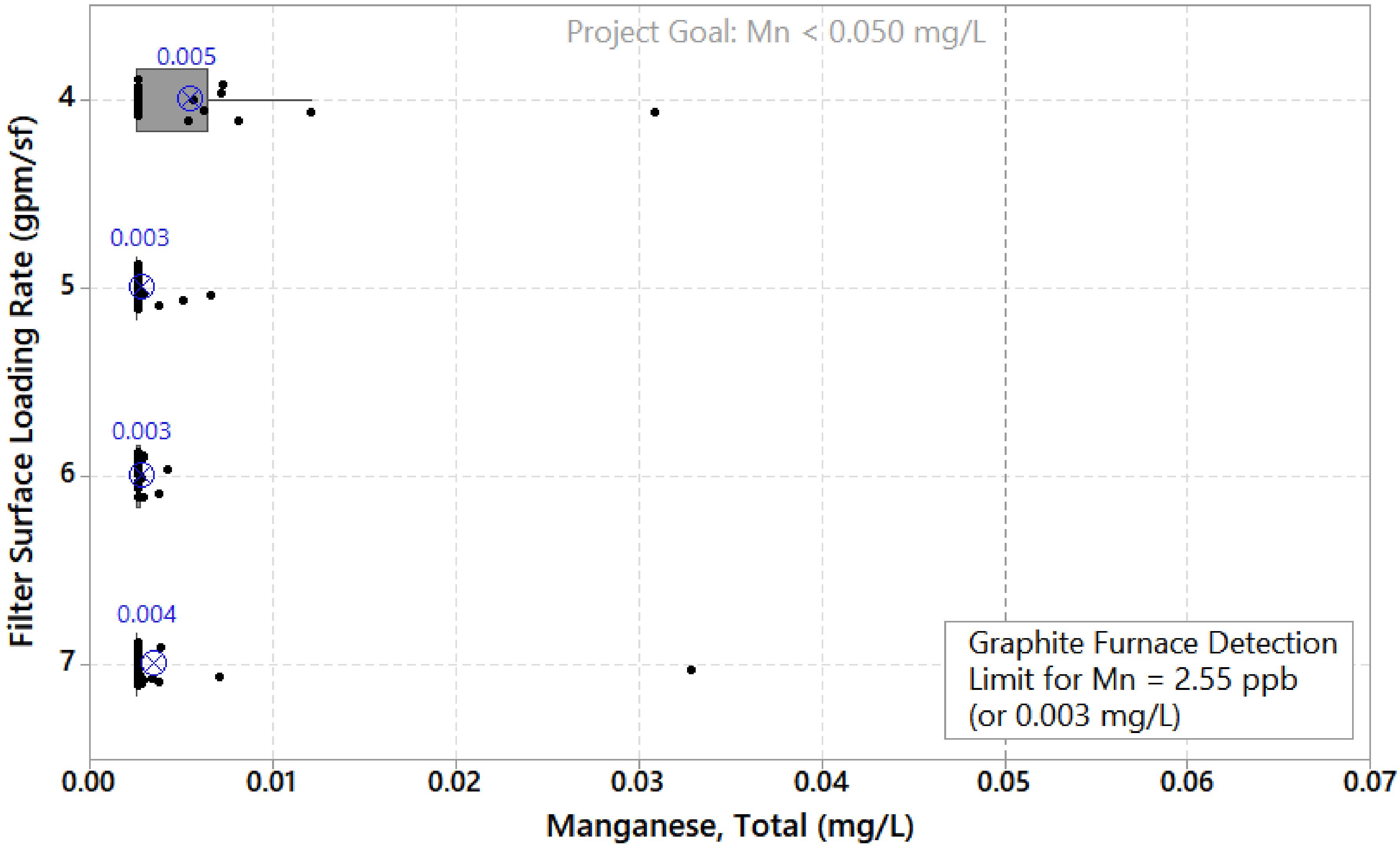
Figure 4.03 and 4.04 show that all representative data collected on greensand filter effluent met the project goal for total iron ($Fe < 0.10$ mg/L) and total manganese ($Mn < 0.050$ mg/L).

Figure 4.03: Total Iron Concentration in Greensand Filter Effluent from HACH Field Analysis



Mean values shown in blue

Figure 4.04: Total Manganese Concentration in Greensand Filter Effluent from GF Analysis

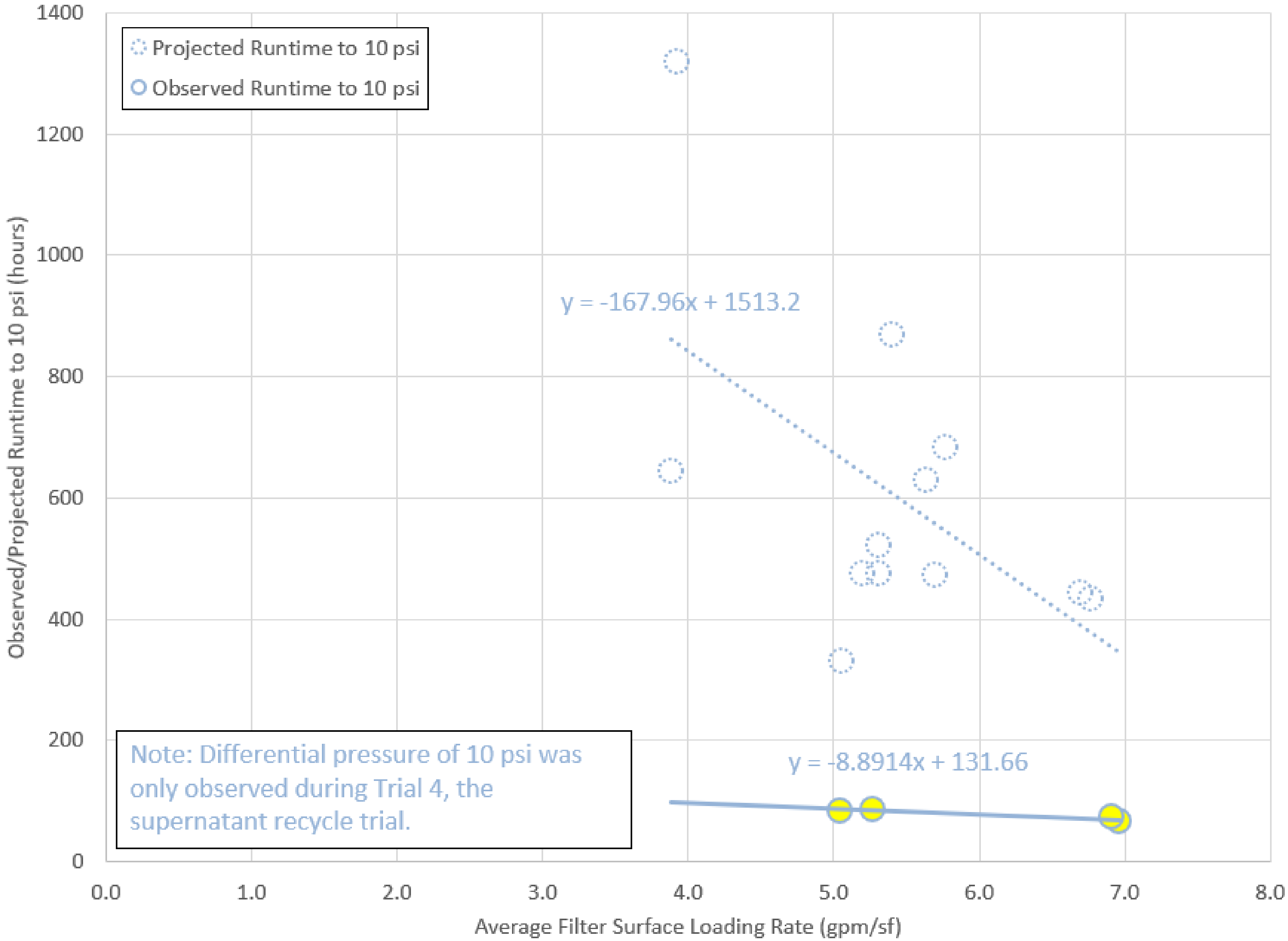


Mean values shown in blue

4.2.2 Filter Runtime vs Loading Rate

Figure 4.05 plots the projected or observed runtime to a differential pressure of 10 psi. Markers filled in with yellow are trials during which supernatant recycle occurred. Markers with a solid outline represent the actual time for the filter to reach 10 psi, while markers with a dotted outline represent projects for the time to reach 10 psi based on headloss data collected. The lines show are fitted trendlines for either observed or extrapolated runtimes.

Figure 4.05: GreensandPlus Filter Projected/Observed Runtime as a function of FSLR



Filter runtimes were a function of the solids loading onto the media, both from the raw water iron and manganese concentrations and the loading rates. Trials 1 – 3 were extrapolated to a differential pressure of 10 psi while Trial 4 was the only trial a differential pressure of 10 psi was observed. Filter runtimes are typically a function of the concentration of iron in raw water. The raw iron concentration from Oakdale Well has a low concentration of iron (Median Raw Fe = 0.05 mg/L) and therefore significant headloss accumulation was not observed during the filter trials. Significant headloss accumulation was only observed during Trial 4, the supernatant recycle trial.

4.2.3 Supernatant Recycle Performance

Settled supernatant was pumped into the raw water feed of the pilot filters for 3.9 hours on May 8 during Trial 4. Recycle flow ended when the supernatant volume had reached a low level to avoid disturbing solids settled at the bottom of the tank.

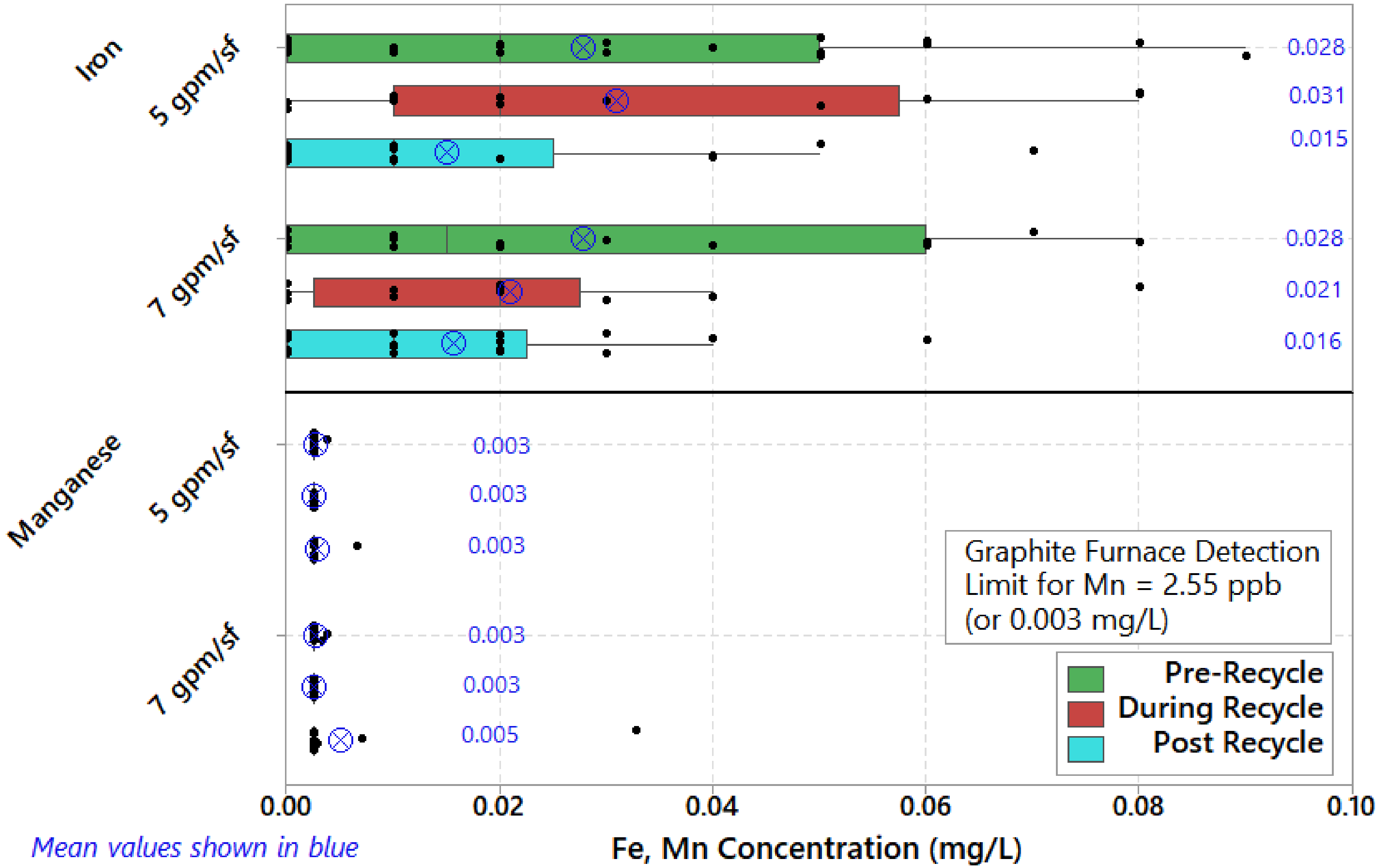
4.2.3.1 Supernatant Recycle Effect on Effluent Water Quality

Water quality was collected prior to, during, and following supernatant recycle. The concentrations of iron and manganese in filter effluent for the recycle trial is shown in Figure 4.06.

Figure 4.06 shows that the average iron concentrations in filter effluent increased during the period of supernatant recycle and then was reduced by half after the recycle while operating at 6 gpm/sf. The average iron concentration in filter effluent decreased during the period of supernatant recycle and then decreased again after the period of recycle while operating at 7 gpm/sf. The difference in effluent iron concentration while operating at either 5 or 7 gpm/sf does not appear to have changed significantly during the period of supernatant recycle or after supernatant recycle concluded.

Figure 4.06 also shows the average manganese concentrations in filter effluent did not change during or post supernatant recycle while operating at 5 gpm/sf. The average manganese concentration in filter effluent did not change during the supernatant recycle and increase marginally post supernatant recycle. The difference in effluent manganese concentration while operating at either 5 or 7 gpm/sf does not appear to have changed significantly during the period of supernatant recycle or after supernatant recycle concluded.

Figure 4.06: Total Fe, Mn Concentrations Detected in Filter Effluent During Supernatant Recycle Trials



4.2.3.2 Supernatant Recycle Effect on Headloss Accumulation

Table 4.03 shows the rate of differential pressure accumulation per hour before, during, and after the conclusion of the supernatant recycle period.

Table 4.03: Rate of Headloss Accumulation during Supernatant Recycle Trial

Target FSLR (gpm/sf)	Filter	Trial Conditions	Duration (hrs)	Rate of Differential Pressure Accumulation (psi/hr)
7	A	Pre-Recycle	48.5	0.04
		During Recycle	3.9	0.10
		Post-Recycle	47.2	0.16
	B	Pre-Recycle	48.5	0.04
		During Recycle	3.9	0.11
		Post-Recycle	47.2	0.09
5	C	Pre-Recycle	48.5	0.07
		During Recycle	3.9	0.22
		Post-Recycle	47.2	0.27
	D	Pre-Recycle	48.5	0.06
		During Recycle	3.9	0.16
		Post-Recycle	47.2	0.30

Table 4.03 shows the rate of differential pressure accumulation increased during the period of supernatant recycle and again after the period of recycle in Filters A, C, and D. The rate of headloss accumulation after the period of supernatant recycle was three to four times greater than the rate prior to the recycle in Filters A, C, and D. The headloss accumulation nearly tripled during the recycle in Filter B but decreased after the recycle.

It is worth noting throughout the greensand filtration pilot the only time a differential pressure of 10 psi was observed as during the supernatant recycle trial. The other trials (Trial 1 – 3), a differential pressure of 10 psi was not observed. Typically, the rate of differential pressure accumulation is a function of raw iron concentration and the filter loading rate. The greater the raw iron concentration or loading rate, the greater amount of precipitated iron is loaded on the filter which causes an increase in differential pressure. As previously discussed, the raw iron concentration in the Oakdale Well was low (Raw Median Fe = 0.05 mg/L) therefore it is not expected to be a significant factor in the rate of headloss accumulation. In addition, if the raw iron concentration is low, it was would be expected the concentration of iron in suspended supernatant would be low so it unlikely to affect the rate of headloss accumulation during the recycle trial.

A possible explanation for the increase in differential pressure accumulation is the formation of manganese solids in filter backwash. While the raw iron concentration from the Oakdale Well was relatively low, the raw manganese concentration was high (Raw Median Mn = 0.764 mg/L). This high raw manganese concentrations caused the filter backwash to have a high manganese concentration (Mn in SSN from Trial 3, 1.14 – 1.70 mg/L). The high manganese concentration in filter backwash could have continued to oxidize to form solids that did not settle adequately and were recycled during the trial.

4.3 BIOLOGICAL PILOT

4.3.1.1 Acclimation of the Previously Seasoned Filters M1

The manganese filter M1 contained media that had been acclimated at another site, a full-scale biological iron and manganese treatment plant located in Putnam CT, from December 2018 until it was transferred to the Oakdale well site on March 20, 2019. M1 began receiving raw water from the Oakdale Well the same day until it was shutdown on March 28. Effluent manganese from M1 increased until it was nearly the same concentration as raw water. This filter was removed from the pilot and replaced with another acclimated filter from Putnam and was designated M1, which would be used for the remainder of the study.

The new M1 did not operate differently than the first set of filters installed from Putnam. It was hypothesized that change to a new water source caused a disruption to the biomass, and an acclimation period would be required. M1 was operated without backwashing in order to minimize disruption to the biomass. Air scour was used in order to remove clogging of the filter and mitigate excessive headloss accumulation. M1 appeared to complete acclimation to the Oakdale Well after approximately 673 hours when effluent manganese was below the project goal (Project Goal: Mn < 0.05 mg/L) with relative consistency.

M1 then operated at the low loading rate (5 gpm/sf) to show representative effluent manganese concentrations when the biological filter is acclimated and functioning normally. After the period during the study showing treatment at the low loading rate, the loading rate was increased to the high loading rate (10 gpm/sf). Effluent manganese concentrations immediately increased to greater than 0.200 mg/L (or 200 ug/L). It was concluded the increase in loading rate also caused a disruption in the biomass and another acclimation period was required for the biomass to adjust to the increased loading rate. M1 appeared to complete acclimation at the higher loading rate after an additional 747 hours when effluent manganese was below the project goal with relative consistency.

Figure 4.07 shows the acclimation time of M1 at the lower and higher loading rates compared to the acclimation of filters during other pilot studies. Figure 4.08 shows filter performance for the full duration M1 was operated.

Figure 4.07: Filter M1 Acclimation compared to other Biological Filter Acclimation Times

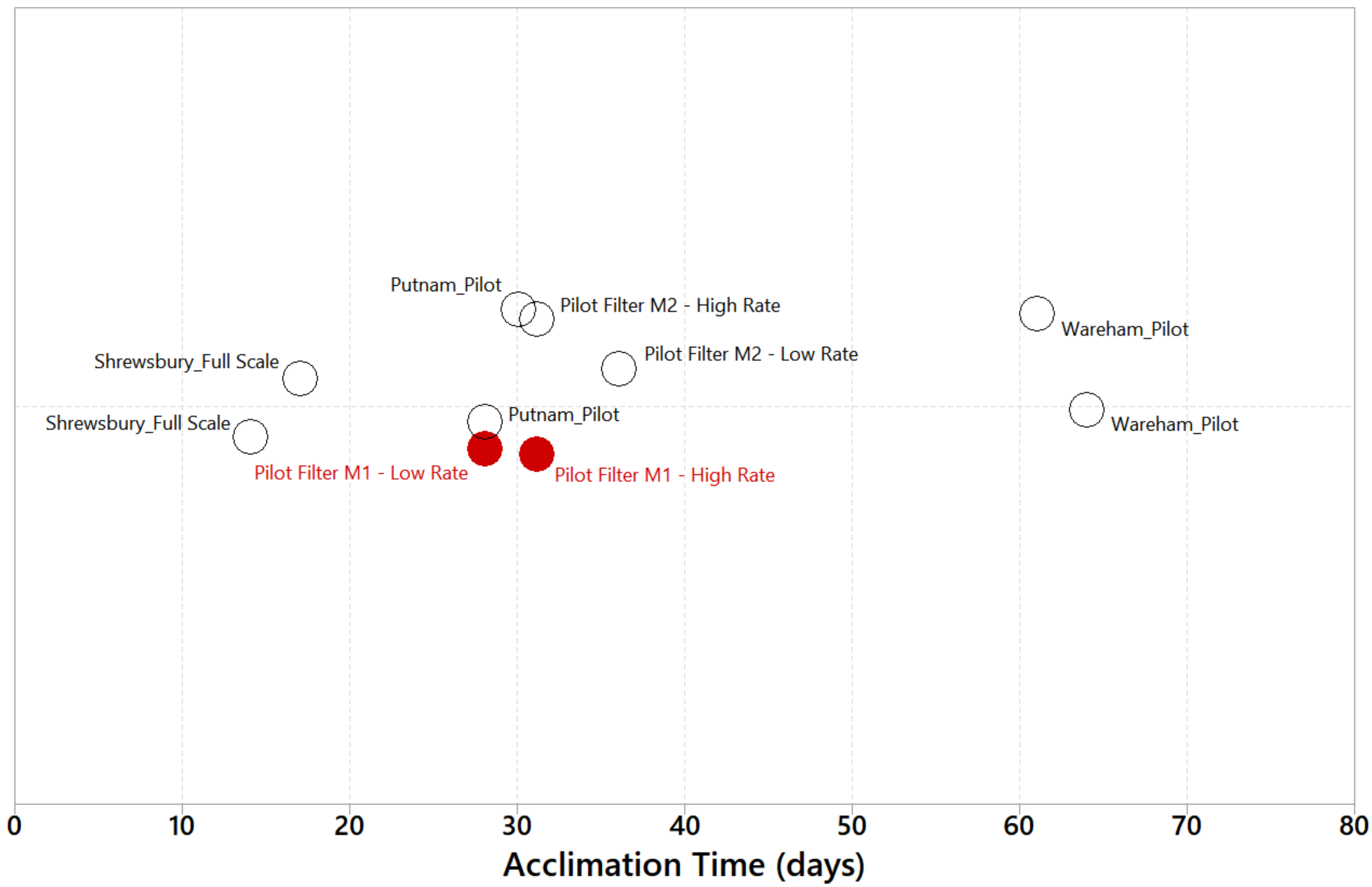
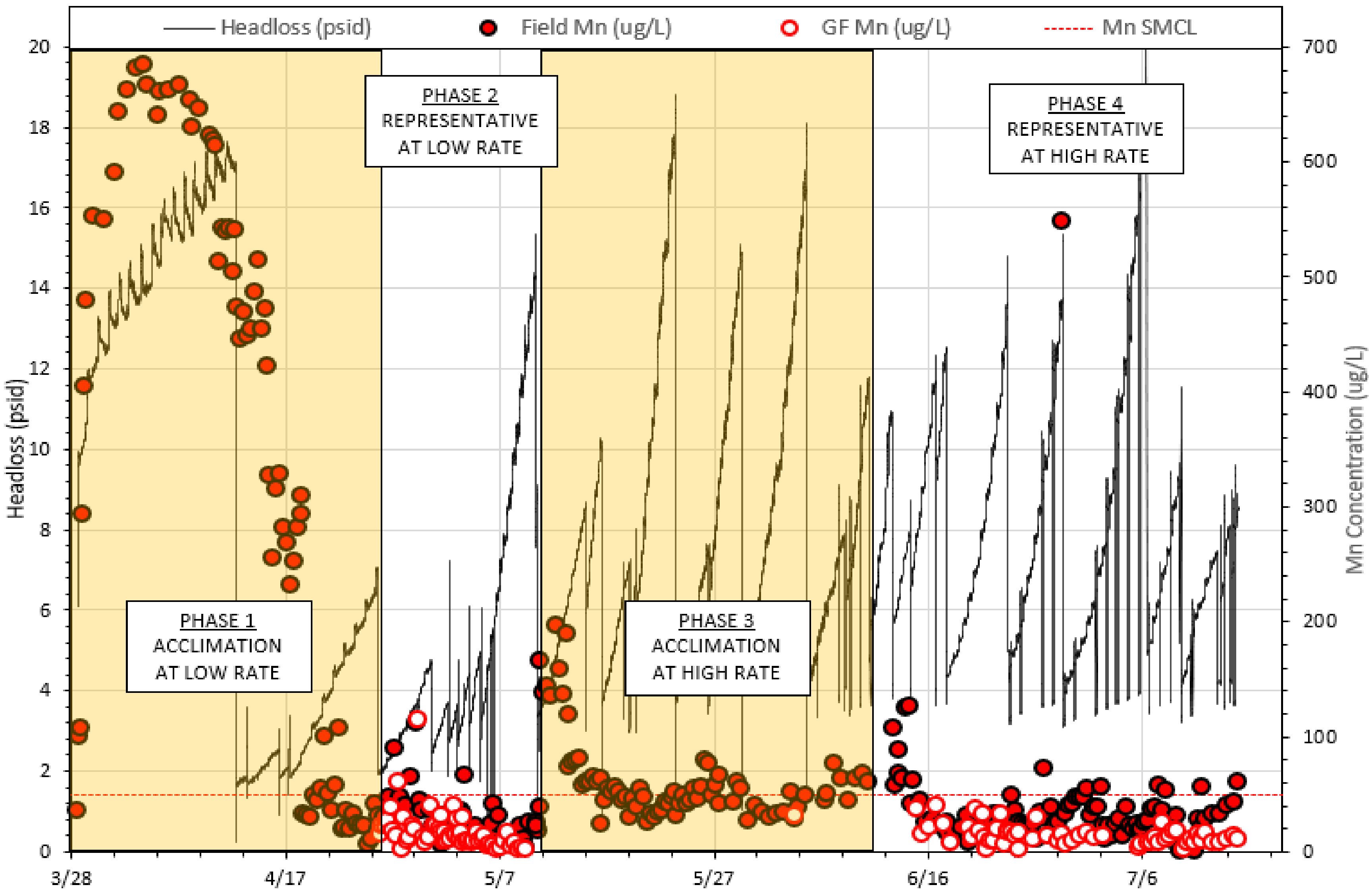


Figure 4.08: Filter M1 Operational Data for Pilot Duration



4.3.1.2 Acclimation of the Manganese Removal Filter M2

The manganese filter M2 contained media that had been acclimated at another site, a full-scale biological iron and manganese treatment plant located in Putnam CT, from January 2019 until it was transferred to the Oakdale well site on March 20, 2019. M2 began receiving raw water from the Oakdale Well the same day until it was shutdown on July 14. During this time, M2 mudballs began to accumulate on the surface of the filter media and treatment of manganese was poor. Effluent manganese from M2 increased until it was nearly the same concentration as raw water. The filter was temporarily shutdown to remove the mudballs from the surface of the media and then put back into service.

It was determined the change to a new water source likely caused a disruption to the biomass, and an acclimation period would be required. M2 was operated without backwashing in order to minimize disruption to the biomass. Air scours were used in order to remove clogging of the filter and mitigate excessive headloss accumulation. M2 appeared to complete acclimation after approximately 864 hours when effluent manganese was below the project goal (Project Goal: Mn < 0.05 mg/L) with relative consistency.

M2 then operated at the low loading rate (5 gpm/sf) to show representative effluent manganese concentrations when the biological filter is acclimated and functioning normally. After the period during the study showing treatment at the low loading rate, the loading rate was increased to the high loading rate (10 gpm/sf). Effluent manganese concentrations immediately increased to greater than 0.200 mg/L (or 200 ug/L). It was concluded the increase in loading rate also caused a disruption in the biomass and another acclimation period was required for the biomass to adjust to the increased loading rate. M2 appeared to complete acclimation at the higher loading rate after approximately 747 hours when effluent manganese was below the project goal with relative consistency.

Figure 4.09 shows the acclimation time of M2 at the lower and higher loading rates compared to the acclimation of filters during other pilot studies. Figure 4.10 shows filter performance for the full duration M2 was operated.

Figure 4.09: Filter M2 Acclimation compared to other Biological Filter Acclimation Times

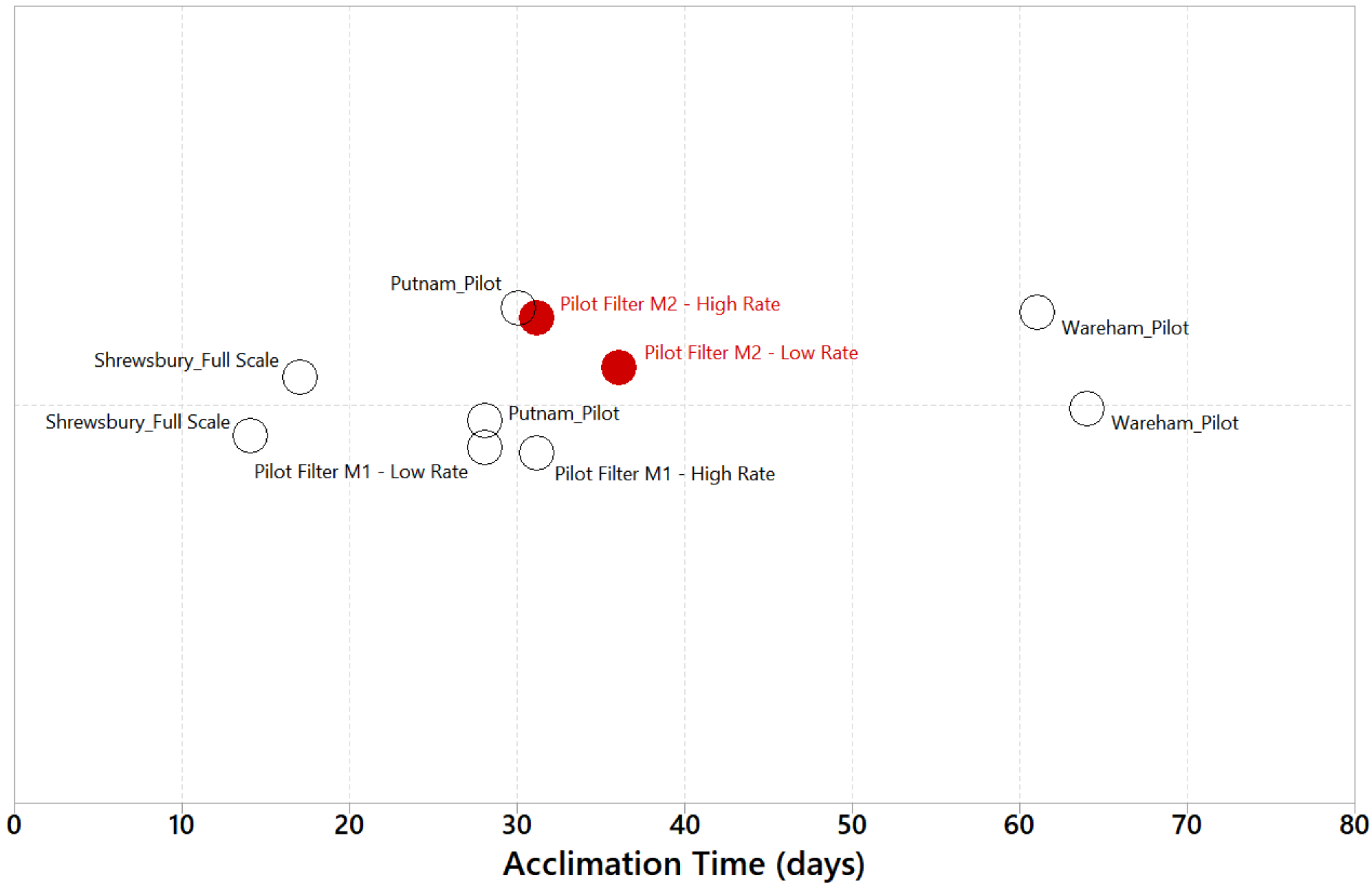
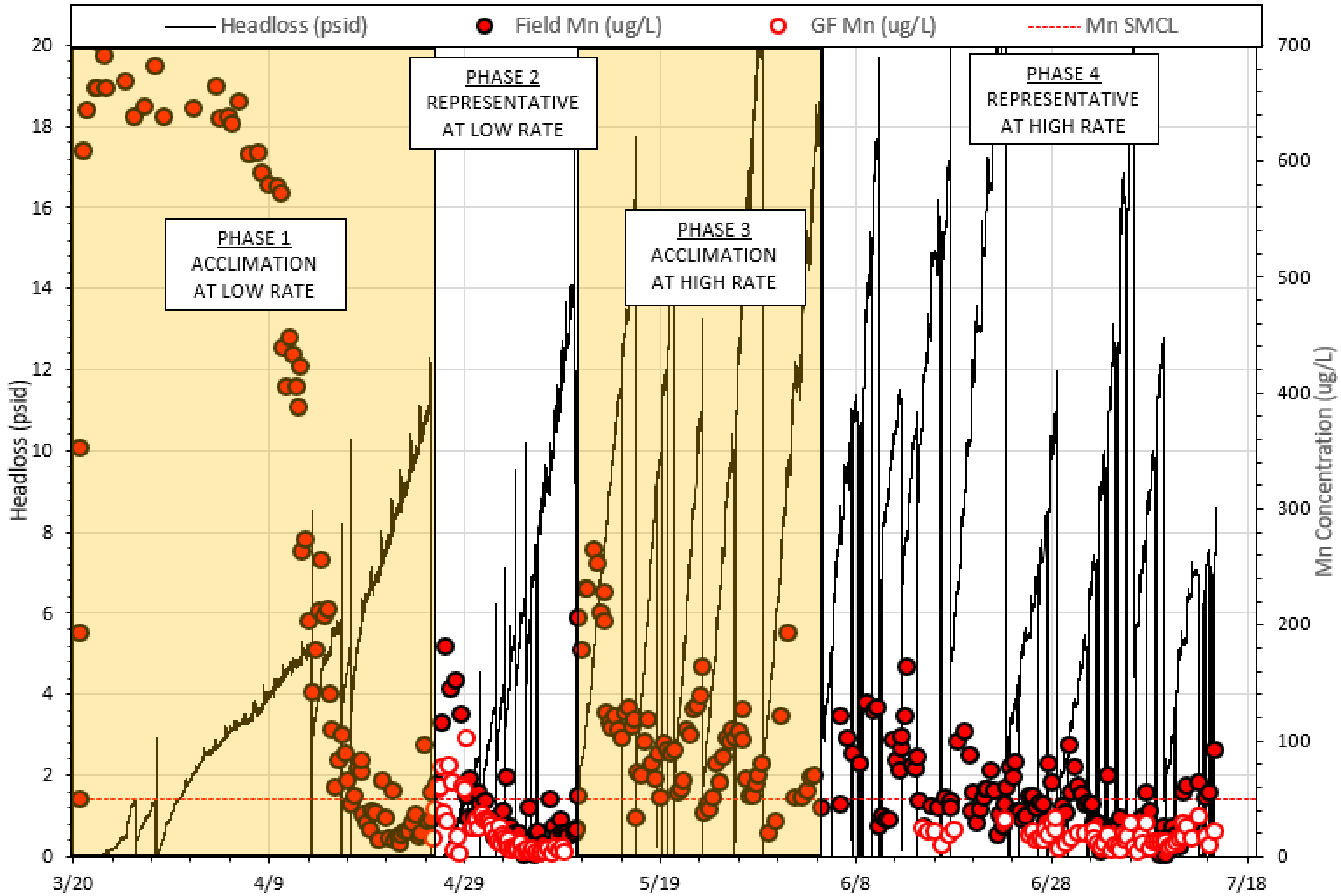


Figure 4.10: Filter M2 Operational Data for Pilot Duration



4.3.2 Biological Filtration Effectiveness for Fe and Mn Removal

Figure 4.11 shows the effluent iron concentrations M1 and M2 measured by field analyses organized by filter surface loading rate (gpm/sf). Water quality data which was not representative of normal operation was excluded from the figures and statistical analysis. In particular, the following data was omitted:

- All data from Phase 1 and Phase 3 was omitted because the filters were not acclimated
- All data collected after 10 psi of different pressure across the filter

Figure 4.11 shows all effluent iron concentrations detected in biological filter effluent were below the SMCL (Fe < 0.30 mg/L) and on average were below the project goal for effluent iron (Project Goal Fe < 0.10 mg/L). On average, the effluent iron concentration from M1 did not change while operating at either the low (5 gpm/sf) or high (10 gpm/sf) loading rate. On average, the effluent iron concentration from M2 appeared to decrease when increasing from the low loading rate (5 gpm/sf) to the high loading rate (15 gpm/sf).

All representative iron samples from both filters were below the SMCL for iron, but not all samples were below the project goal. To determine if the biological pilot filters met the project goal, a t-test was performed. The results of the t-test for iron concentrations detected in filter effluent are shown in Table 4.04.

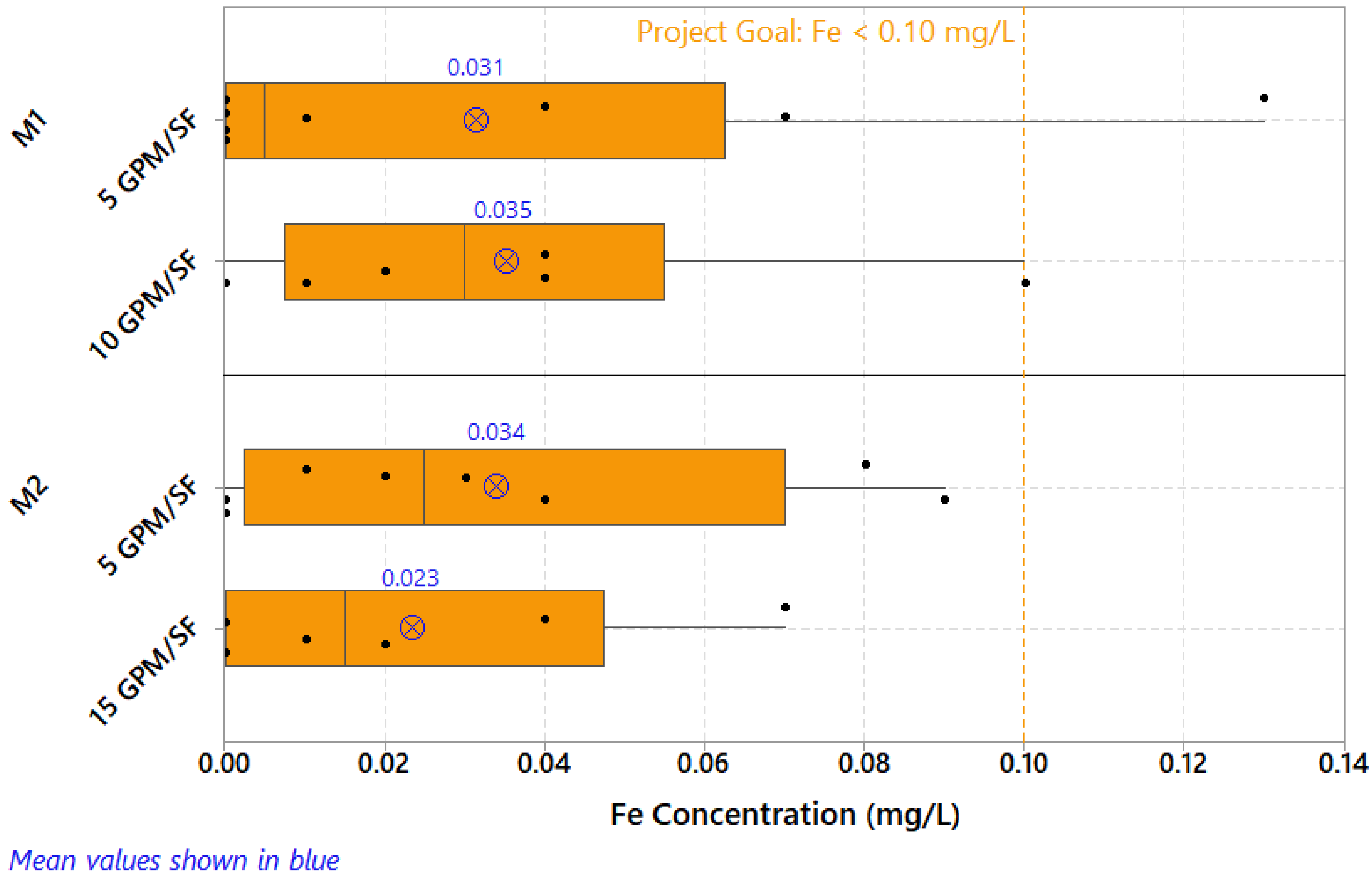
Table 4.04: Results of t-test for Effluent Iron versus Project Goal

Test of μ = 0.1 vs < 0.1

Variable	N	Mean	StDev	SE Mean	95% Upper Bound	T	P
M1 (5 GPM/SF)	8	0.031	0.047	0.017	0.063	-4.11	0.002
M1 (10 GPM/SF)	6	0.035	0.036	0.015	0.064	-4.47	0.003
M2 (5 GPM/SF)	8	0.034	0.035	0.012	0.057	-5.41	0.000
M2 (15 GPM/SF)	7	0.023	0.027	0.011	0.046	-6.87	0.000

Table 4.06 shows the p-values for each of the data sets (highlighted in yellow) subject to the t-test were below the alpha (0.05). This result concludes each of the biological pilot filters at both the low and high loading rates met the project goal with greater than 95% confidence. For each data set, the 95% upper bound has been highlighted in green. The 95% upper bound is the value 95% of the data in the data set are below.

Figure 4.11: Total Iron Concentration in Biological Filter Effluent from HACH Field Analysis



Four laboratory samples were taken from filter effluent, two from each filter, and analyzed for total iron. One set of samples were taken during representative operations at the low loading rate and the other set of samples were taken during representative operations at the high loading rate. All four results for total iron were determined to be below the laboratory limit (BDL Fe < 0.050 mg/L).

In order to determine if any statistically significant difference existed between effluent iron concentrations when operating at either of the evaluated loading rates, an ANOVA was performed. The results of the ANOVA are shown in Table 4.05.

Table 4.05: Results of ANOVA for Effluent Iron versus FSLR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	3	0.001	0.000	0.12	0.948
Error	25	0.034	0.001		
Total	28	0.035			

Factor	N	Mean	StDev	95% CI
M1 (5 GPM/SF)	8	0.031	0.047	(0.004, 0.059)
M1 (10 GPM/SF)	6	0.036	0.036	(0.003, 0.067)
M2 (5 GPM/SF)	8	0.034	0.035	(0.006, 0.061)
M2 (15 GPM/SF)	6	0.023	0.027	(-0.009, 0.055)

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
M1 (5 GPM/SF)	8	0.031	A
M1 (10 GPM/SF)	6	0.035	A
M2 (5 GPM/SF)	8	0.034	A
M2 (15 GPM/SF)	7	0.023	A

The results of the ANOVA shown in Table 4.05 determined a p-value of 0.948 when comparing the four data sets. This p-value concludes there is no statistically significant difference in effluent iron.

Figure 4.12 shows the effluent manganese concentrations M1 and M2 measured by field analyses organized by filter surface loading rate (gpm/sf). Water quality data which was not representative of normal operation was excluded from the figures and statistical analysis. In particular, the following data was omitted:

- All data from Phase 1 and Phase 3 was omitted because the filters were not acclimated
- All data collected after 10 psi of different pressure across the filter

Figure 4.12 shows the majority of effluent manganese concentrations detected in biological filter effluent were below the SMCL (Mn < 0.05 mg/L) and on average were below the project goal for effluent manganese (Project Goal Mn < 0.05 mg/L). On average, the effluent manganese concentration from M1 did not change while operating at either the low (5 gpm/sf) or high (10 gpm/sf) loading rate. On average, the effluent manganese concentration from M2 appeared to decrease when increasing from the low loading rate (5 gpm/sf) to the high loading rate (15 gpm/sf).

The majority of representative manganese samples from both filters were below the project goal for manganese, but not all. To determine if the biological pilot filters met the project goal, a t-test was performed. The results of the t-test for manganese concentrations detected in filter effluent are shown in Table 4.06.

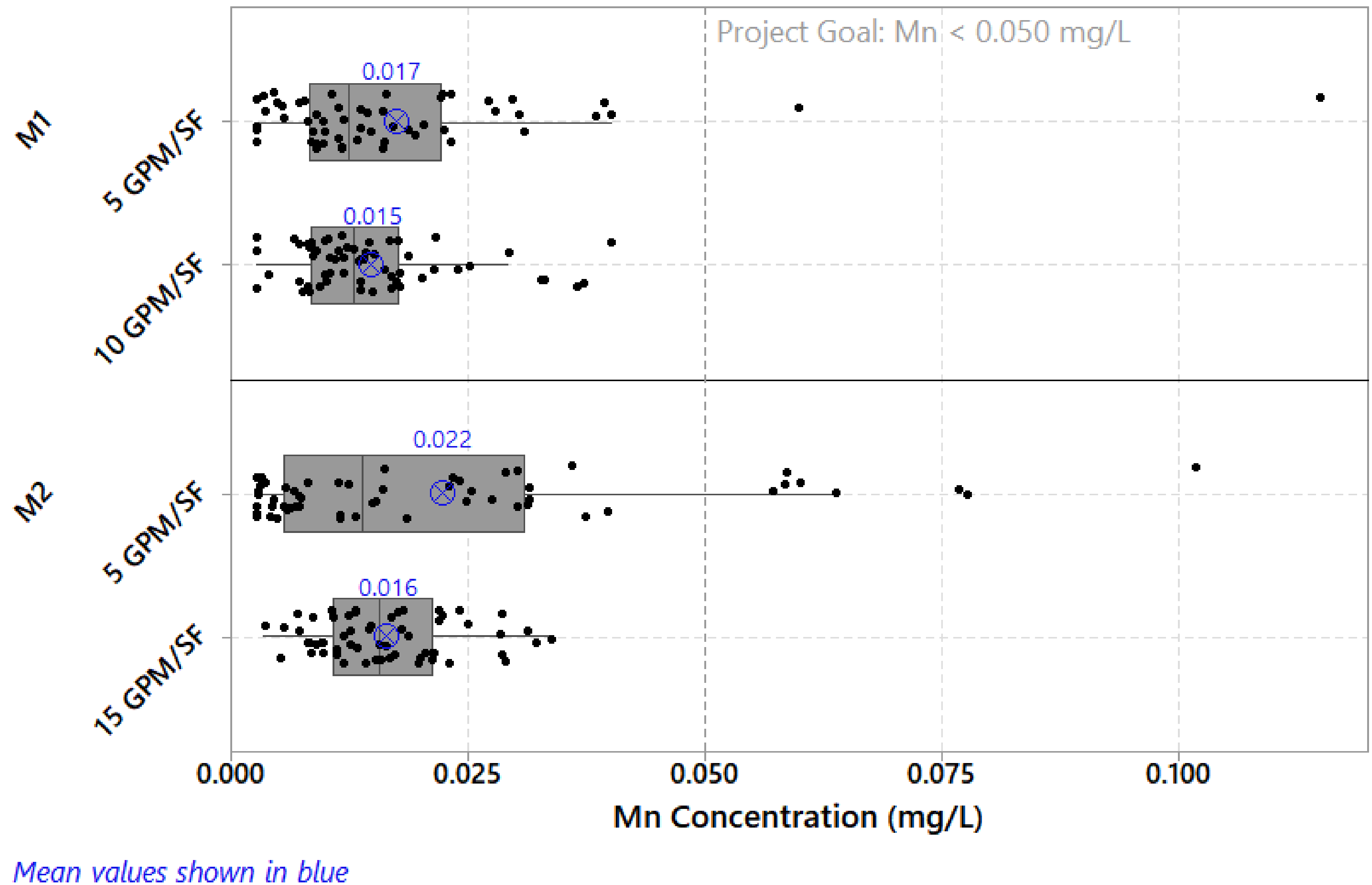
Table 4.06: t-test, Mn Concentrations in Biological Filter Effluent versus Project Goal

Test of μ = 0.05 vs < 0.05

Variable	N	Mean	StDev	SE Mean	95% Upper Bound	T	P
M1 (5 GPM/SF)	56	0.017	0.017	0.002	0.021	-14.05	0.000
M1 (10 GPM/SF)	59	0.015	0.009	0.001	0.016	-31.98	0.000
M2 (5 GPM/SF)	56	0.022	0.023	0.003	0.027	-9.14	0.000
M2 (15 GPM/SF)	59	0.016	0.007	0.001	0.018	-35.71	0.000

Table 4.06 shows the p-values for each of the data sets (highlighted in yellow) subject to the t-test were below the alpha (0.05). This result concludes each of the biological pilot filters at both the low and high loading rates met the project goal with greater than 95% confidence. For each data set, the 95% upper bound has been highlighted in green. The 95% upper bound is the value 95% of the data in the data set are below.

Figure 4.12: Total Manganese Concentration in Biological Filter Effluent from GF Analysis



Four laboratory samples were taken from filter effluent, two from each filter, and analyzed for total manganese. One set of samples were taken during representative operation at the low loading rate and the other set of samples were taken during representative operation at the high loading rate. All four samples analyzed for total manganese were below the project goal. The samples taken while operating at the low loading rate were 0.0032 and 0.0029 mg/L for M1 and M2, respectively. The samples taken while operating at the high loading rate were 0.01497 and 0.03466 mg/L for M1 and M2, respectively.

In order to determine if any statistically significant difference existed between effluent manganese concentrations when operating at either of the evaluated loading rates, an ANOVA was performed. The results of the ANOVA are shown in Table 4.07.

Table 4.07: Results of ANOVA for Effluent Manganese versus FSLR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	3	0.001859	0.000620	2.67	0.048
Error	226	0.052462	0.000232		
Total	229	0.054321			

Factor	N	Mean	StDev	95% CI
M1 (5 GPM/SF)	56	0.017	0.017	(0.013, 0.021)
M1 (10 GPM/SF)	59	0.015	0.009	(0.011, 0.018)
M2 (5 GPM/SF_	56	0.022	0.023	(0.018, 0.026)
M2 (15 GPM/SF)	59	0.016	0.007	(0.012, 0.020)

Grouping Information Using the Tukey Method and 95% Confidence

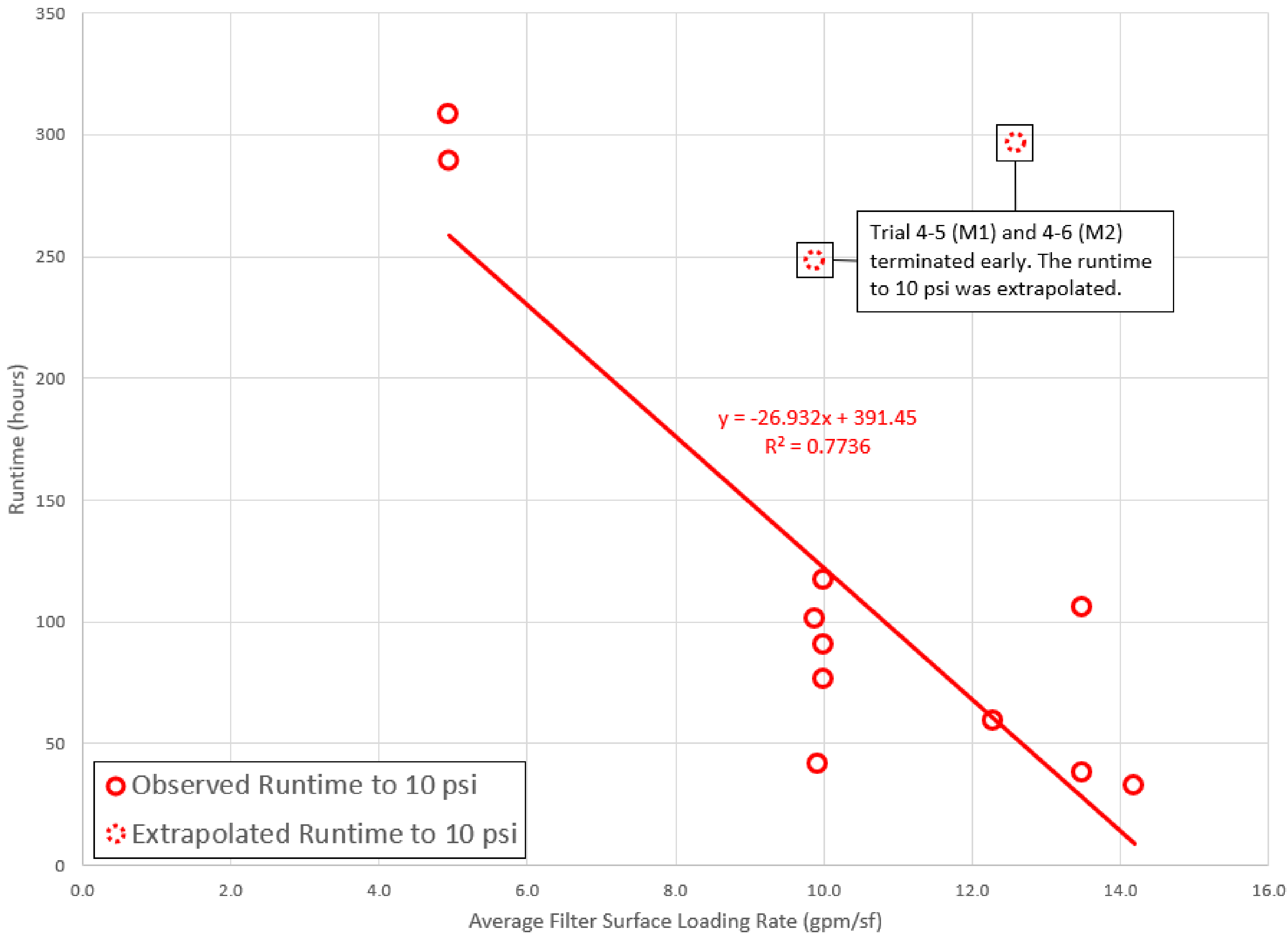
Factor	N	Mean	Grouping
M1 (5 GPM/SF)	56	0.017	A B
M1 (10 GPM/SF)	59	0.015	B
M2 (5 GPM/SF)	56	0.022	A
M2 (15 GPM/SF)	59	0.016	A B

The results of the ANOVA shown in Table 4.07 determined a p-value of 0.048 when comparing the four data sets. This p-value concludes there was a statistically significant difference between one or more of the data sets. Based on the grouping by the Tukey Method, the difference between effluent manganese concentrations was not statistically significant when operating at 5 gpm/sf and the increased loading rate (M1 at 10 gpm/sf and M2 at 15 gpm/sf) for each biological pilot filter, respectively. In addition, the difference between effluent manganese concentrations was not statistically significant for each individual filter when the loading rate was increased from the low rate to the high rate. The grouping shows the statistically significant difference existed between M1 operating at 10 gpm/sf and M2 operating at 5 gpm/sf.

4.3.3 Filter Runtime vs Loading Rate

Figure 4.13 plots the projected or observed runtime to a differential pressure of 10 psi. Markers with a solid outline represent the actual time for the filter to reach 10 psi, while markers with a dotted outline represent projects for the time to reach 10 psi based on headloss data collected. The lines show are fitted trendlines for either observed or extrapolated runtimes.

Figure 4.13: Filter Runtime versus FLSR for Biological Filters



Filter runtimes were a function of the solids loading onto the media, both from the raw water iron and manganese concentrations and the loading rates. All trials were observed to a differential pressure of 10 psi with the exception of the final trial for each respective filter (4-5 for M1 and 4-6 for M2) which was terminated early due to the conclusion of the study.

4.4 COMPARISON OF GREENSAND AND BIOLOGICAL FILTRATION PROCESSES

4.4.1 Comparison of Pretreatment Conditions and Effectiveness

Pretreated water quality data presented in Table 3.07 through 3.09 was used to determine the fraction of iron and manganese that was precipitated by the process pretreatment. The individual values were used to calculate the fraction of total iron and manganese which had been precipitated by pretreatment. The percentage is calculated using the following formula:

$$Precipitated\ Fraction = \left[1 - \left(\frac{dissolved\ metal}{total\ metal}\right)\right]$$

The precipitated fraction of iron and manganese was calculated for each sample where both total and dissolved metal concentrations were measured.

Knowing the relative fractions of precipitated iron and manganese is useful in determining the removal mechanism for each contaminant. For instance, it is generally believed that iron removal through a greensand filter is through precipitation and filtration while manganese removal is through adsorption, so it is expected that the fraction of precipitated Fe is high and fraction of precipitated Mn is low. The percent precipitated in filter influent for both piloted processes in shown in Figure 4.14 and 4.15 for iron and manganese, respectively.

Figure 4.14: Precipitated Fraction of Iron in Pretreated Samples from Field Analysis

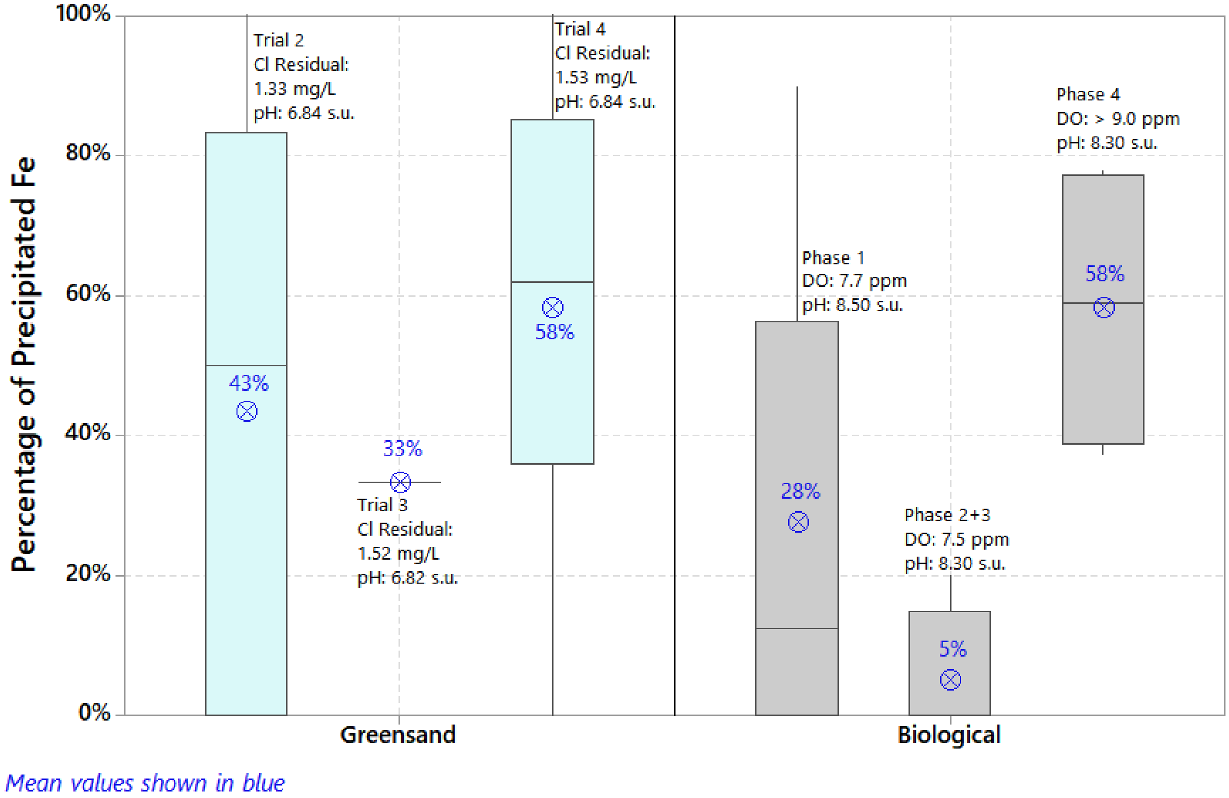


Figure 4.14 shows that the chlorine addition and pH adjustment upstream of the greensand filters oxidized iron to 33-58%, on average. The figure also shows the addition of air and pH adjustment upstream of the biological filters oxidized iron to 5-60%, on average. Typical pilot studies, particular using chlorine addition upstream of greensand filters, it would be expected these percentages to be closer to 100% or iron may not be entirely oxidized and therefore not removed by the pilot filters. The raw iron concentration detected from the Oakdale Well was typically at or below the estimated detection limit for the field method (Fe < 0.04 mg/L). This may cause the detected concentrations of total iron in raw water and dissolved iron in pretreated samples to be variable and may appear to not be oxidized prior to filtration. Due to the low effluent iron concentrations from both the greensand pilot filters and biological pilot filters, it can be assumed iron was adequately oxidized for during both treatment processes.

Figure 4.15: Precipitated Fraction of Manganese in Pretreated Samples from Field Analysis

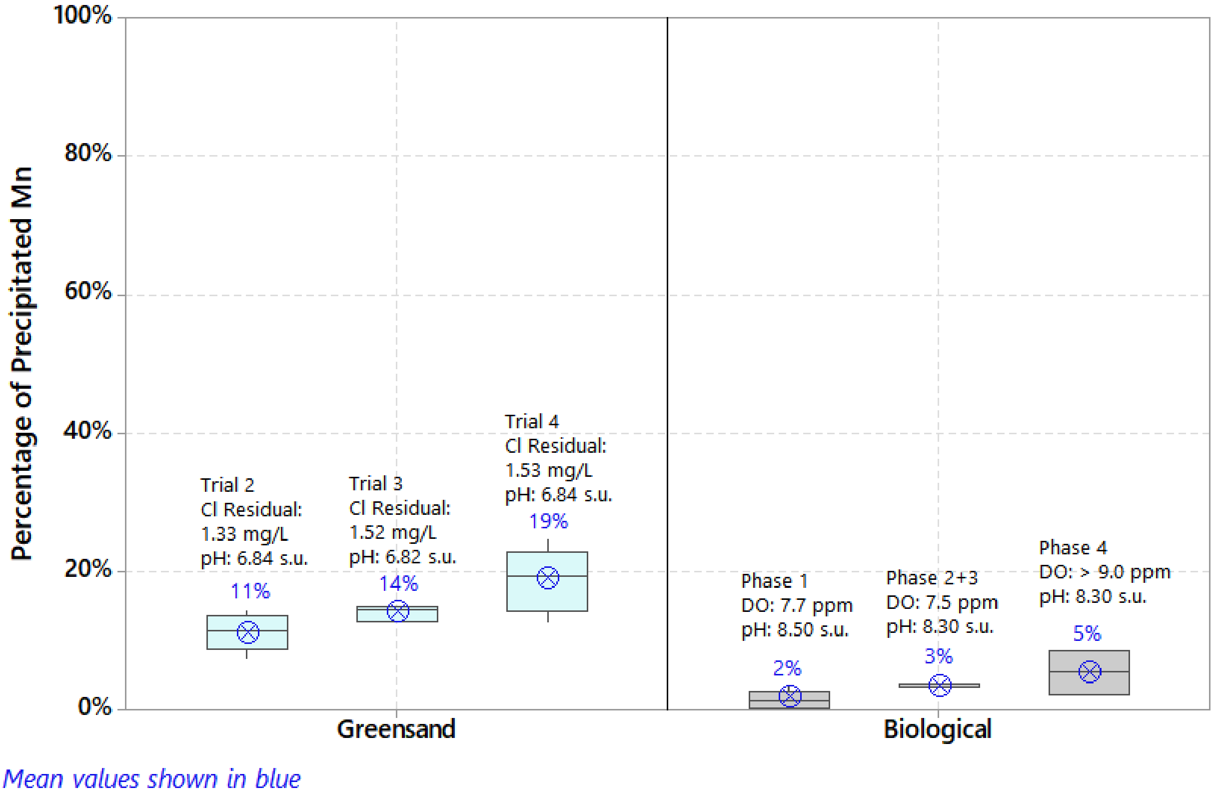


Figure 4.15 shows chlorine addition and pH adjustment upstream of the greensand filters oxidized between 11-19%, on average. The figure also shows the addition of air and pH adjustment upstream of the biological filters oxidized between 2-5%, on average. The low percentage of precipitated manganese in all filters is expected because the mechanism for removal is adsorption in all filters.

4.4.2 Comparison of Water Quality (Fe and Mn)

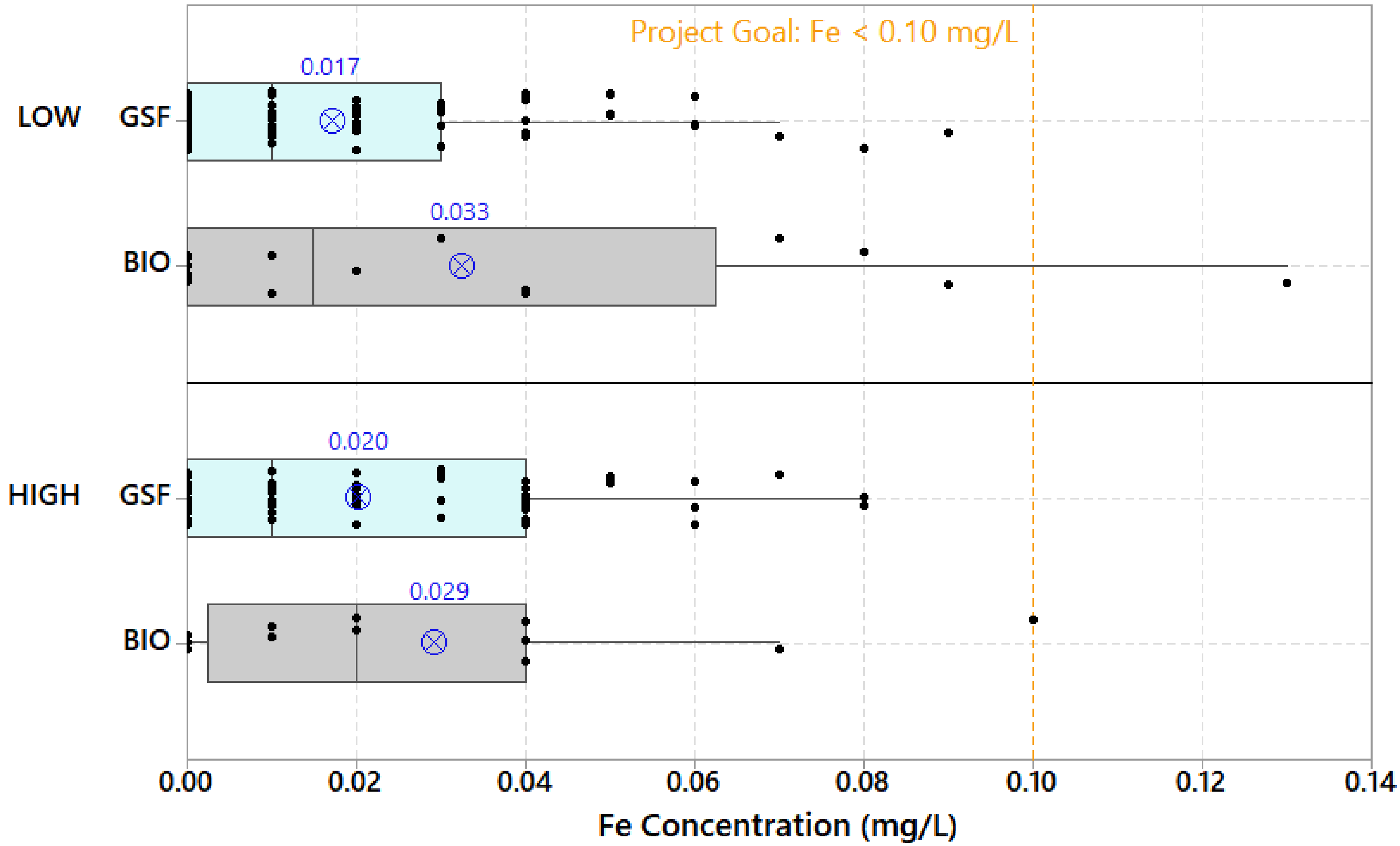
In order to compare the effluent water quality of both greensand Filtration (GSF) and Biological Filtration, the data sets were split into "Low" or "High" loading rates. Table 4.08 shows how the loading rates for each process were categorized.

Table 4.08: High and Low Loading Rates by Process

Process	Code	FSLR
GSF	LOW	4, 5 gpm/sf
	HIGH	6, 7 gpm/sf
M1	LOW	5 gpm/sf
	HIGH	10 gpm/sf
M2	LOW	5 gpm/sf
	HIGH	15 gpm/SF

Figure 4.16 shows the representative iron concentrations in filter effluent from field analyses organized by pilot process and high or low filter surface loading rate. Figure 4.17 shows the representative manganese concentrations in filter effluent from grab samples later analyzed by BLI's graphite furnace organized by pilot process and high or low filter surface loading rate. "GSF" in filter effluent water quality from all four of the greensand pilot filters.

Figure 4.16: Total Iron Concentrations in Filter Effluent (GSF, BIO) from Field Analysis



Mean values shown in blue

Figure 4.17: Total Mn Detected in Filter Effluent (GSF, BIO) from Field Analysis/GF Method

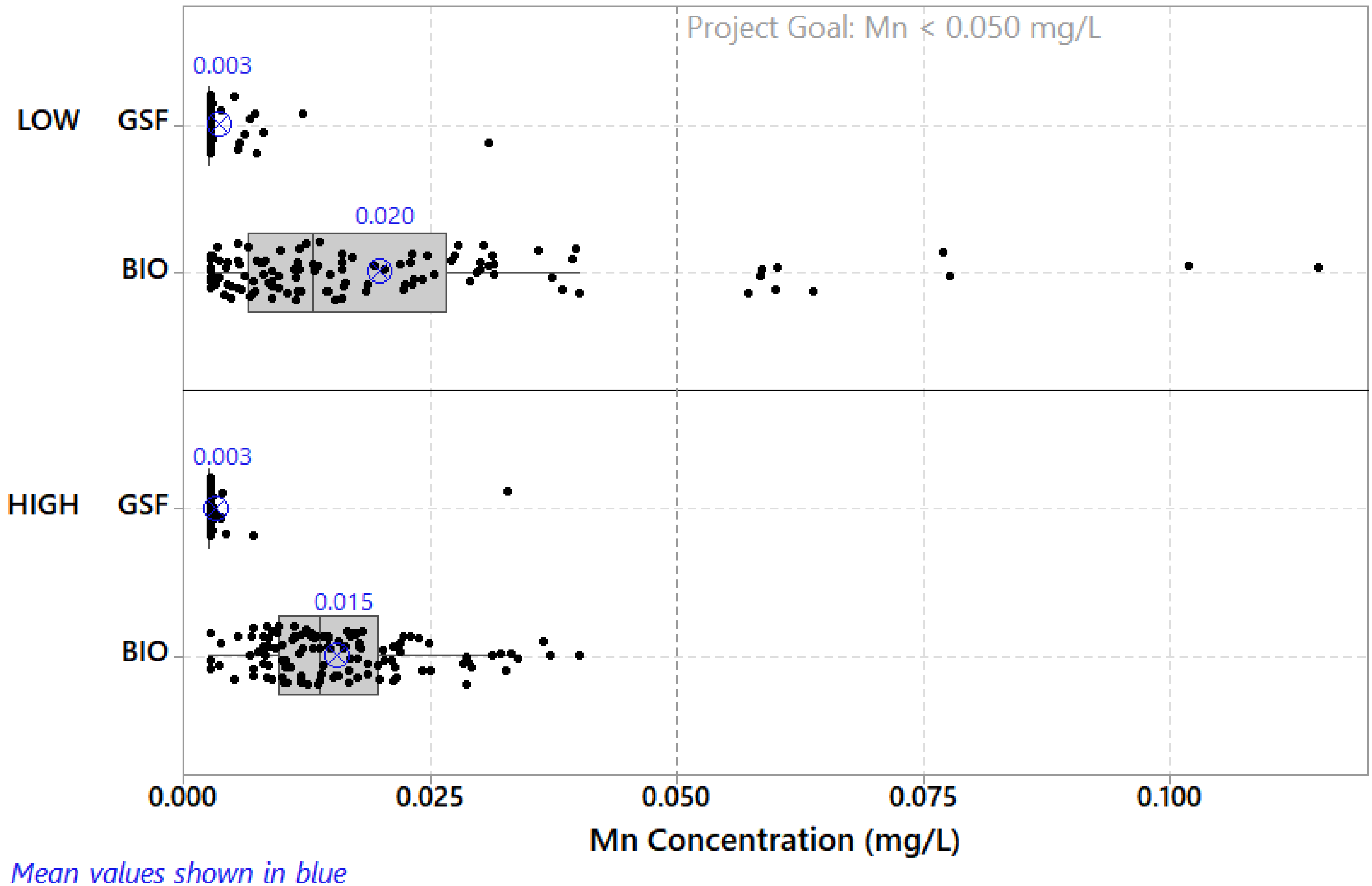


Figure 4.16 shows GSF produced effluent iron concentrations that were, on average, lower than the biological filters. At the low loading rates, the average iron concentrations from GSF was approximately half the average iron concentrations from the biological filters. At the high loading rates, the average iron concentration from GSF was also less than the biological filters, however the spread of observed effluent iron concentrations was similar between the two processes.

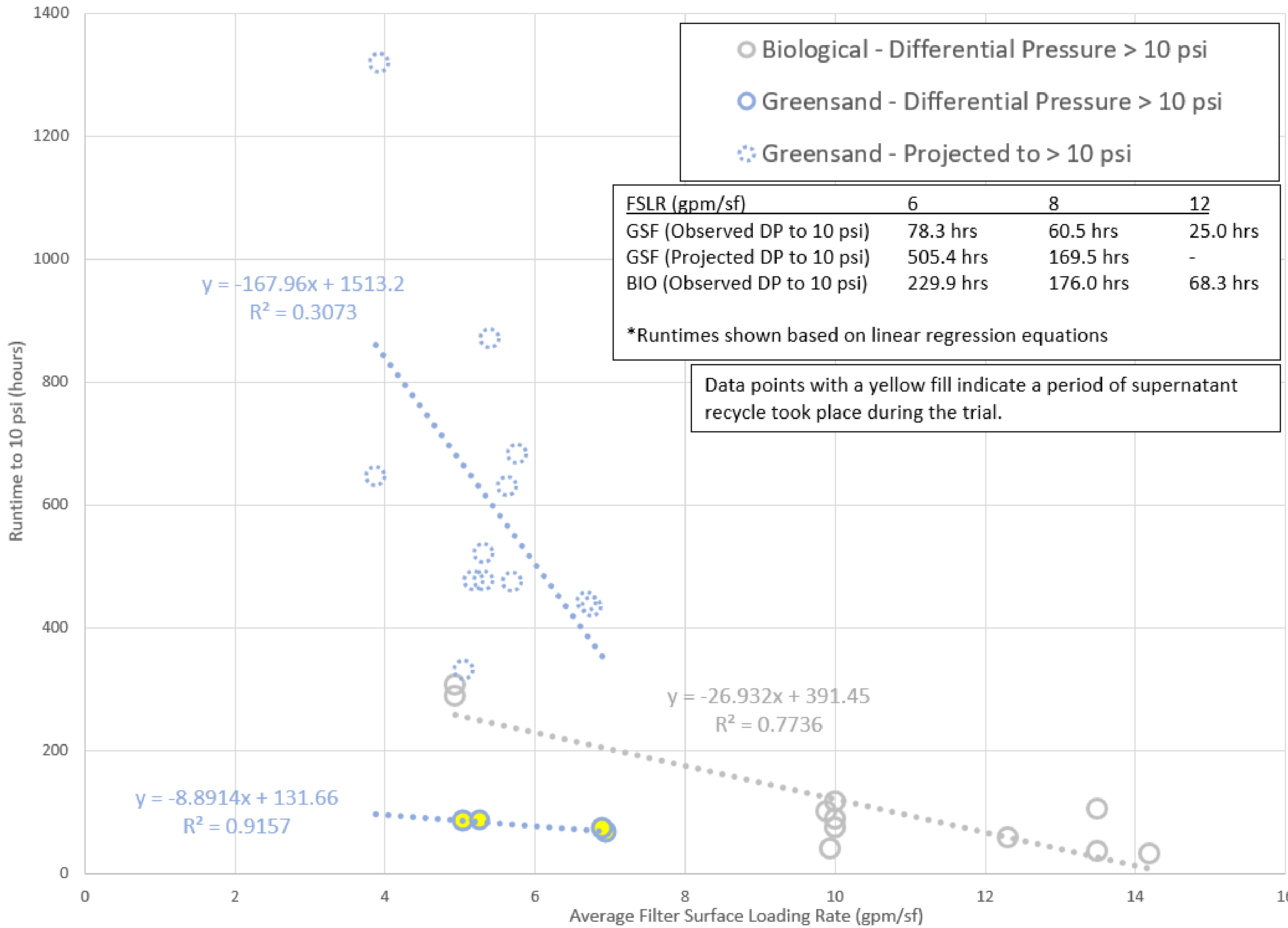
Figure 4.17 shows GSF produced effluent manganese concentrations were, on average, lower than the biological filters. At the low loading rates, effluent manganese concentrations were typically non-detect by the graphite furnace methods, while effluent manganese concentrations from the biological filters were at times above the project goal. At the high loading rates, effluent manganese concentrations were typically non-detect (GF Detection Limit Mn = 0.003 mg/L) by the graphite furnace methods, while effluent manganese concentrations from the biological filters were 0.015 mg/L, on average, and all met the project goal.

4.4.3 Comparison of Hydraulic Filter Performance

Figure 4.18 shows the observed runtime for different FLSR for both the greensand filters (Filters A – D) and both biological filters (M1, M2). For the purposes of comparing hydraulic performance, three loading rates (6, 8, and 12 gpm/sf) are shown in a table in the plot along with expected runtimes for the biological filters (observed to 10 psi) and the greensand filters (observed and project to 10 psi). The expected runtimes were calculated using the linear regression equations created for each data set, respectively.

The figure shows the greensand filters are expected to have much longer runtimes than the biological filters, based on the projected runtimes of the greensand filters due to limited terminal headloss observed during the greensand study. The regression for the projected runtime to 10 psi for the greensand filter does however had a large negative slope, much larger than the biological filters, which suggests increasing the loading rate could significantly decrease the filter runtime while it may not have as big an effect on the biological filters.

Figure 4.18: Filter Runtime versus FLSR for all Pilot Filters (GSF, F1/M1, FM2)



FSLR (gpm/sf)	6	8	12
GSF (Observed DP to 10 psi)	78.3 hrs	60.5 hrs	25.0 hrs
GSF (Projected DP to 10 psi)	505.4 hrs	169.5 hrs	-
BIO (Observed DP to 10 psi)	229.9 hrs	176.0 hrs	68.3 hrs

5 CONCLUSIONS

RAW WATER QUALITY CONCLUSIONS

1. Oakdale Well: Based on the field analyses, the median total manganese, total iron, and pH were:
   i. Median total Fe = 0.05 mg/L
   ii. Median total Mn = 0.764 mg/L
   iii. Median pH = 6.50 s.u.
2. Raw iron stayed consistent throughout the study and statistical analysis showed it was consistent with historical data.
3. Raw manganese concentrations increased marginally towards the middle of the study (May) and decreased until the end of the study (July). These variations were however did not appear to be significant. Statistical analysis showed the raw manganese concentrations observed during the pilot study was similar to historical data.

GREENSAND PILOT CONCLUSIONS

4. Oxidation with sodium hypochlorite (NaOCl) on average precipitated variable percentages of dissolved iron (33-58%). This is likely due to the low concentrations of raw iron and the estimated detection limit of the iron field method.
5. Oxidation with NaOCl precipitated dissolved manganese between 11-19% on average. This is to be expected due to the primary removal mechanism for greensand filtration is adsorption.
6. The doses of NaOCl were between 50.6 - 81.1 ppm 6% NaOCl to maintain a target free chlorine residual in filter effluent of 0.8 mg/L. Assuming a chlorine stock strength of 6%, the doses of Cl_2 were between 3.7-5.8 mg/L.
7. KOH was used to adjust pH from a raw pH of 6.5 to a target of 6.8 s.u. The KOH dose response curve indicates that a dose of approximately 2.0 mg/L of KOH is necessary for this adjustment. The KOH doses used in the greensand pilot study were 13.3-23.4 mg/L.
8. All filter trials met the Project Goal for total Fe and Mn of 0.10 and 0.050 mg/L, respectively. 100% of the Fe and Mn data were below the goal.
9. Filter run times were generally limited by the pilot schedule. The only filter trials which reached a differential pressure of 10 psi was during Trial 4, the supernatant recycle trial. The first three trials were terminated early based on the pilot schedule and the runtimes to 10 psi were estimated. Estimated runtimes to 10 psi were determined by fitting a linear regression to recorded headloss data.
10. Runtimes to 10 psi were observed during the supernatant recycle trial. Runtimes ranged from 87.1 hours operating at 5 gpm/sf to 67.1 hours operating at 7 gpm/sf.
11. Projected runtimes to 10 psi ranged from 1320.0 hours operating at 4 gpm/sf to 434.9 hours operating at 7 gpm/sf.
12. Recycling suspended supernatant did not appear to have a significant impact on filter performance.

BIOLOGICAL PILOT CONCLUSIONS

13. The biological pilot filter, M1, acclimated at the low loading rate (5 gpm/sf) in approximately 673 hours and reacclimated at the high loading rate (10 gpm/sf) in approximately 747 hours.
14. The biological pilot filter, M2, acclimated at the low loading rate (5 gpm/sf) in approximately 864 hours and reacclimated at the high loading rate (15 gpm/sf) in approximately 747 hours.
15. Filter M1 and M2 met the Project Goal for Total Fe with 95% confidence at all loading rates. There was not a statistically significant difference in Effluent Fe from either biological filter at all evaluated loading rates.
16. Filter M1 and M2 met the Project Goal for Total Mn with 95% confidence at all loading rates. The only statistically significant difference in Effluent Mn from either biological filter at all evaluated loading rates was between M1 operating at 10 gpm/sf and M2 operating at 5 gpm/sf.
17. Filter M1 operated at a target of 5 gpm/sf for 308.3 hours before reaching a differential pressure of 10 psi. At a target of 10 gpm/sf, M1 ran for 41.2 – 117.0 hours before reaching a differential pressure of 10 psi.
18. Filter M2 operated at a target of 5 gpm/sf for 289.5 hours before reaching a differential pressure of 10 psi. At a target of 15 gpm/sf, M2 ran for 32.3 – 105.6 hours before reaching a differential pressure of 10 psi.

COMPARISON OF ALTERNATIVE FILTRATION TECHNOLOGIES CONCLUSIONS

19. Pretreatment:
    i. Greensand and Biological Filtration both relied on pH adjustment with KOH.
    ii. Greensand filtration achieved effective oxidation with sodium hypochlorite for a high fraction of precipitated iron and manganese necessary for removal by adsorption and physical entrapment.
    iii. Biological filtration achieved oxidation by air injection to adjust DO to concentrations suitable for a healthy biomass within the filter bed and is not intended to precipitate iron and manganese which should remain in their dissolved form for proper biological treatment.
20. Water Quality:
    i. Iron Removal at Low Loading Rate: Greensand and Biological Filtration effectively removed iron to below the pilot study goal of 0.10 mg/L. The mean effluent concentrations were:
        a. Greensand Filtration (A/B/C/D): 0.017 mg/L
        b. Biological Filtration (M1/M2): 0.033 mg/L
    ii. Iron Removal at High Loading Rate: Greensand and Biological Filtration effectively removed manganese to below the pilot study goal of 0.05 mg/L. The mean effluent concentrations were:
        a. Greensand Filtration (A/B/C/D): 0.020 mg/L
        b. Biological Filtration (M1/M2): 0.029 mg/L
    iii. Manganese Removal at Low Loading Rate: Greensand and Biological Filtration effectively removed manganese to below the pilot study goal of 0.05 mg/L. The mean effluent concentrations were:

   a. Greensand Filtration (A/B/C/D): 0.003 mg/L
   b. Biological Filtration (M1/M2): 0.020 mg/L

iv. Manganese Removal at High Loading Rate: Greensand and Biological Filtration effectively removed manganese to below the pilot study goal of 0.05 mg/L. The mean effluent concentrations were:
   a. Greensand Filtration (A/B/C/D): 0.003 mg/L
   b. Biological Filtration (M1/M2): 0.015 mg/L

29. Blueleaf believes that the Greensand process is more suited to treatment at the Oakdale site. The biological process was difficult to start at Oakdale and operated inconsistently.
    i. In general, many trials had periods with high effluent manganese concentrations. Of the 10 trials conducted for Filter M1, Table 3.14 shows that 9 trials had at least one manganese concentration that exceeded the SMCL. Of the 8 trials conducted for Filter M2, Table 3.15 shows that all 8 trials had at least one manganese concentration that exceeded the SMCL.
    ii. The greensand process worked very well at the Oakdale site, with consistently low Mn concentrations, high FSLRs and long run times.
30. Filter run times for the filtration technologies were compared at common loading rates. The runtimes were calculated from the linear equation equations which were fitted to each respective data set. At 6 gpm/sf, it is estimated greensand filtration would reach 10 psi after 505.4 hours, while biological filtration is estimated to last approximately half as long (229.9 hours). At 8 gpm/sf it is estimated greensand filtration would reach 10 psi after 60.5 hours.