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Performance Assessment of an Iron-Enhanced Sand Filtration Trench for Capturing Dissolved Phosphorus

By

Andrew J. Erickson and John S. Gulliver
St. Anthony Falls Laboratory
University of Minnesota
2 Third Avenue SE Minneapolis, MN 55455
http://www.safl.umn.edu/

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City of Prior Lake
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2. Introduction

Nutrients (phosphorus and nitrogen) in excess can cause nuisance algae blooms that generate negative aesthetic and eutrophic conditions in receiving lakes and rivers (U.S. EPA., 1999). In temperate fresh water, dissolved phosphorus is the limiting nutrient (Aldridge and Ganf, 2003; Schindler, 1977) and exists in the form of phosphates (H_XPO_4, (Stumm and Morgan, 1981)) contributed to urban stormwater from sources such as lawn fertilizers, leaf litter, grass clippings, unfertilized soils, detergents, and rainfall, among others (American Public Health Association, 1998; U.S. EPA., 1999). A recent study of nationwide monitoring data (Pitt et al., 2005) reports that the median values of total and dissolved phosphorus (phosphates) are 0.27 and 0.12 mg P/L, respectively and therefore the fraction of dissolved phosphorus to total phosphorus is approximately 44%. Removing dissolved phosphorus from stormwater at a substantial rate requires capture of both the particulate and dissolved fractions of total phosphorus.

While most stormwater treatment practices can capture particulate phosphorus through settling or filtration, very few practices have a mechanism to consistently capture dissolved phosphorus over the life-cycle of a treatment practice. Wet detention basins, in particular, are typically designed to capture greater than 80% total suspended solids and, on average, achieve a ~50% total phosphorus load reduction but do little to remove dissolved contaminants from stormwater. Because dissolved phosphorus has a higher bioavailability factor than particulate forms (Sharpley et al., 1992), removing only particulate fractions from stormwater only minimally reduces phosphorus bioavailability. To capture dissolved phosphorus, a chemical adsorption or precipitation process must be added to stormwater treatment practices. Adding steel wool or elemental iron to a sand filter has been shown to capture a significant amount of dissolved phosphorus (Erickson et al., 2007). As the elemental iron forms iron oxides (rust), dissolved phosphorus binds to these iron oxides by surface adsorption.

To reduce the dissolved phosphorus load entering phosphorus-impaired water bodies such as Upper Prior Lake and Spring Lake, the City of Prior Lake, Minnesota (the City) installed four iron-enhanced sand filtration trenches along the perimeter of two wet detention basins in Prior Lake, MN in January and February, 2010. The City, the Scott Watershed Management Organization (Scott WMO), and the Prior Lake Spring Lake Watershed District (PLSLWD) provided funding for St. Anthony Falls Laboratory, University of Minnesota to measure the performance of these “Minnesota Filter Trenches” for capturing dissolved phosphorus from stormwater. Therefore, the objective of this study was to assess an iron-enhanced sand filtration trench for capture of dissolved phosphorus from synthetic and natural runoff.

3. Iron-Enhanced Sand Filtration Trench Design

The “Minnesota Filter Trenches” were designed to be below the normal water level created by the outlet structure of the wet detention basin (see Figure 1). During rainfall events, stormwater flows into the wet detention basin and increases the water level such that stormwater begins to flow over the surface of the trenches and into the media. The stormwater flows through the mix of iron and sand to a perforated pipe under-drain where it is captured and conveyed to the outlet structure of the wet detention basin. The trenches are set below the weir overflow, creating a filter volume in the basin (see Figure 1). For small rainfall events which are less than the filter volume, all of the stormwater passes through the trenches. For large rainfall events (greater than the filter volume), the water level in the wet detention basin overflows the weir in the outlet structure and a portion of the stormwater runoff bypasses the trenches. When the water level drops below the weir, the remaining stormwater is filtered by the trenches to capture dissolved phosphorus. All trenches are connected to the outlet through individual under-drains that only drain stormwater that passes through that trench. The filter media should be aerobic, which is typically achieved by having the under-drain outlet be placed above the downstream water level, and filter material separated from nearby soils with an impermeable liner so that air can reach the filter material from both sides when the filter is not operating and material can dry between events.

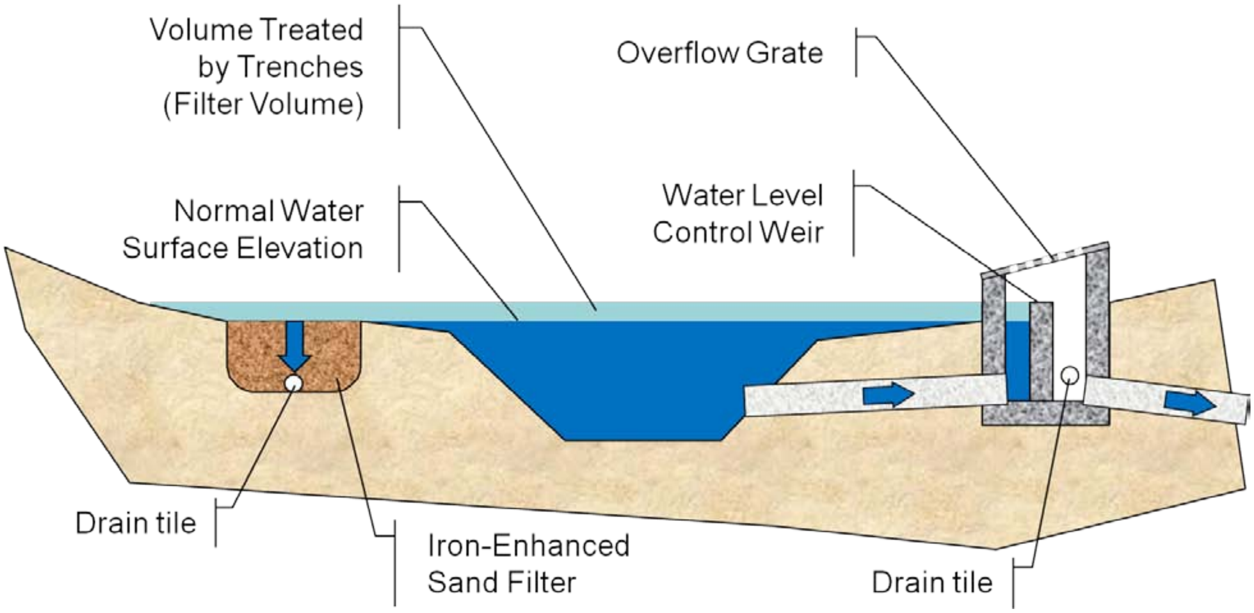

Figure 1: Schematic of iron enhanced sand filtration trench installed in a wet detention basin.

The Minnesota Filter Trenches were installed along the perimeter of two wet detention basins. The first basin, “Pond 1,” is located adjacent to County Road 42 (140th street NE) between Pike Lake Trail NE and Rolling Oaks Circle NE, on the south side of County Road 42, in Prior Lake, MN. Two trenches were installed along the western edge of Pond 1 (Figure 2), one with approximately 7.2% by weight iron filings (the elemental iron) and the other with approximately 10.7% by weight iron filings. The trenches are each approximately 40 feet (12 meters) long, 5 feet (1.5 meters) wide, and 2 feet (0.6 meters) deep. The drainage area for the wet detention basin is approximately 15 acres (6.2 ha) in size and composed of suburban residential land use. The wet detention basin can capture approximately 1.4 ft (0.4 m) of water depth or 0.21 ac-ft (1,300 m^3) on top of the pond before overflow occurs. The cost to install the trenches on Pond 1 was approximately $5,000. Additional costs to retrofit these trenches in other wet detention basins may also include additional pipe, connection to outlet structure, and outlet structure modification.

Figure 2: Pond 1 with iron enhanced filtration trenches in Prior Lake, MN

The second basin, “Pond 7,” is located between County Road 21 (Eagle Creek Ave) and Blind Lake Trail SE, and between Windsor Lane and Lexington Court SE. Two Minnesota Filter Trenches were installed along the northeastern edge of Pond 7, one with approximately 11.3% by weight iron filings and the other with approximately 18.2% by weight iron filings. The trenches are each approximately 36 feet (11 meters) long, 5 feet (1.5 meters) wide, and 1.5 feet (0.5 meters) deep. The trenches installed on Pond 7 were exposed to a backwater condition from the downstream wetland system such that the under-drain outlets were underwater throughout the summer of 2010. This caused inundation of both the under-drains and the trenches such that minimal flow was measured through these trenches. Therefore only a few measurements and samples were collected at Pond 7 as discussed in section 5.2. The cost to install the trenches on Pond 7 was approximately $3,500. Additional costs to retrofit these trenches in other wet detention basins may also include additional pipe, connection to outlet structure, outlet structure modification, and site restoration and mobilization.

4. Methods

The performance of the trenches was measured using both synthetic and natural stormwater runoff. In both cases, the flow rate of stormwater was measured at the outlet of the under-drain systems for each of the trenches and samples were collected in the basin and from the outlet of the under-drains for phosphorus analysis.

4.1. Flow Rate

The flow rate of stormwater was measured at the outlet of the under-drain systems for each of the trenches. To measure the flow rate, weirs were constructed from plastic five-gallon buckets which were calibrated at the St. Anthony Falls Laboratory. The flow over the weirs was calibrated throughout the range of possible water depths to develop a stage-discharge relationship. Flow rates were measured by measuring the time required to fill a known volume of water. The stage-discharge relationships for the two weirs used in this study are given in Equation 1 and shown in Figure 3.

Equation 1: Stage-Discharge relationship

$$Q = C_0 \frac{8}{15} C_d \tan\left(\frac{\theta}{2}\right)\sqrt{2g}\left(h\right)^{5/2}$$

Where: Q = flow rate (gallons/minute, GPM)
C_0 = unit conversion factor, 448.831 gallons/minute per ft^3/s
C_d = discharge coefficient, varies by weir
θ = weir angle, varies by weir (radians)
g = gravitational acceleration, 32.2 ft/s^2
h = depth of water flowing over the weir (feet)

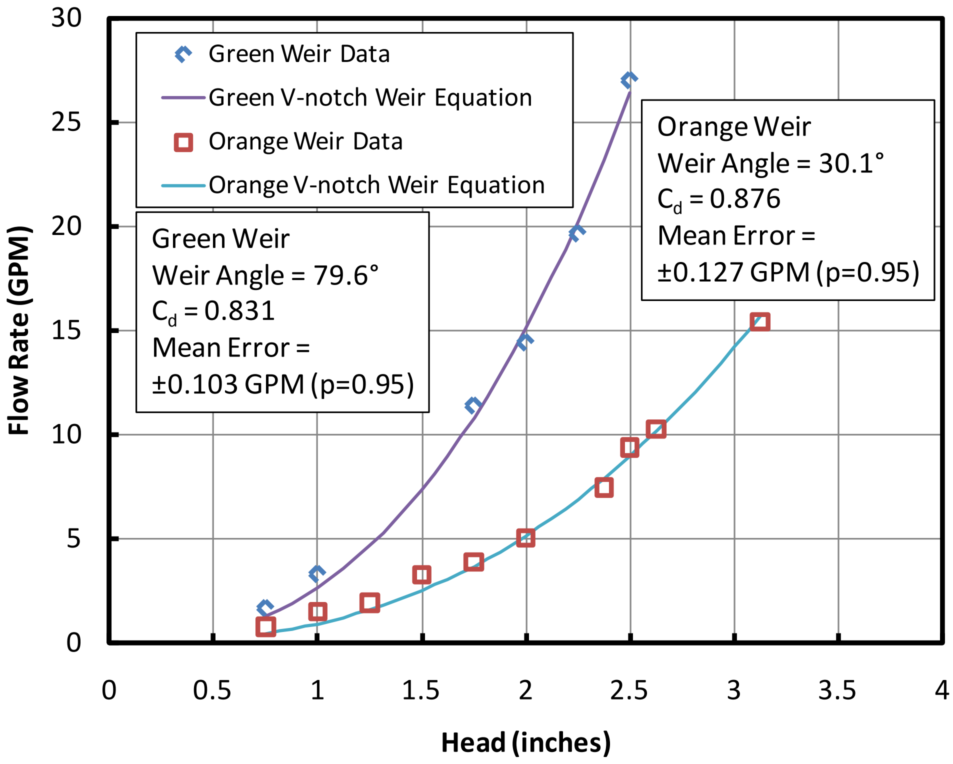

Figure 3: Stage-Discharge relationship for constructed bucket weirs.

The bucket weirs were placed in the outlet structure below the under-drains such that the outflow from each under-drain filled one of the bucket weirs. The water then overflowed the weir and the water level was measured at regular intervals and recorded. The flow rate was then calculated from stage-discharge relationship developed for each weir.

4.2. Phosphorus Sampling and Analysis

Samples were collected in two locations for each trench: within the wet detention basin as an influent sample (see Figure 4) and from the under-drain system as an effluent sample. Samples were collected using acid-washed glass sample bottles.

Figure 4: Sampling for phosphorus concentration from within the wet detention basin.

Stormwater samples were collected, stored, and transported back to St. Anthony Falls Laboratory to be analyzed for dissolved phosphorus concentration according to standard methods section 4500-P E (Ascorbic Acid) with a minimum detection limit of 0.010 mg P/L (American Public Health Association, 1998).

4.3. Synthetic runoff testing

Synthetic runoff testing is one of two methods used to measure performance of the trenches. Fittings and flow control values were connected to a local fire hydrant by the City to supply synthetic runoff (no pollutants were added). The fire hydrant was turned on and the synthetic stormwater was allowed to flow down the street via the gutter to a catch basin directly upstream of Pond 1. The synthetic stormwater entered Pond 1 and increased the water level such that natural stormwater already stored within the basin began to flow over the surface of and into the trenches. The flow rate of stormwater leaving the trenches through the under-drains were measured as described in section 4.1 and samples were collected as described in section 4.2. The fire hydrant was allowed to flow for a period of time (approximately 1 hour) such that a significant volume of synthetic stormwater was added to Pond 1. Flow rates were measured and samples were collected for approximately eight hours as stormwater flowed through the trenches.

4.4. Natural runoff testing

Natural runoff testing is the second method of testing used to measure performance of the trenches. Rainfall events periodically fill Pond 1 with natural stormwater which increased the water level such that the stormwater would flow into the trenches. During some of these storm events, the flow rate of stormwater leaving the trenches through the under-drains were measured as described in section 4.1 and samples were collected as described in section 4.2. Flow rates were measured and samples were collected for approximately eight hours as natural stormwater flowed through the trenches.

5. Results and Discussion

5.1. Pond 1

Five tests were conducted for Pond 1 under various conditions as listed in Table 1 and Table 2. Two of these tests (July 1 and July 13) were conducted with synthetic stormwater as described in section 4.3 while the other three tests (August 11, 12, September 24) occurred immediately following a natural rainfall event as described in section 4.4. It is important to note that the limit of detection for the analytical method is 0.01 mg P/L and several samples were found to be below detection limits during this study as shown in Tables 1 and 2. For calculation purposes, the concentration was assumed to be at the detection limit (0.01 mg P/L) for all samples measured below detection limits. Therefore, the reported values of removal efficiency are conservative estimates of removal because it can be assumed that the actual effluent EMCs are the same or smaller than the values reported in Tables 1 and 2.

When comparing the influent event mean concentrations (EMCs) in Tables 1 and 2, it is evident that the synthetic stormwater had approximately 50 to 75% less dissolved phosphorus concentration than the natural stormwater events. This is likely due to algae and other biological activity within the basin converting dissolved phosphorus to particulate phosphorus between storm events. Also, all of the influent EMCs, with the exception of the September 24th test, were below the median values of dissolved phosphorus concentration in stormwater, 0.12 mg P/L (Pitt et al., 2005). No dissolved phosphorus was added to the synthetic discharge, but there is roughly 0.395 ± 0.017 mg P/L (average ± 95% confidence interval, n = 4) in the domestic water supply to reduce pipe corrosion. A comparison of the water quality upstream (within the pond) and downstream (outflow from the underdrains) is provided in Figure 5.

Figure 5: Water clarity within the pond (left, shown in the outlet structure) and after treatment by the iron-enhanced filtration trenches (right, shown at the effluent of the underdrains).

Table 1: Testing results for an iron-enhanced filtration trench mixed with 7% iron filings, Pond 1.

Test Date	7/1/2010	7/13/2010	8/11/2010	8/12/2010	9/24/2010
Runoff Test Method	Synthetic	Synthetic	Natural	Natural	Natural
Average Filtration Rate ± 95% Confidence Interval (in/hr)	10.5 ± 1.69	5.5 ± 0.66	27.1 ± 0.66	18.1 ± 1.22	5.2 ± 0.00
Influent Phosphorus Flow-weighted EMC (mg/L)	0.032	0.027	0.101	0.077	0.140
Effluent Phosphorus Flow-weighted EMC (mg/L)	0.023	0.013	0.016	0.021	0.020
Percent of effluent samples below detection (0.01 mg P/L)	3.4%	25.0%	0%	18.2%	0%
Flow-weighted Phosphorus EMC Reduction Efficiency	28.6%	52.7%	84.2%	72.2%	85.5%
Influent Phosphorus Load (mg)	1,456	570	205	74	1,718
Effluent Phosphorus Load (mg)	1,040	270	32	21	248
Phosphorus Load Reduction Efficiency	28.6%	52.7%	84.2%	72.2%	85.5%

Approximately 5,000 ft^3 (145 m^3) of synthetic stormwater was added to Pond 1 during each test on July 1 and July 13 and the total storage volume of Pond 1 at the normal water level is approximately 25,000 ft^3. Because the influent EMCs entering the trenches were a factor of 10 less (0.026 to 0.032 mg P/L) than the phosphorus concentration in the synthetic stormwater, it is evident that the synthetic stormwater that was added to the system did not significantly mix with the stormwater already in the wet detention basin prior to the test. Various methods to achieve mixing (including a fountain pump) in the pond were tested but none were found to successfully mix the basin within a short (< 1 hour) period of time.

Table 2: Testing results for an iron-enhanced filtration trench mixed with 11% iron filings, Pond 1.

Test Date	7/1/2010	7/13/2010	8/11/2010	8/12/2010	9/24/2010
Runoff Test Method	Synthetic	Synthetic	Natural	Natural	Natural
Average Filtration Rate ± 95% Confidence Interval (in/hr)	4.0 ± 0.64	3.6 ± 0.62	6.4 ± 0.76	4.1 ± 0.24	4.0 ± 0.13
Influent Phosphorus Flow-weighted EMC (mg/L)	0.033	0.026	0.101	0.077	0.140
Effluent Phosphorus Flow-weighted EMC (mg/L)	0.014	0.010	0.016	0.018	0.014
Percent of effluent samples below detection (0.01 mg P/L)	33.3%	100%	15.8%	36.4%	22.2%
Flow-weighted Phosphorus EMC Efficiency	58.4%	60.9%	84.4%	76.2%	90.1%
Influent Phosphorus Load (mg)	443	264	45	16	1,188
Effluent Phosphorus Load (mg)	184	103	7.0	3.7	117
Phosphorus Load Efficiency	58.4%	60.9%	84.4%	76.2%	90.1%

The influent dissolved phosphorus EMC for these tests varied from approximately 0.026 to 0.101 mg/L and the effluent EMC was consistently between 0.01 and 0.023 mg/L (although many values were below detection limits). The dissolved phosphorus removal efficiency varied between approximately 29% and 90% but for most tests (only excluding July 1), dissolved phosphorus capture is greater than 50%. From the data in Tables 1 and 2 it is clear that as the influent dissolved phosphorus EMC increased, the dissolved phosphorus capture efficiency increased and the percentage of samples below detection limits decreased. The median dissolved phosphorus concentration in stormwater is 0.12 mg P/L (Pitt et al., 2005), which is larger than the influent concentration for the test on August 11 (84% phosphorus removal) and less than the influent concentration for the test on September 24th (90% phosphorus removal). Therefore for most rainfall events, the iron-enhanced sand filtration trenches are expected to capture approximately 85-90% of the dissolved phosphorus. Additional test data is provided in Appendix A.

The filtration rates reported in Tables 1 and 2 can be used to estimate the contact time between the phosphorus in the water and the iron-enhanced filter media (contact time = bed depth / filtration rate). Assuming an iron-enhanced media bed depth of 1.4 feet (0.4 m), phosphorus removal as a function of contact time for the 7 % iron filings and 11% iron filings trenches is shown in Figure 6.

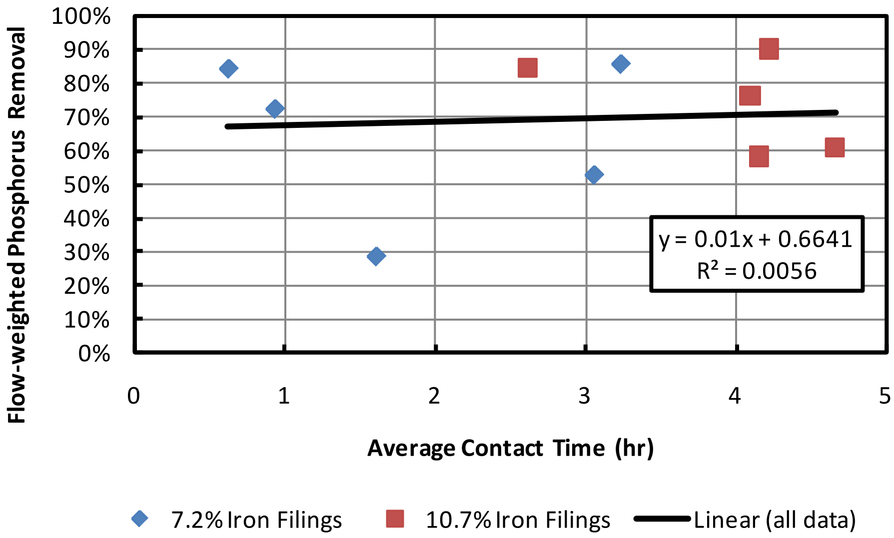

Figure 6: Relationship between flow-weighted phosphorus removal and average contact time with iron-enhanced filter media (assumes media depth = 1.4 feet).

Laboratory experiments with steel wool or elemental iron has shown a strong relationship between contact time and phosphorus capture (Erickson et al., 2007), but no such relationship is apparent from the data collected during these tests (Figure 6). As mentioned previously, several measurements during these tests were below detection limits (which affects percent removal) and therefore these results may not be accurate enough to determine a relationship between contact time and phosphorus capture.

5.2. Pond 7

One synthetic runoff test (July 15, 2010) was conducted on the trenches at Pond 7 in which several flow rate measurements and samples were collected. The average filtration rate ± 95% confidence interval from the trench with 11% iron filings was approximately 2.15 ± 0.02 in/hr and approximately 0.49 ± 0.01 in/hr from the trench with 18% iron filings. The filtration rate for these trenches is considerably less than the filtration rates measured in the trenches in Pond 1 (see Table 3).

Table 3: Average filtration rates for the iron-enhanced filtration trenches.

Pond	**1**	**1**	**7**	**7**
Percent Iron	7.2%	10.7%	11.3%	18.2%
Average Filtration Rate ± 95% Confidence Interval (in/hr)	12.2 ± 1.69	4.4 ± 0.34	2.2 ± 0.02	0.5 ± 0.01

The trench with 10.7% iron filings in Pond 1 exhibited at least double the filtration rate as the iron-enhanced sand filtration trench with 11.3% iron filings in Pond 7. It is apparent from the data in Table 3 that a trend exists between decreasing filtration rate with increasing iron content. This is likely due to the additional volume occupied by the iron after oxidation begins. At some point, the slow filtration rate becomes an obstruction to the main function of a pond to store stormwater flows. When the filtration rate is too small, the pond will not have the designed storage before the next storm. Although this calculation is site-specific, it is likely that the filtration rates of 18% iron and sand will not drain the pond with sufficient quickness to meet this functionality criterion. The dissolved phosphorus concentration in all phosphorus samples collected in the wet detention pond and from the under-drains was below detection limits so it is impossible to estimate dissolved phosphorus capture efficiency from this data.

6. Conclusions

Iron enhanced sand filtration trenches have been installed in the City of Prior Lake, MN to remove dissolved phosphorus from stormwater runoff. These trenches can capture between 30% and 90% dissolved phosphorus, even for influent concentrations as low as 0.025 mg P/L. Most rainfall events will have a dissolved phosphorus concentration close to the median of 0.12 mg P/L reported in the literature(Pitt et al., 2005), and the testing results from this report shows that the iron-enhanced sand filtration trenches are expected to capture approximately 85-90% of the dissolved phosphorus for these events. Iron enhanced sand filtration trenches of this size require approximately $3,500 to $5,000 in material costs and achieve 85-90% removal efficiency. Therefore iron enhanced filtration trenches are a low-cost solution to supplement existing ponds to remove dissolved phosphorus from stormwater runoff.

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8. Appendix A

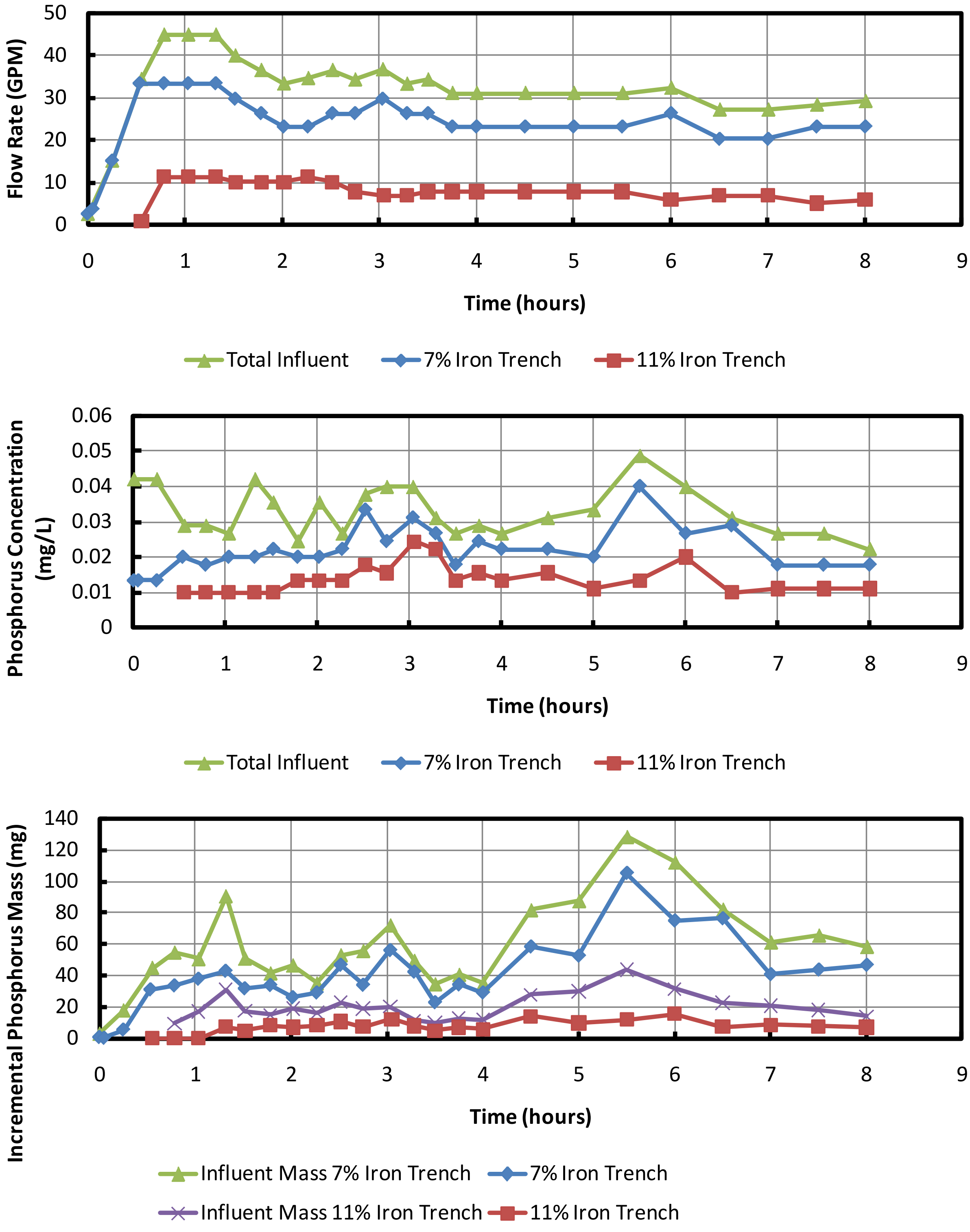

Figure 7: Detailed test results for July 1, 2010 at Pond 1.

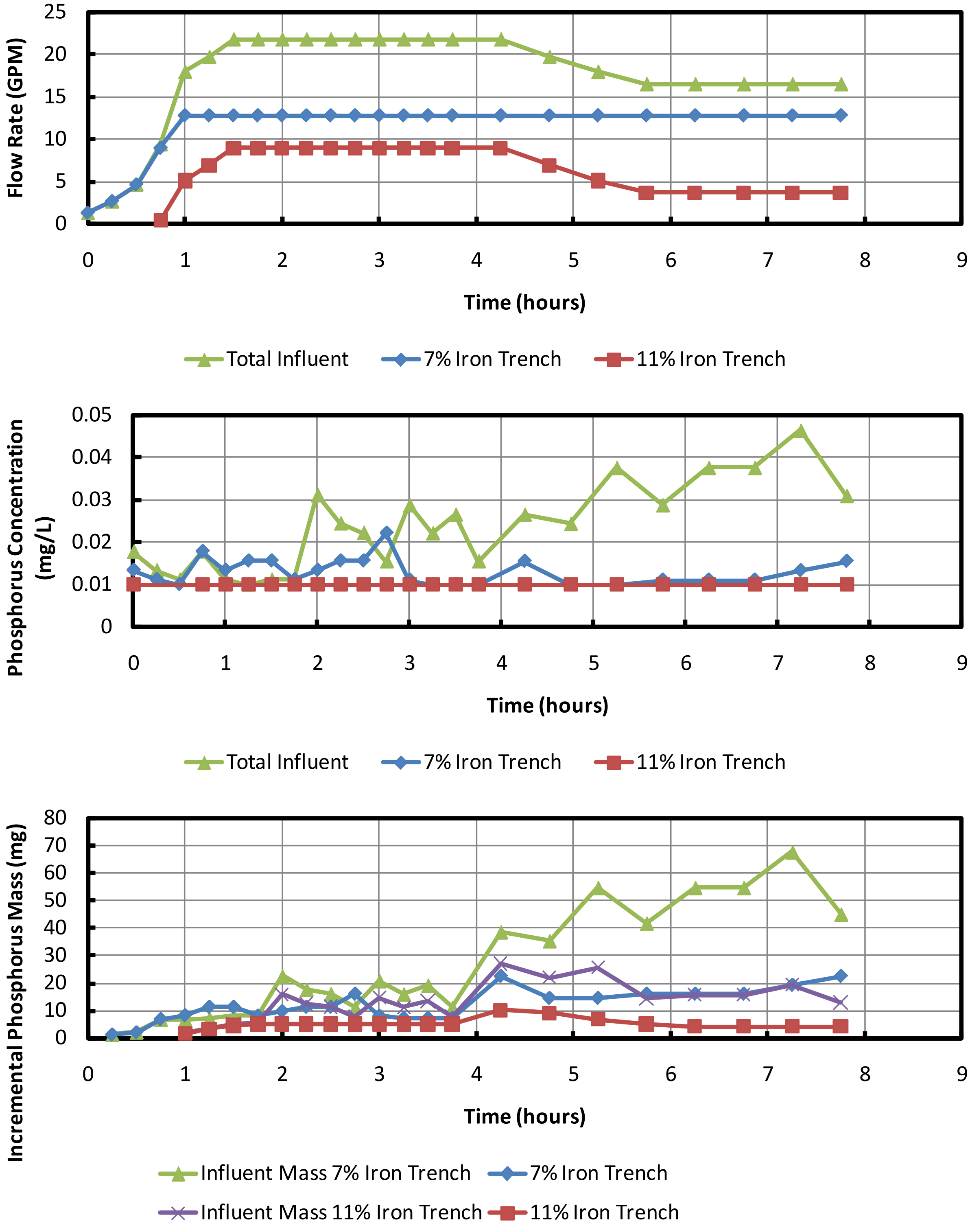

Figure 8: Detailed test results for July 13, 2010 at Pond 1.

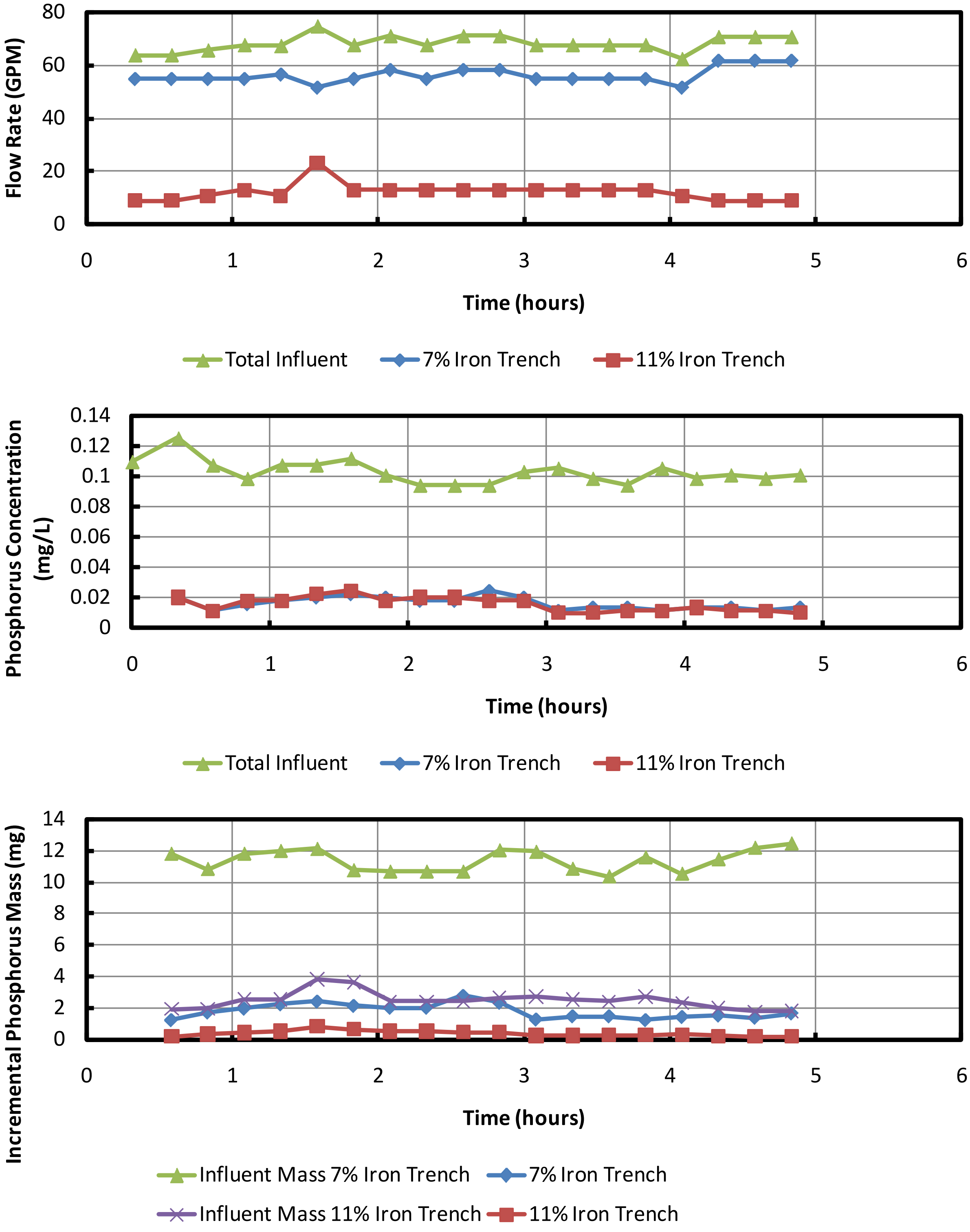

Figure 9: Detailed test results for August 11, 2010 at Pond 1.

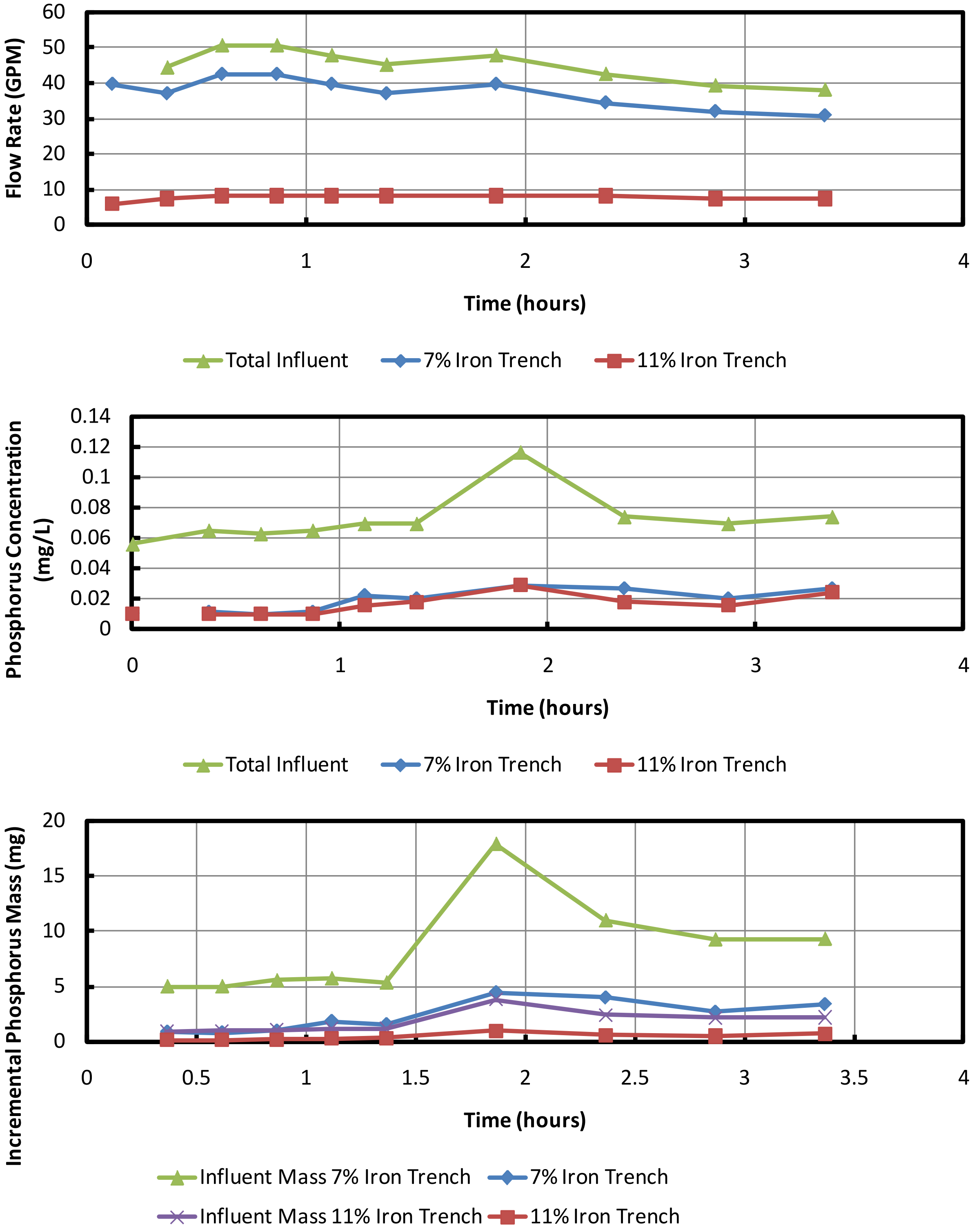

Figure 10: Detailed test results for August 12, 2010 at Pond 1.

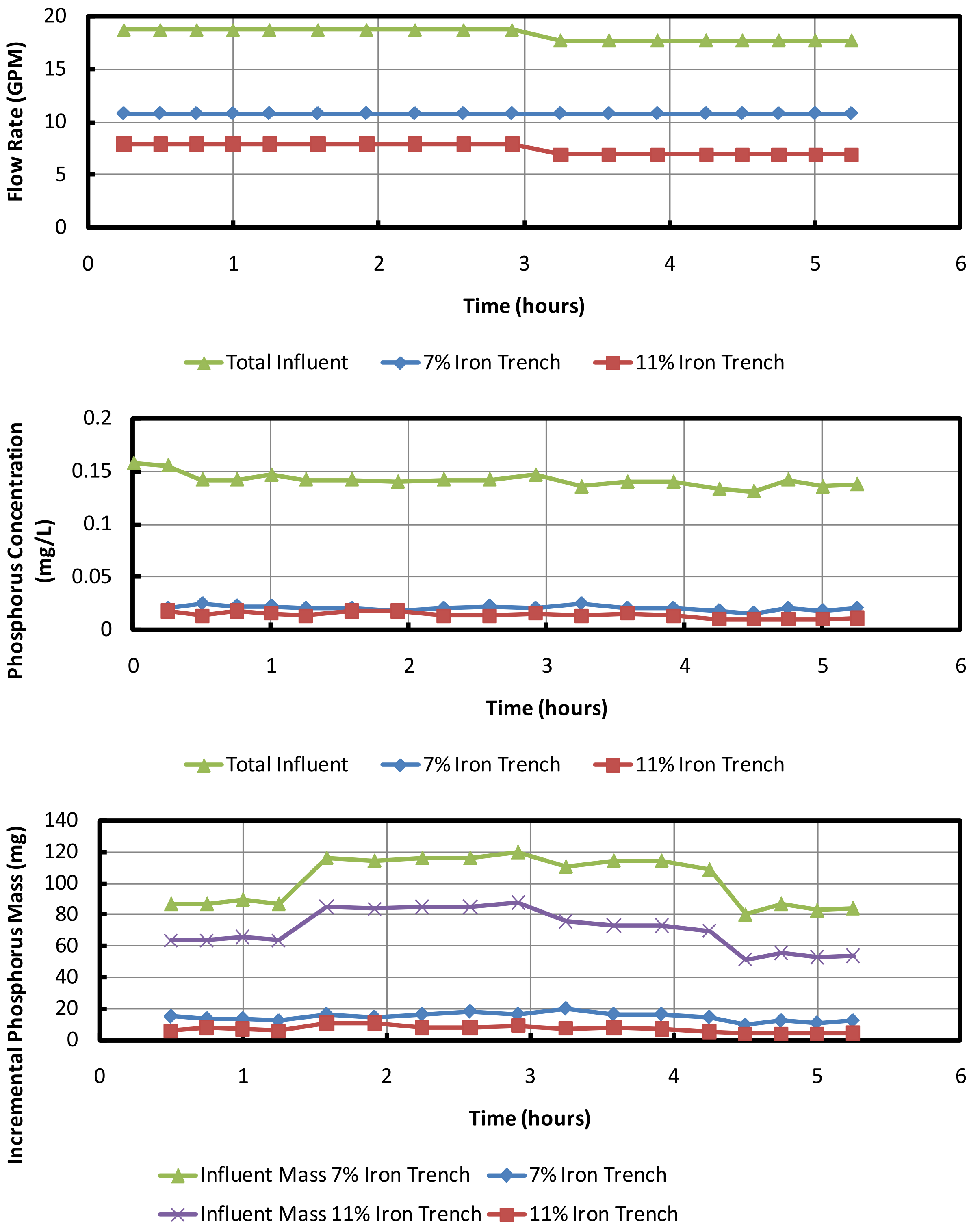

Figure 11: Detailed test results for September 24, 2010 at Pond 1.

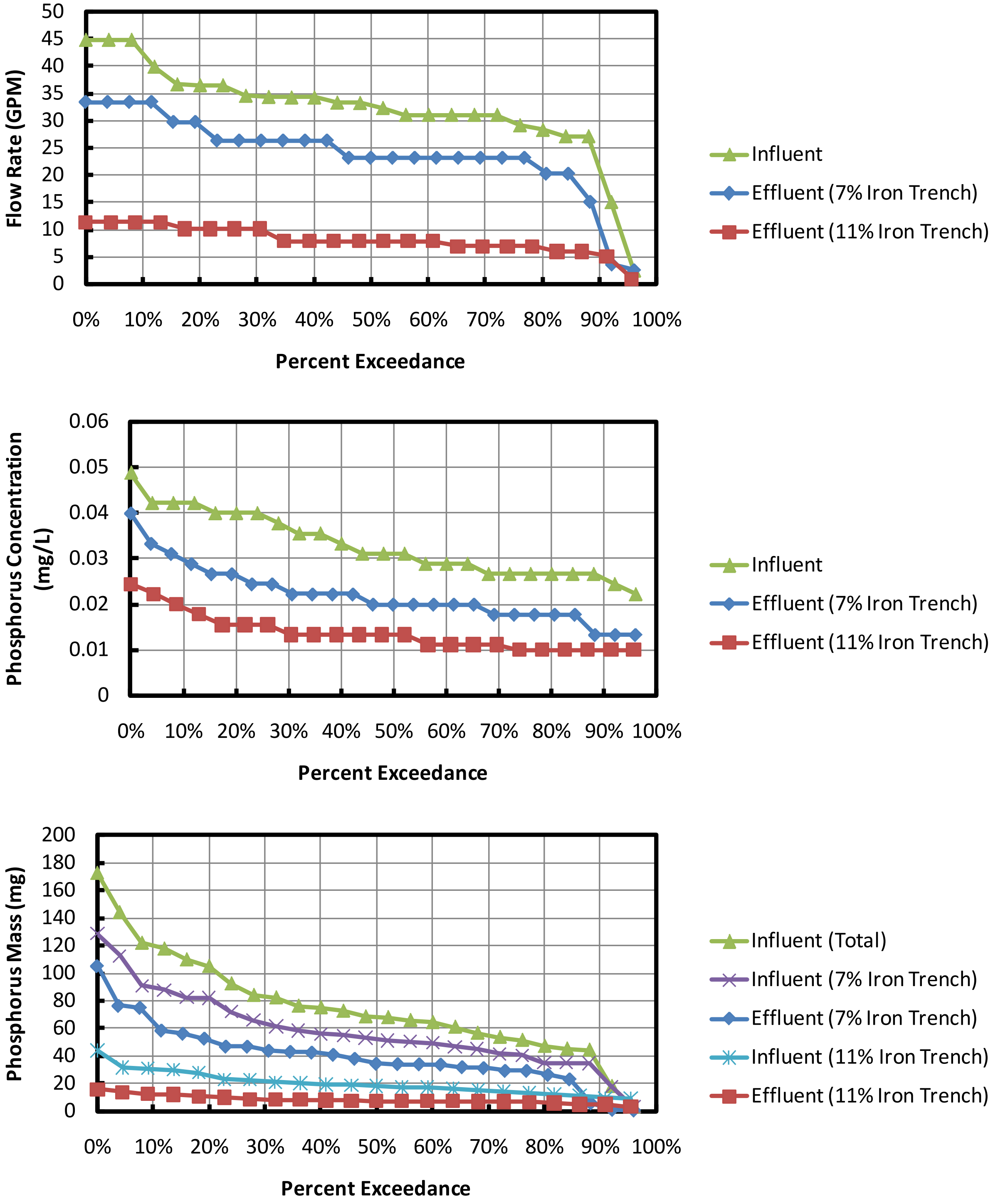

Figure 12: Percent Exceedance for July 1, 2010 at Pond 1.

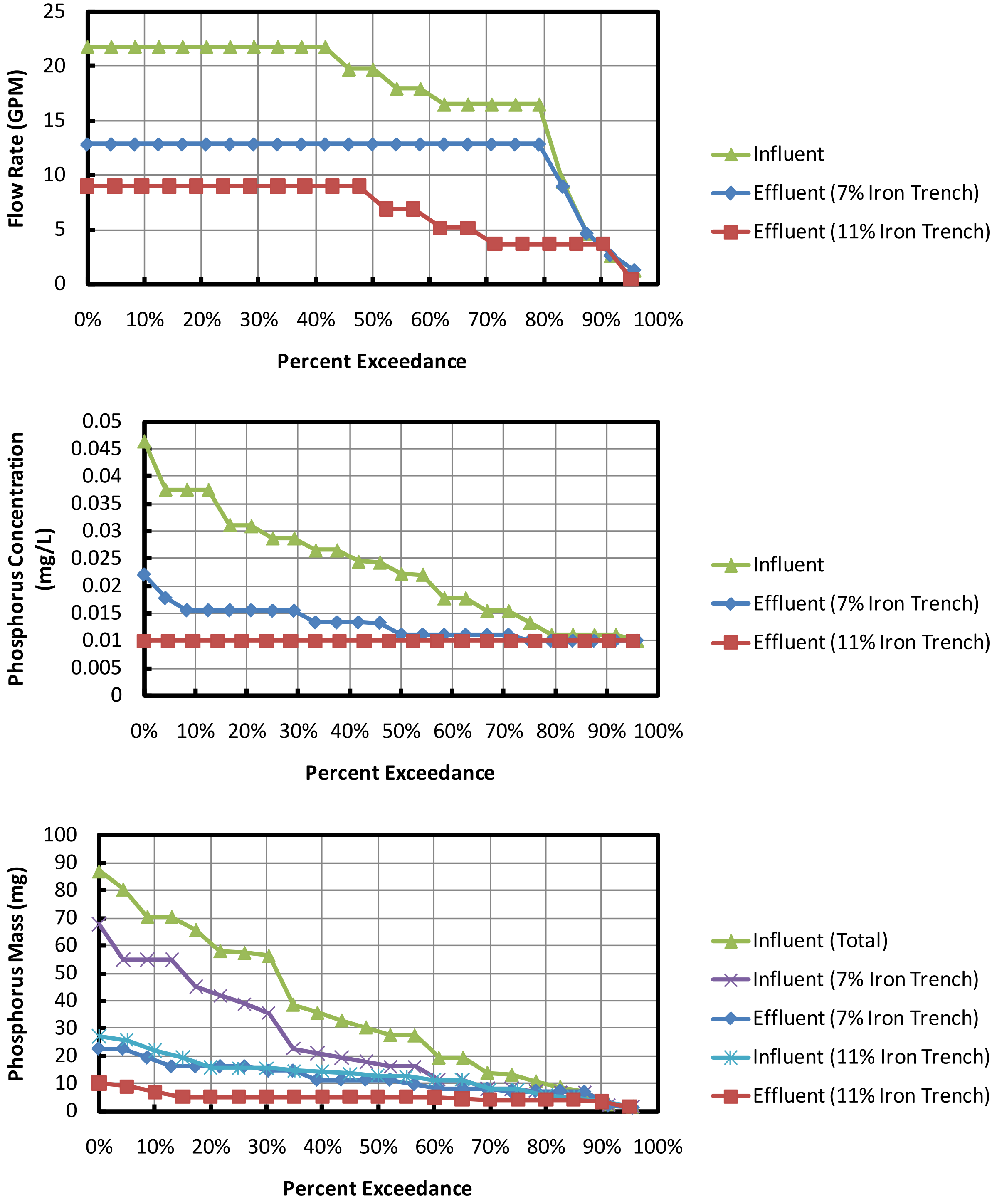

Figure 13: Percent Exceedance for July 13, 2010 at Pond 1.

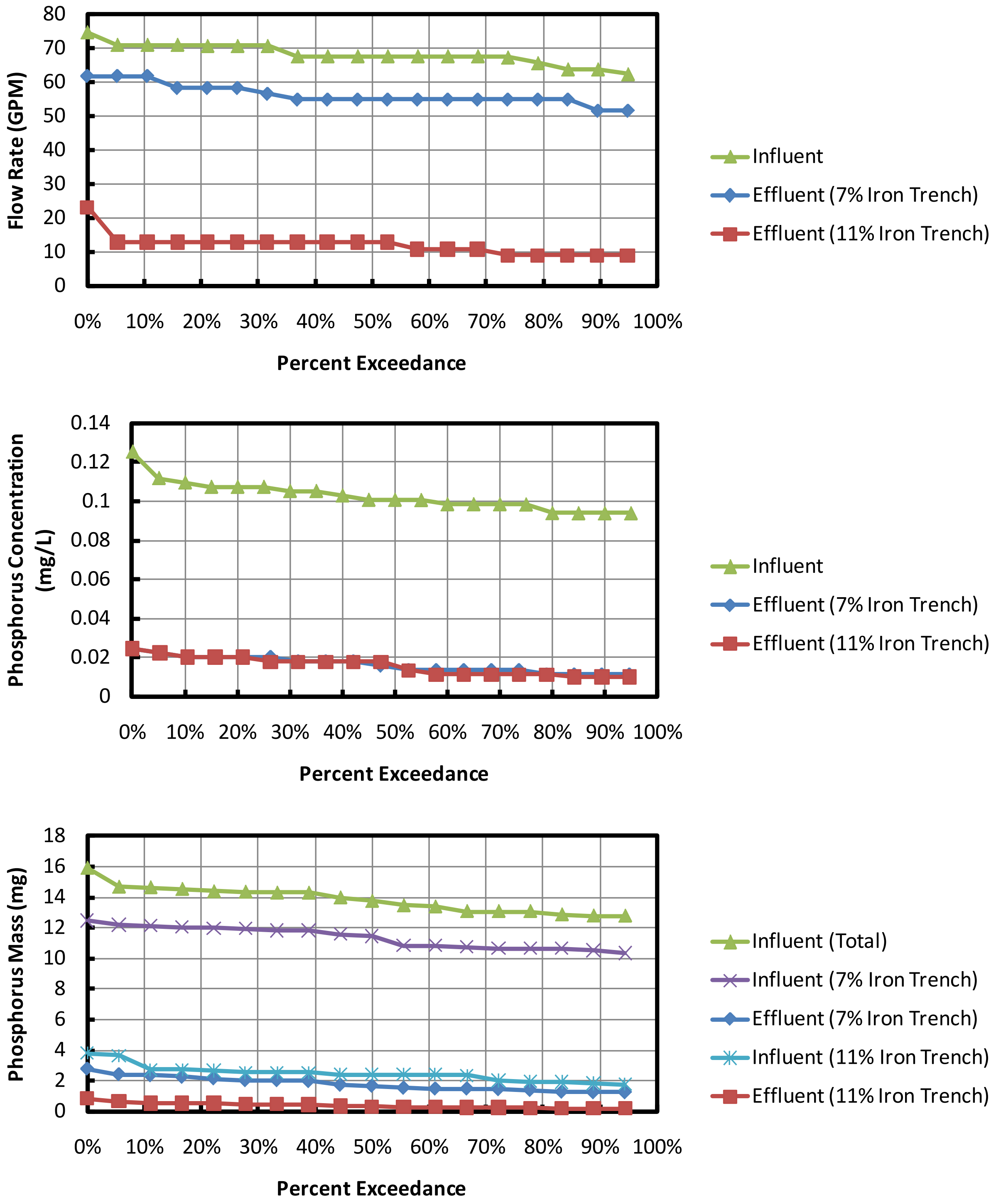

Figure 14: Percent Exceedance for August 11, 2010 at Pond 1.

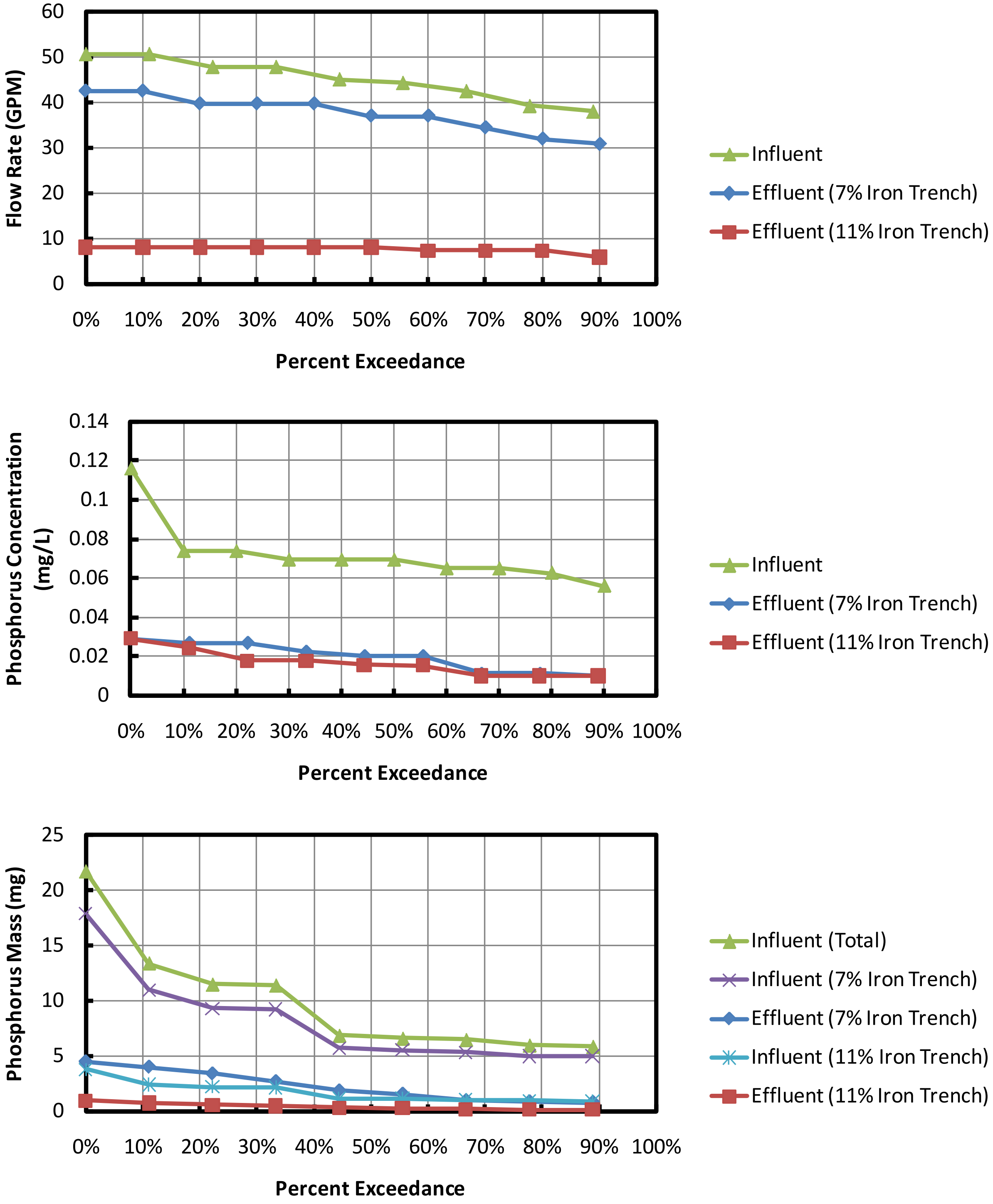

Figure 15: Percent Exceedance for August 12, 2010 at Pond 1.

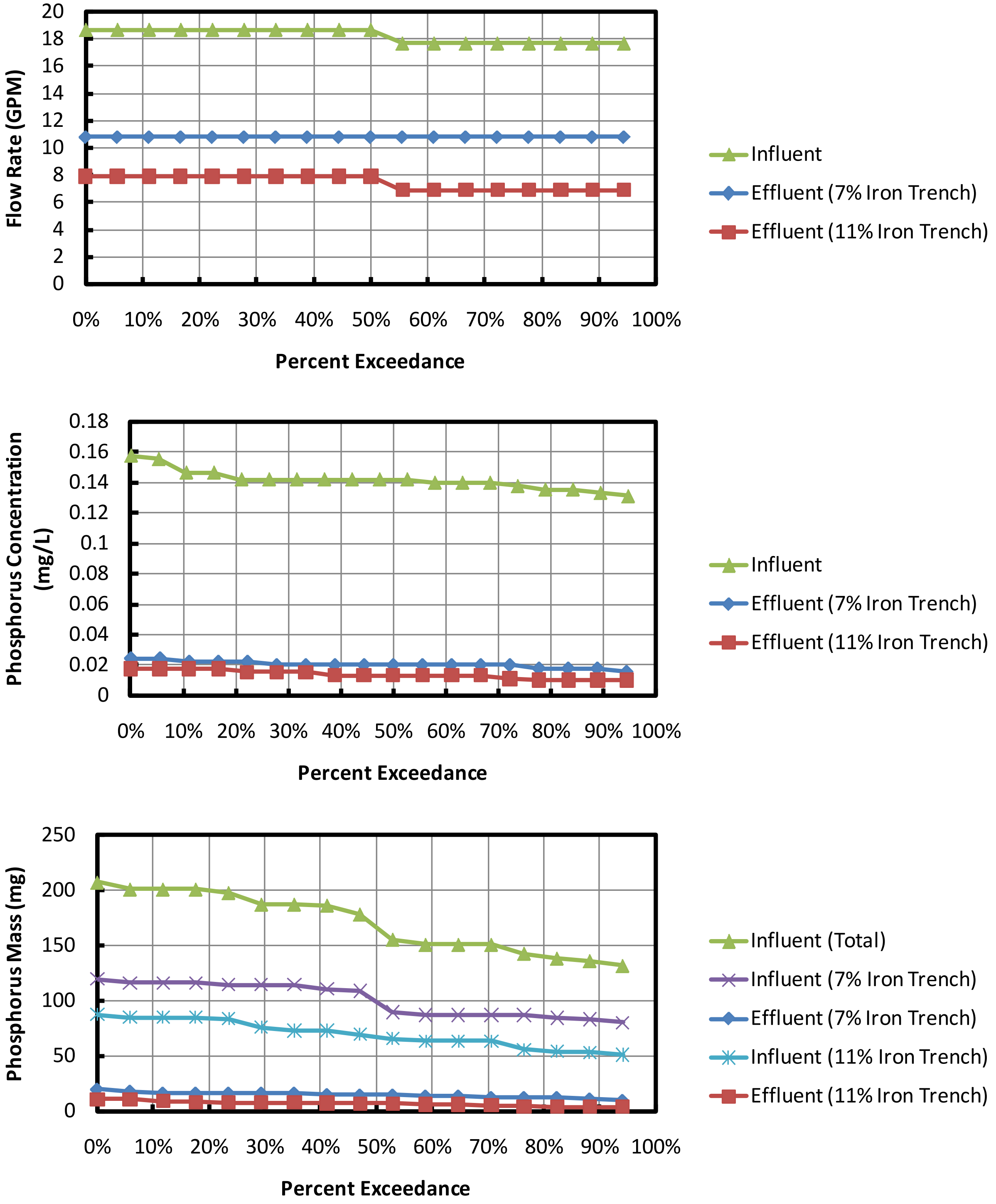

Figure 16: Percent Exceedance for September 24, 2010 at Pond 1.