APPENDIX D

UNIDIRECTIONAL FLUSHING PILOT EVALUATION TECHNICAL MEMORANDUM

confluence ENGINEERING GROUP LLC
517 NE 92nd Street, Seattle, WA 98115 ph (206) 527-6832 fx (206) 527-3148 confluence-engineering.com

FINAL TECHNICAL MEMORANDUM

To:	Chris Hill, Rebecca Slabaugh – ARCADIS	Date:	31-August-2017
From:	Andrew Hill, Melinda Friedman – Confluence	Project:	Flint Drinking Water Distribution System Optimization
cc:	Jim Cooper – ARCADIS	Subject:	Unidirectional Flushing Pilot Evaluation

INTRODUCTION

This Technical Memorandum summarizes key findings and observations associated with implementation of a unidirectional flushing (UDF) pilot in a small portion of the City of Flint's (City) water distribution system (DS). Also included are recommendations for full-scale UDF program application in the City's system.

PURPOSE AND APPROACH

The purpose of the UDF pilot was several-fold:

- Provide the City with UDF program startup support for eventual inclusion of UDF as a maintenance tool for responding to DS water quality upsets and as a preventative main cleaning strategy. This included developing protocols, identifying resources needed, and procuring equipment.
- Provide City crews with onsite hands-on training of Standard Operating Procedures (SOPs) related to UDF field practices and techniques.
- Evaluate flushing performance, effectiveness, and risks within the City's distribution system. This included velocity optimization and assessment of scale stability.

Confluence coordinated with City staff to identify a suitable pilot area to meet these objectives. The area studied is located immediately north of Thread Lake – see **Figure 1**. The local DS network is fed by an 18-inch transmission main running along Pingree Avenue (the designated clean water source) and includes a grid of 6-inch and 8-inch diameter unlined cast iron pipe. Confluence developed "loops" for this area and traveled to Flint to implement the pilot and train crews. Field activities were conducted June 27-28, 2017.

FIELD OBSERVATIONS

Key findings and conclusions from the UDF pilot field effort are provided in the following sections, organized to reflect three key areas of UDF application: (a) infrastructure and maps; (b) hydraulics; and (c) water quality.

Infrastructure and Maps

- There were a variety of infrastructure deficiencies that impeded effective UDF loop development and field progression (in addition to posing other challenges with system operation). For example:
    - Line valves are reportedly often paved over by streets department, even newly-installed and replacement valves. During the pilot, in the seven loops that were completed with Confluence, there were four valves (that needed to be turned to a closed position to ensure unidirectional flow) that were found to be paved over and thus could not be operated or closed.

    In some cases, a nearby alternate valve was identified that served the intended need. However, in one case, a paved-over valve had to be jack-hammered open to support the loop – see **Figure 2**.

  - Line valves cannot always be located or accessed. During the pilot, two separate valves that were shown on the system map could not be located and several others could not be operated due to a variety of reasons, e.g., broken, shifted in box, unable to key the operating nut, etc.
  - Line valves often get stuck in a closed position – see **Figure 3**.
  - Reportedly, fire hydrants are frequently damaged, in some cases due to vehicles driving into them. During the pilot, one hydrant could not be used because the bolts to the base flange were broken, allowing the hydrant to lift up and leak from the base – see **Figure 4**. Another hydrant could not be used due to damaged port threads.
  - System maps do not reflect these deficiencies. Therefore, in their current state, system maps cannot be used with much confidence to develop loops. As part of future UDF planning for a given area, it is imperative that the City conduct field reconnaissance to pre-inspect assets, make necessary repairs, and/or update the maps with asset status – all prior to loop development for the area.
- With regard to loop development, valves were not always conveniently located at intersections or junctions as needed to support UDF. This finding further complicates the loop development challenges associated with the infrastructure deficiencies noted above.
- The condition of the City's old unlined cast iron pipe appears to be relatively fragile.
  - Crews reported hundreds of main breaks per year, with most attributed to pressure transients from WTP finished water pumping operations.
  - There is moderate buildup of corrosion scale on UCI pipe, and the scale seems to be weakly-adhered and hydraulically-mobile. Regarding scale thickness, an 8-inch diameter unlined iron pipe specimen previously removed from the DS had an average scale thickness of one inch, with extreme roughness – see **Figure 5**. During flushing, tubercles were seen in the flush discharge stream when flushing at 450 gpm in an 8-inch diameter main (approximate velocity of 5 feet per second, or fps).

Local Hydraulics

- **Table 1** provides a summary of hydraulic conditions achieved for the seven pilot area loops completed while Confluence was onsite.
- Extreme flow rate limitations were observed throughout the area. Maximum attainable flow rates were, on average, about 360 gpm for 8-inch mains and 180 gpm for 6-inch mains. These flow rates correspond to flushing velocities in the range 3.5 to 5 feet per second (fps) based on an assumed average scale thickness of one inch (per Figure 5).
- When conducting UDF at these flow rates, crews received numerous customer complaints of negligible pressure or loss of service.
- The maximum attainable flow rate decreased sharply with increasing distance from the designated clean water source, i.e., the connection to the 18-inch transmission line at Pingree and Howard. This is indicative of significant headloss, potentially due to restrictions presented by scale buildup and a relatively high pipe roughness/friction factor.

- One crew member stated that closure of the 8-inch valve on the east branch of Lippincott/Howard (which was necessary to ensure unidirectional flow from the 18-inch transmission main clean water source) likely had a major impact on the attainable flow in the pilot area. This closed valve connects to additional gridded 8-inch and 6-inch mains to the east. This suggestion is contradicted by field data indicative of significant headloss over short distances, such that even the use of the nearby 18-inch transmission line resulted in flow limitations.
- In light of the asset deficiency issues noted previously, it is possible that there are one or more closed or partially closed valves in the area that restrict flow.
- Considering the various constraints and relatively low flow rates attained, it will be important to use hydraulic modeling (preferably via a UDF module) for future loop development. This will allow for quicker iteration of differing loop layout and progression schemes to determine how to most effectively prepare loops to achieve or approach target flow rates and maintain service to customers.

Table 1. Summary of Hydraulic Data from UDF Pilot

Pilot Loop #	Length (ft)	Flow Rate (gpm)	Pipe ID (in)		Flush Velocity (fps)		Time per PV (min)	Notes
			Nominal	Effective[1]	Nominal	Effective[1]		
1	375	450	8	6	2.9	5.1	1.2	Maxed out; Tubercles observed
2	810	400	8	6	2.6	4.5	3.0	Maxed Out
3	2,175	300	8	6	1.9	3.4	10.6	Broken Hydrant
4	2,600	300	8	6	1.9	3.4	12.7	Maxed Out
5	625	185	6	4	2.1	4.7	2.2	Maxed Out; could not close V20
6	1,125	150	6	4	1.7	3.8	4.9	Maxed Out
7	1,000	175	6	4	2.0	4.5	3.7	Maxed Out

1. Assumed average scale thickness of one inch

Local Water Quality

- **Table 2** provides a summary of flush water quality data obtained for pre-selected pilot area loops. These data represent the concentration of key constituents mobilized during the first pipe volume (PV) of flushing a given loop, i.e., *hydraulically-mobile accumulation*. They reflect a realistic release scenario associated with events such as main breaks, fire-fighting, construction activity, etc.

- Hydraulically-mobile deposit accumulation was highly variable between the loops. Order-of-magnitude concentration differences were observed between loops for several key constituents – see **Figure 6**.

Solids/Color

- The highest velocity tested (5 fps) sheared tubercles off from the pipe scale – see **Figure 7**. For all subsequent loops, the flushing flow rate was lowered such that the velocity was ≤ 5 fps. These lower velocities did not dislodge tubercles.
- Discolored (red/brown) discharge water was observed for all flushes. Turbidities reached as high as 375 NTU – see **Figure 8**.
- Turbidity gradually dropped to 10 NTU for each flushing loop, typically after about five PV – see **Figure 9**, which depicts the flush turbidity profile for Loop #2. The rate of turbidity decline slowed considerably as it neared 10 NTU, indicative of diminishing returns and suggesting that 10 NTU is an appropriate flush-terminating criterion to balance cleaning performance with resource utilization.

Table 2. Summary of Flush Water Quality Data from UDF Pilot

Pilot Loop #	Velocity (fps)	Elapsed Time (min)	PV Turnover	TSS (mg/L)	Turbidity (ntu)	Free Cl2 (mg/L)	AC (PtCo)	Fe (mg/L)	Fe:TSS (%)	Mn (mg/L)
3	3.4	0.2	0.0	114.0	200.0	0.1	31.0	42.35	37%	0.42
4	3.4	0.0	0.0	251.0	375.0	1.4*	38.0	61.73	25%	5.33
6	3.8	0.0	0.0	14.0	18.9	0.3	0.0	6.31	45%	0.55
6	3.8	4.0	0.8	13.0	3.9	0.6	10.0	2.42	19%	0.18
7	4.5	0.0	0.0	14.0	26.3	0.5	0.0	6.78	48%	0.08
7	4.5	3.5	0.9	45.0	75.5	0.1	0.0	12.03	27%	0.3

Pilot Loop #	Velocity (fps)	Elapsed Time (min)	PV Turnover	Pb (mg/L)	Ca (mg/L)	Al (mg/L)	PO4 (mg/L)	HPC-SPC (cfu/mL)	ATP (pg/mL)	TOC (mg/L)
3	3.4	0.2	0.0	0.008	28.1	0.94	14.4	132	49.1	1.89
4	3.4	0.0	0.0	0.002	28.1	3.77	27.3	33	21.8	3.94
6	3.8	0.0	0.0	< 0.001	28.1	0.51	4.2	26	0.55	2.05
6	3.8	4.0	0.8	< 0.001	28.1	0.23	3.2	2	0.22	2.37
7	4.5	0.0	0.0	0.006	28.1	0.31	3.8	10	0.72	2.18
7	4.5	3.5	0.9	0.001	30.5	1.34	12.6	97	8.83	2.25

*Probable Mn interference

Inorganics

- Iron (Fe) represented the most concentrated (identified) element of total suspended solids (TSS) removed by flushing, averaging 33% of deposit mass. As a result, Fe exhibited a strong correlation to turbidity (which itself had a near-perfect correlation to TSS) – see **Figure 10**. Iron concentrations in the flush discharge ranged from 2.4 to 62 mg/L, indicative of significant accumulation of hydraulically-mobile iron particulate and destabilized scale particles.
- Lead (Pb) was present in 4 of 6 flush samples, at levels up to 0.008 mg/L (8 ppb). Pb did not correlate with any other measured water quality parameter. Note that this finding of detectable Pb in DS deposits is not unusual or specific to Flint. To the contrary, Pb accumulation has been observed to some extent in numerous DS pipe and flush samples obtained from utilities throughout the country as a result of its tendency to adsorb/co-precipitate with various metal and phosphate-based solids (Friedman et al, 2010). The accumulation of hydraulically-mobile Pb on distribution system deposits represents a potential source of particulate Pb contribution to customer plumbing and consumer exposure. However, given that the levels observed during flushing were produced during extremely dynamic hydraulic conditions, they would not likely co-occur with levels that result from water stagnation (e.g., LCR sample conditions).
- High levels of orthophosphate buildup, i.e., in excess of 10 mg/L as PO_4, were observed in 3 of the 4 monitored loops. Orthophosphate strongly correlated to Fe (see **Figure 11**) and aluminum (Al), reflecting formation of Fe-PO4 and Al-PO4 precipitates on pipe surfaces, respectively. Orthophosphate also exhibited a strong correlation to turbidity – possibly via its association with Fe – further supporting the conclusion that turbidity serves as a good indicator parameter for multiple water quality constituents.
- Aluminum (Al) concentrations ranged from 0.2 to 3.8 mg/L, versus a secondary MCL of 0.05 to 0.2 mg/L. Therefore, removal of legacy Al is an additional benefit of UDF. Legacy Al accumulation

could be due to post-flocculation of Al coagulant and/or precipitation of residual Al with orthophosphate. In soft, aggressive waters, aluminum can also leach from cement-mortar lining; however, the iron pipe throughout the UDF pilot area was unlined.

- Legacy manganese (Mn) was detected in all flush samples. While most levels were low (< 0.5 mg/L) manganese was detected at 5 mg/L on Loop #4.

Microbials/Disinfection

- Cellular ATP – representative of viable microbial activity – ranged from 0.2 pg/mL (typically considered good control) to 49 pg/mL (corrective action recommended), indicating large spatial variability in pipe wall biofilm presence and stability. Heterotrophic plate count (HPC), which represents less than 1% of viable bacterial activity, correlated to ATP and thus demonstrated similar spatial variability.
- Microbial activity was inversely related to free chlorine residual – see **Figure 12**. A free chlorine residual of approximately 0.3 mg/L appeared to represent an inflection point between regions of good and poor microbial control.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

- In the piloted area of Flint's drinking water DS, there is a large accumulation of hydraulically-mobile deposits susceptible to hydraulic release and thus amenable to removal by UDF. These deposits include corrosion scale, microbially-active sediment, and precipitated forms of iron, aluminum, and orthophosphate. Flushing to remove total and hydraulically-mobile legacy accumulation and destabilized scale presents a meaningful opportunity to improve Flint's water quality.
- Flushing velocity control and monitoring of discharge water quality should be applied during UDF activities to optimize scouring performance while avoiding tubercle removal. A flushing velocity of 4 ± 0.5 fps (based on effective pipe diameter) appears optimal for the City's unlined cast iron pipe.
- The City should conduct water quality monitoring during flushing to ensure that cleaning objectives and water quality restoration goals are met. At a minimum, turbidity, free chlorine residual, and orthophosphate should be monitored during flushing.
- The City should develop and implement a routine asset inspection and maintenance program for its valves and hydrants. UDF cannot be reliably or cost-effectively implemented until an asset maintenance program is developed and applied. City maps should be updated in conjunction with asset inspection and maintenance activities to ensure that they reflect the status of system components.
- As part of future UDF planning for a given area, it is imperative that the City conduct field reconnaissance to pre-inspect assets, make necessary repairs, and update the maps with asset status.
- Given the fragile, aged condition of much of the City's unlined cast iron pipe, efforts to replace this pipe type should be accelerated and prioritized as part of the City's CIP. The replacement of these pipes will benefit hydraulic capacity, water quality, and reduce labor associated with dealing with frequent main breaks.

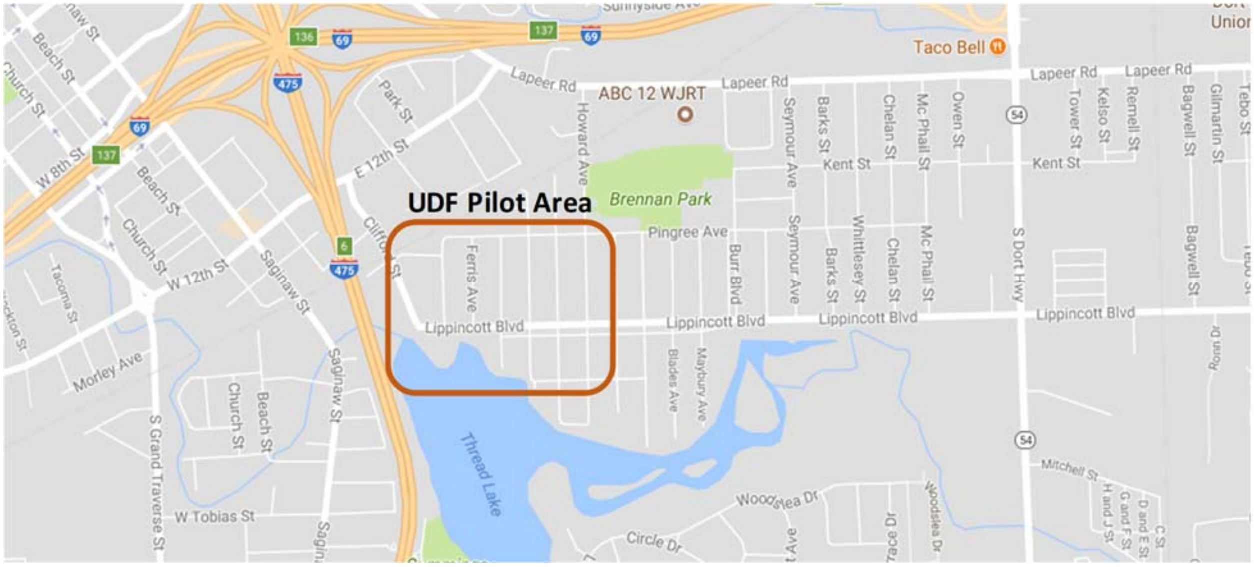

Figure 1. Location of Flint's Unidirectional Flushing Pilot Area

Figure 2. Jack-hammering needed to uncover paved valve on Loop #3.

Figure 3. Example gate valve stuck in closed position (located in City boneyard).

Figure 4. Hydrant for Loop #3 leaked due to broken bolts around the base flange.

Figure 5. Tuberculation and scale thickness in an 8-inch cast iron pipe removed from Flint's system.

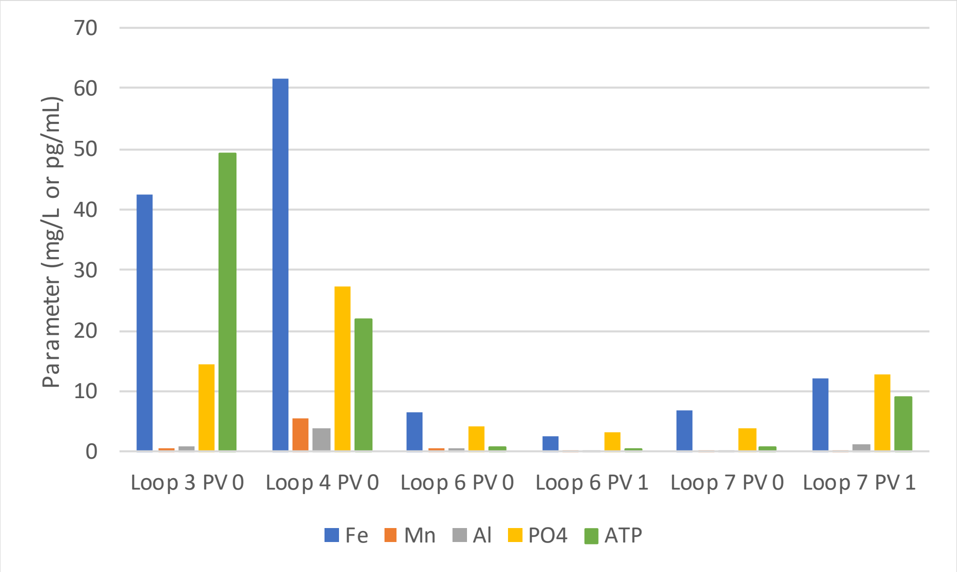

Figure 6. Flush water quality variability observed between loops.

Figure 7. Tubercles removed on Loop #1 at 5 fps flushing velocity.

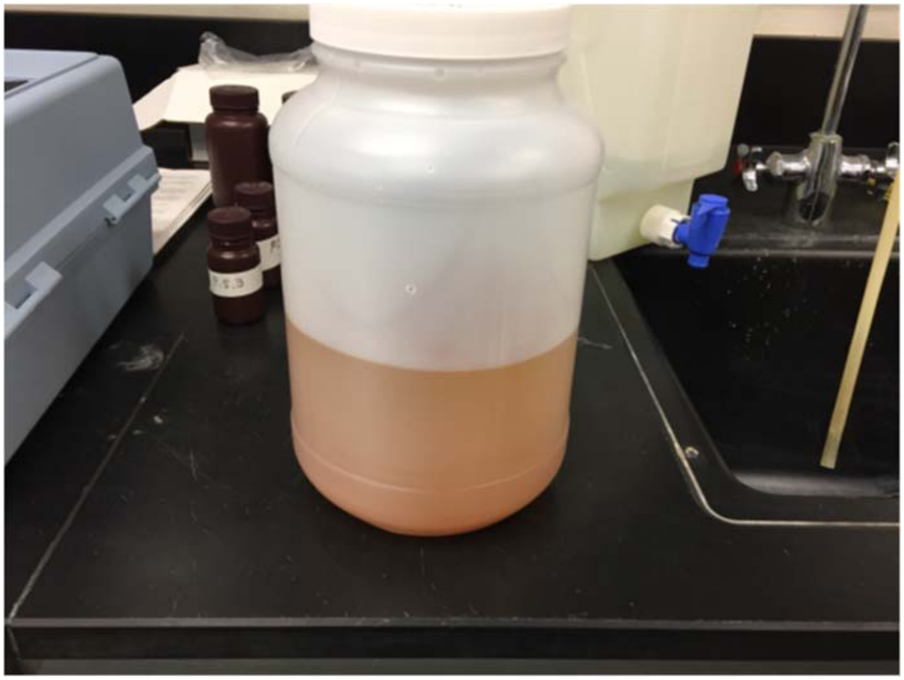

Figure 8. Flush turbidity of 375 NTU on Loop #4.

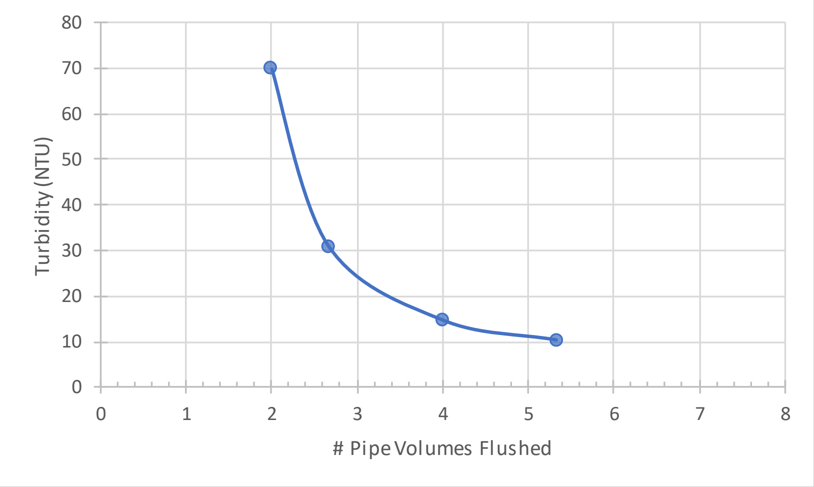

Figure 9. Turbidity profile for Loop #2.

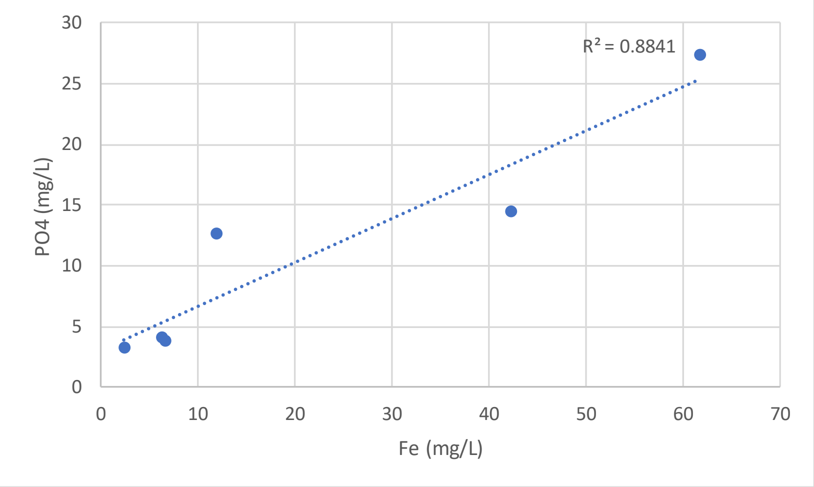

Figure 11. Correlation between orthophosphate and iron.

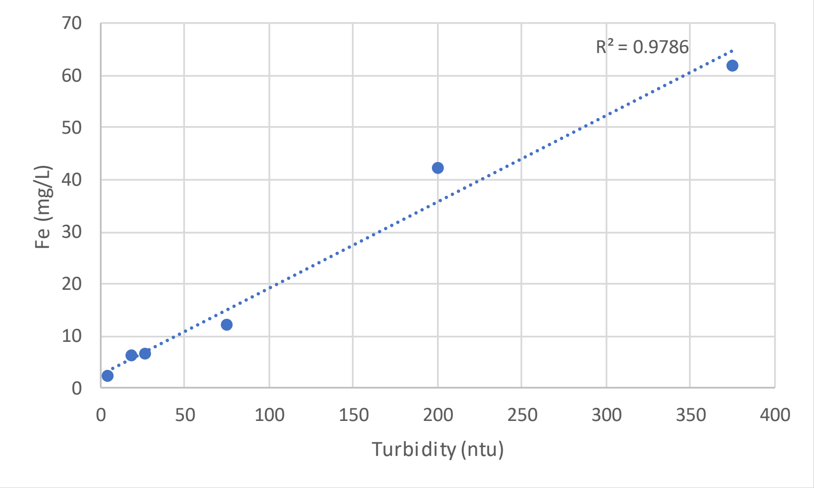

Figure 10. Correlation between iron and turbidity.

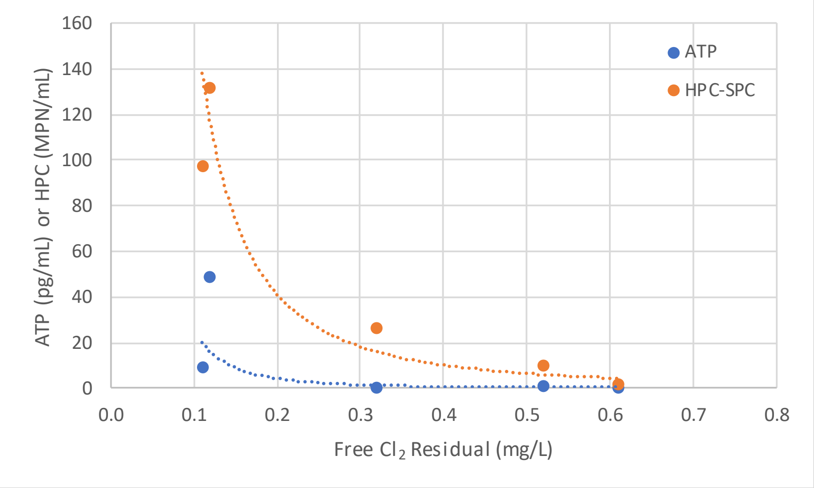

Figure 12. Correlation between microbial parameters and free chlorine residual.