2009 General Sewer Plan and Wastewater Facilities Plan Amendment

Phosphorus Removal

PREPARED FOR
City of Cashmere
101 Woodring Street
Cashmere, WA 98815

PREPARED BY
RH2 Engineering, Inc.
22722 29th Drive SE, Suite 210
Bothell, WA 98021

Prepared November 2014
Updated April 2015

TABLE OF CONTENTS

Appendices

INTRODUCTION AND BACKGROUND

The City of Cashmere (City) Washington is located in Chelan County, approximately 12 miles northwest of Wenatchee. The City owns and operates a wastewater collection and treatment system located within the City limits. In 2009, RH2 Engineering, Inc., (RH2) completed the City's 2009 *General Sewer Plan and Wastewater Facilities Plan* (2009 Facilities Plan). The purpose of the 2009 Facilities Plan, in part, was to evaluate wastewater treatment alternatives to meet future surface water discharge permit requirements. The City's existing wastewater treatment facility (WWTF) consisted of sewage treatment lagoons. The 2009 Facilities Plan recommended an enhanced biological phosphorus removal (EBPR) activated sludge treatment alternative to reduce the effluent phosphorus concentration to the maximum extent practical biologically. By 2020, the City will need to meet the phosphorus waste load allocations set forth in the *Wenatchee River Watershed Dissolved Oxygen and pH Total Maximum Daily Load Water Quality Improvement Report* (TMDL Report) published by the Washington State Department of Ecology (Ecology) in April 2009. A tertiary treatment system may be necessary to further reduce the phosphorus concentration to comply with the future National Pollutant Discharge Elimination System (NPDES) permit.

The new WWTF went on-line August 2014. United States Department of Agriculture Rural Development (USDA Rural Development) funds remaining from the construction of the new WWTF are available for construction of a portion of the tertiary treatment process prior to mid-2015. The City plans to complete preliminary work utilizing these funds and complete construction over the next several years with additional City funds.

The City currently discharges to the lower Wenatchee River. The critical periods for the Wenatchee River watershed occur March through May (prior to snow melt runoff) and July through October (after snow melt runoff). A critical period is a time of year when the river has low stream flows. The TMDL Report established a phosphorus mass loading limitation in order to meet dissolved oxygen and pH criteria. The waste load allocations presented in the TMDL Report are reproduced in **Table 1**.

Table 1
Wasteload allocation in concentration and kg/Day for NPDES dischargers to the lower Wenatchee River (ug/L of phosphorus)
Excerpted from the *Wenatchee River Watershed Dissolved Oxygen and pH Total Maximum Daily Load Water Quality Improvement Report (Table 15 in the TMDL report)*

Wastewater treatment plant name and permit number	Wasteload allocation (micrograms/liter) of total phosphorus (daily maximum)	Load at TMDL: 90 ug/L TP daily maximum WLA concentration (kg/day)	
		2002 Flow	Design Flow
Leavenworth WA0020974D	90	0.146	0.286
Peshastin WA0052175C	90	0.021	0.037
Cashmere WA0023183D	90	0.225	0.64

Ecology's current goal is to fully implement the limits during the critical periods by January 1, 2020. Since becoming fully operational in the Fall of 2014, Cashmere's EBPR treatment facility has performed very well. Effluent phosphorus levels for the first three months of 2015 are summarized in **Table 2**.

Table 2
Effluent Phosphorus Summary

Month 2015	Average Total P (mg/L)	Average Soluble P (mg/L)
January	0.14	ND (<0.07)
February	0.21	0.09
March	0.3	0.13

Additional filtration and/or chemical treatment may be required during the critical periods to further reduce the phosphorus mass loading to meet the 0.64 kg/day limit allocated to the City at design flows. The 2009 Facilities Plan did not provide an alternatives analysis or recommendations for the tertiary treatment system. The purpose of this amendment to the 2009 Facilities Plan is to provide the design criteria, alternatives analysis, preliminary cost estimates, and recommended alternative for the tertiary treatment system.

FLOW ANALYSIS SUMMARY AND PHASE I DESIGN FLOW CONSIDERATIONS

Chapter 4 of the 2009 Facilities Plan presented the existing and projected flow analysis for the City. The total influent flow to the WWTF is composed of untreated municipal, commercial, and industrial flow. Prior to 2007, industrial discharges contributed a large portion of the influent flow. Currently, there are only two primary industrial sources, Crunch Pak and Blue Star Growers. The largest industrial discharger, Tree Top, ceased operation in 2007 and has not yet made plans to resume operations. Crunch Pak has expanded operations over the last several years. The flow analysis in the 2009 Facilities Plan included Crunch Pak and Blue Star Growers in the existing (2008) and 20-year (2030) flow analysis and a portion of the future influent flow attributed to Tree Top has been allocated to Tree Top or another industrial discharger if Tree Top does not resume operations.

Table 4-16 of the 2009 Facilities Plan included projected flows under various scenarios. This table is reproduced as **Table 3**. The average annual, maximum month, and peak day municipal flows include Blue Star Growers and Crunch Pak. The flow attributed to Tree Top or another industrial discharger is included in the peak day pre-treated industrial flow.

Table 3
Table 4-16: Flow Analysis Summary
Excerpted from the *2009 General Sewer Plan and Wastewater Facilities Plan*

Description	2008 Existing	2020 Projected	2030 Projected
Population Data			
Service Area Population	3,200	4,195	5,034
Increase from Base Year 2009		995	1,834
Flow Basis Data (gpcd)			
Average Day Flow Per Capita	110	110	110
Plant Flow (MGD)			
Average Annual Muncipal Plant Flow*	0.36	0.53	0.66
Maximum Month Muncipal Plant Flow*	0.43	0.55	0.79
Peak Day Muncipal Plant Flow*	0.95	1.25	1.78
Peak Day Pre-treated Industrial Flow	0.00	0.44	0.44
Average Annual Total Plant Flow	0.36	0.97	1.10

gpcd = gallons per capita day MGD = million gallons per day

* Excludes pre-treated industrial flows

Subsequent to the 2009 Facilities Plan, RH2 completed a predesign report for the WWTF upgrades. The WWTF has a 20-year hydraulic flow capacity of 1.1 million gallons per day (MGD) average annual and a maximum day flow of 2.6 MGD. **Table 4** (Table 1-5 of the *City of Cashmere WWTF Predesign Report*) presents this information and other flow scenarios.

Table 4
Table 1-5: Design Hydraulic Flow Conditions
Excerpted from the *City of Cashmere WWTF Predesign Report*

	2012	Design 2030
Design Population	3,200	5,034
Design Hydraulic Flow Conditions (MGD)		
Low Flow	0.16	--
Average Annual Design Flow (AADF)	0.37	1.10
Maximum Month Design Flow (MMDF)	0.43	1.23
Maximum Week Design Flow (MWDF)	0.70	1.32
Maximum Day Design Flow (MDDF)	1.12	2.60
Peak Hour Design Flow (PHDF)	1.50	3.46
Peak Instantaneous Design Flow (PIDF)	2.16	3.46

Since the 2009 Facilities Plan was completed, additional flow data was evaluated by RH2 to verify influent flow trends as part of the *City of Cashmere WWTF Predesign Report* (Predesign Report) and more recently, as part of this Facilities Plan Amendment. **Table 5** presents a compilation of the flow analysis from the 2009 Facilities Plan, Predesign Report, and 2013 through 2014 influent flow data.

Table 5
Flow Data Summary

Year	Flow Scenario	Flow (MGD)	Peaking Factor (in terms of AAF)
2006	Average Annual Flow	0.36	1.00
	Maximum Month Flow	0.45	1.26
	Maximum Day Flow	0.61	1.70
2007	Average Annual Flow	0.37	1.00
	Maximum Month Flow	0.44	1.20
	Maximum Day Flow	1.02	2.80
2008	Average Annual Flow	0.36	1.00
	Maximum Month Flow	0.43	1.20
	Maximum Day Flow	0.95	2.70
2009	Average Annual Flow	0.37	1.00
	Maximum Month Flow	0.42	1.15
	Maximum Day Flow	1.12	3.06
2010*	Average Annual Flow	0.36	1.00
	Maximum Month Flow	0.40	1.11
	Maximum Day Flow	0.74	2.04
2013	Average Annual Flow	0.33	1.00
	Maximum Month Flow	0.37	1.12
	Maximum Day Flow	0.63	1.92
2014*	Average Annual Flow	0.32	1.00
	Maximum Month Flow	0.34	1.05
	Maximum Day Flow	0.54	1.69
2013-2014	Average Annual Flow	0.33	1.00
	Maximum Month Flow	0.37	1.13
	Maximum Day Flow	0.63	1.93

*2010 only includes 1/1/2010 until 9/30/2010 and 2014 only includes 1/1/2014 until 4/30/2014

Based on this data, the average annual flow (AAF), maximum month, and maximum day influent flows to the WWTF are generally decreasing. The estimated population in the City in 2007 was 2,980. According to the Office of Financial Management (OFM), the estimated population in 2013 was 3,055. Based on the minimal population increase and reduced influent flows, the 2020 and 2030 flow projection values presented in the 2009 Facilities Plan can be shifted out 5 years or more. The City will evaluate the population and influent flows annually to verify if this trend continues and will plan to install additional treatment equipment when needed.

The City has a limited amount of funds from USDA Rural Development; these funds will be used to design and construct a portion of the Phase I phosphorus removal treatment system until they are exhausted. Equipment for the system will be initially sized to manage the projected 2020 maximum day flow of 1.3 MGD (**Table 3**) for the Phase I improvements. Buildings and piping systems will be sized for the Phase II design flow of 2.6 MGD. Additional equipment will be required to meet the 2030 to 2035 flow rate of 2.6 MGD (Phase II). The City will complete the procurement, construction, and startup of the Phase I phosphorus removal system in 2017 and 2018 in order to be in compliance with the total maximum daily load (TMDL) by 2020. As the City expands and influent flow increases to the WWTF, an additional treatment system train will be added (Phase II) as needed to continue meeting the TMDL on the Wenatchee River.

PHOSPHORUS REMOVAL SYSTEM DESIGN CRITERIA – PHASE I

Flow and load design criteria for the Phase I tertiary treatment system is as follows:

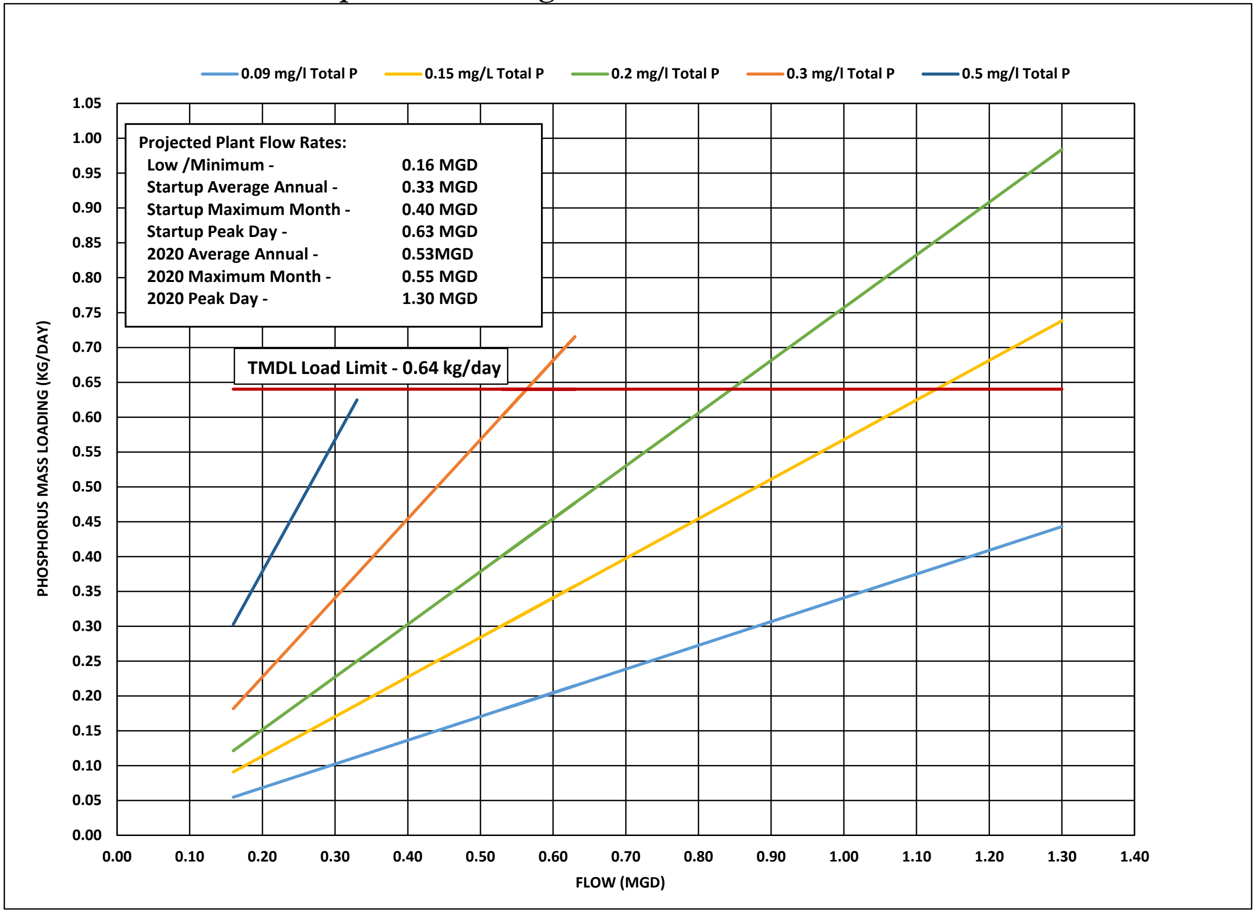
- Average day design flow of 0.6 MGD
- Maximum day design flow of 1.3 MGD
- Influent biological oxygen demand (BOD) and total suspended solids (TSS) range of 5 to 10 milligrams per liter (mg/L)
- Influent total phosphorus of 1.0 mg/L

The design of the selected phosphorus removal system will:

- Provide a reasonable means of expansion up to and beyond the 20-year planning period as the City expands and grows.
- Be installed upstream of the ultraviolet light disinfection system with effluent discharged to the Wenatchee River.
- Be designed not to exceed 0.64 kilograms per day (kg/day) of phosphorus based on a seasonal average (March through May and July through October) and 1.1 kg/day based on a monthly average. Refer to **Appendix A** for additional information regarding the monthly average.

Figure 1 shows several loading scenarios under varying flow rates and effluent phosphorus concentrations.

Figure 1
Phosphorus Loading Under Various Flow Scenarios



As **Figure 1** demonstrates, an effluent phosphorus concentration of 0.5 mg/L at the City's current average annual flow rate of 0.33 MGD provides a mass load of 0.64 kg/day. Similarly, a mass load of 0.64 kg/day can be met at the maximum day design flow rate of 1.3 MGD for the tertiary treatment system if the effluent phosphorus concentration is 0.1 mg/L or less. This is important to note since the treatment system may initially be operated without the addition of metal salts. The addition of metal salts may be detrimental to the biological phosphorus removal process; therefore, backwash streams from the treatment system may be directed to the evaporation pond or a new storage pond for stabilization and settling. The City will need to periodically remove the accumulation of phosphorus / metal salt precipitates. This additional maintenance item was considered in the evaluation of alternatives in addition to the cost of using chemicals.

SCREENING OF THE IDENTIFIED TREATMENT ALTERNATIVES

The following treatment alternatives were identified for screening and evaluation.

1. No action alternative.
2. Cloth media filtration.
3. Continuous backwash granular media filter.
4. Conventional granular media filtration.

5. High rate ballasted clarification.
6. Membrane filtration.

Alternative 1 – No Action Alternative

The No Action Alternative may not always meet the phosphorus loading limitations that will be required for the Wenatchee River in 2020. This alternative was eliminated from consideration in the initial screening of alternatives.

Alternative 2 – Cloth Media Filtration

Effluent from a flocculation tank enters the inlet of the cloth media filter where solids are deposited on the cloth media. The solids form a mat as the filtrate flows through the cloth media. The heavier solids settle to the bottom of the tank. As the tank liquid level rises, the solids are backwashed via a vacuum pump or backwash spray nozzles. Filtration continues even during backwashing. The settled solids are removed using a backwash pump and will be conveyed to the solids handling system.

The advantages to this alternative include simple operation and maintenance, a small footprint, and low capital cost (**Table 6**). This alternative was retained for further evaluation. A cloth media filtration system can be operated with or without chemical addition depending on what is needed to meet the mass loading limit at future flow rates.

Alternative 3 – Continuous Backwash Granular Media Filter

This alternative consists of sand media installed in steel or fiberglass reinforced plastic (FRP) filter vessels. The influent enters near the top of the vessels and is distributed at the bottom of the vessel via radial distribution arms. The influent moves upwards through the downward moving sand bed and the contaminants are captured by the media. The clean filtrate exits at the top of the filter vessel over a weir. The media is periodically scoured using compressed air and continuously backwashed. The reject consists of the removed contaminants in a liquid stream.

The advantages to this alternative include simple operation and maintenance, a small footprint, and low capital cost (**Table 6**). This alternative was retained for further evaluation.

Alternative 4 – Conventional Granular Media Filtration

This filtration alternative consists of sand media installed in pre-packaged filter bays that remove contaminants that are in large flocs. After coagulant addition to bind the phosphorus particles, the solids are removed by the filter media. The filter requires periodic backwashing to remove the retained solids from the media. The filter bays operate independently of each other to allow continuous filtration during backwashing.

This system requires a large footprint and a sizable backwash supply. This alternative was not retained for further evaluation due to the large footprint and backwash volume requirements.

Alternative 5 – High Rate Ballasted Clarification

This alternative incorporates the use of finely divided magnetic ballast (CoMag®) to bind precipitated phosphorus and other fine particulates. The reported quality of effluent produced by this technology approaches or meets the performance of ultrafiltration. Magnetite provides a "magnetic ballast seed" that when mixed with a metal salt and polymer, significantly increases flocculation and settling rates. The floc then flows to a tertiary treatment clarifier for settling. The magnetite ballast is recovered from the waste sludge magnetically and returned to the treatment system.

This alternative was eliminated from further consideration due to its high capital cost (**Table 6**).

Alternative 6 – Immersed Membranes

This alternative would use pressurized membrane filters to produce a high-quality effluent. An example of such a system is Z-Pak™, a patented ultrafiltration water treatment system marketed by GE Water and Process Technologies. The process consists of banks of ultrafiltration hollow fiber membranes immersed in the secondary effluent liquid; treated water is pumped through the membrane pores and into the hollow fibers.

The capital cost associated with this alternative is significantly more than the cost of the other alternatives. Due to the high capital cost (**Table 6**), the availability of simpler technologies, and the higher operation and maintenance costs, this alternative was eliminated from further consideration.

Table 6 presents the equipment proposal prices and planning-level total constructed costs of the phosphorus removal alternatives evaluated. These estimates include a 20-percent contingency and 8.2-percent sales tax.

Table 6
Equipment and Total Constructed Cost for the Phase I Phosphorus Removal Alternatives

	Process	Manufacturer/ Equipment	Equipment Proposal	Total Constructed Cost
1	High Rate Ballasted Clarification	Parkson CoMag	$743,000	$3,400,000
2	Cloth Media Filtration	Aqua-Aerobic AquaDisk	$190,000	$2,100,000
3a	Continuous Backwash Granular Media Filter	Blue Water Technologies	$375,000	$2,000,000
3b	Continuous Backwash Granular Media Filter	Parkson Dynasand	$1,067,000	$4,100,000
4	Conventional Granular Media Filtration	IDI Aquazur	$440,000	$3,000,000
5	Immersed Membranes	GE Z-pak	$1,390,000	$6,500,000

EVALUATION OF SCREENED PHOSPHORUS REMOVAL ALTERNATIVES

Based on the initial screening described above, the following alternatives were evaluated in greater detail.

- Alternative 2 – Cloth Media Filtration
- Alternative 3 – Continuous Backwash Granular Media Filter

Considerations used for the evaluation of the alternatives included:

- Initial cost comparison;
- Operation and maintenance cost;
- Environmental stewardship;
- Operability and maintainability;
- Land use; and
- References.

Alternative 2 – Cloth Media Filtration

This alternative would use cloth media submerged in wastewater to filter particulates and the phosphorus flocs. Two manufacturers were considered in this alternative, Aqua-Aerobic Systems, Inc. (Aqua-Aerobic) and Kruger, Inc. The following description is based on the AquaDisk™ by Aqua-Aerobic. The system includes one 4 disk cloth media filter with a nominal filtration rating of 5 microns submerged in a painted carbon steel round bottomed tank, backwash and waste pump, and a local control panel. The secondary effluent will flow by gravity through the cloth media with an outside-in mode. The backwash cycle is initiated at a predetermined level or time and the solids are removed by a stationary backwash suction head. The suction head functions similar to a vacuum cleaner. A manifold creates suction to force filtrate back through a small portion of the filter panels from both sides of each disk. The disk rotates slowly to allow the entire surface of the filter panels to be cleaned. The disks are cleaned in multiples of two and during backwash cycles filtration is continuous. The cloth disks are stationary except during a backwash cycle. There is one 2 horsepower (hp) backwash pump and one 0.5 hp shaft driver. The backwash valves and motors are automatically controlled. The filtration surface area is 215 square feet. The average hydraulic loading is 1.9 gallons per minute per square foot (gpm/sf) and the maximum hydraulic loading is 4.2 gpm/sf.

It is anticipated that this alternative can be used without chemical addition to remove some phosphorus at the average annual influent flow rate. Addition of chemicals significantly improves phosphorus removal but it increases cost, complexity, and environmental impacts. Chemical addition involves rapid mixing of the metal salt (ferric or alum) and may require pH adjustment and/or polymer upstream of the filtration system. A flocculation tank with a 5 to 8 minute detention time at the maximum day flow will be required. The filtrate will be returned to the ultraviolet (UV) disinfection system for disinfection prior to discharge to the Wenatchee River. The backwash waste will be sent to the in-plant pump station (if no metal salts are used) or to the existing evaporation pond (if metal salts are used, which is anticipated to be a future condition). An evaluation of the sizing of the existing evaporation pond will be required in the future since it was sized for the belt filter press filtrate and did not include considerations for the tertiary treatment waste. Additional storage may be required as influent flows increase in the future, especially as the City adds an additional treatment train for Phase II. The solids retained in the bottom of the disk filter that is periodically removed will be conveyed to the solids handling system for processing. This process will increase the loading to the belt filter press when in operation which means the belt filter press will need to be operated more frequently (see **Conclusions and Recommendations** section).

The advantages to this system is simple operation with low power requirements and operation and maintenance costs. Operator attention is minimal. The cloth media does need to be periodically replaced. The disks come apart into six segments so that they are lightweight and easily handled.

Alternative 3 – Continuous Backwash Granular Media Filter

Two types of continuously backwashed granular media filters were evaluated. The first system was the Blue Pro® sand filter by Blue Water Technologies. This filtration system uses reactive filter media within a moving bed filter that is continuously regenerated to lower phosphorus levels. This system requires a continuous feed of ferric chloride to coat the media surface to provide an adsorptive surface to facilitate the attachment of the phosphorus particles. This coating is continuously regenerated with the ferric chloride feed. Since this system uses ferric to coat the sand, the City would be obligated to use ferric chloride. Ferric may have an adverse effect on the UV disinfection system quartz sleeves due to iron burning.

The second system evaluated was Parkson's Dynasand® D2 sand filtration system. This system is similar to Blue Water Technologies. It consists of six continuously self-cleaning fiberglass reinforced plastic (FRP) or steel filters arranged in series for a dual pass system; this is Parkson's standard when phosphorus removals are required below 0.1 mg/L. The filter operation is similar to Blue Water Technologies. The first stage has a larger sand volume, will remove the greater amount of contaminants, and will function as the coagulation, flocculation, and separation steps. The second stage will serve as a polishing filter for the filtrate of the first stage. The Dynasand D2 media can use alum or ferric salts to assist with phosphorus removal.

Both of the continuous backwash granular media filtration systems require metal salts to get good filtration. The metal salt addition can be injected via a static mixer. According to both manufacturers, a separate rapid mixing and flocculation tank is not required.

The advantages to this system is simple operation with low power requirements and operation and maintenance costs. Operator attention is minimal. Both continuous backwash granular media filtration systems are continuously backwashed using an internal washing system; therefore, there is no need for a separate backwash supply tank and pump. The air lifts need to be annually inspected and replaced every 2 to 5 years and roof hatches are required for the inspection and periodic replacement.

NON-ECONOMIC EVALUATION OF PHOSPHORUS REMOVAL ALTERNATIVES

Alternatives 2 (cloth media filtration) and 3 (continuous backwash granular media filter) were further compared using non-economic criteria that consisted of:

- Environmental stewardship;
- Operability and maintainability;
- Land use; and
- References.

Environmental stewardship refers to the assessment of the extent to which pollution is minimized, energy and resources are used efficiently, use of hazardous chemicals are decreased, environmental quality is improved, and the desired outcome is achieved. An important component of environmental stewardship is the ability of the technology to reduce phosphorus without the use of metal salts.

Alternative 3 requires the use of metal salts in order to reduce the phosphorus to any level. This is especially true with the Blue Water Technologies reactive media since the media relies on the ferric addition to coat the media with an adsorptive surface. Alternative 3 will require metal salt addition upon startup and will continue to be needed in perpetuity. The phosphorus/metal salt precipitates resulting from the filtration process will need to be stored and periodically removed by the City. The production and disposal of the chemicals and related waste products have a long-term impact on the environment.

Alternative 2 can reduce some phosphorus and suspended solids without the addition of metal salts. Since influent flows to the City's WWTF plant currently average between 0.3 to 0.6 MGD, the small amount of reduction obtained by the cloth media filters (without chemical addition) may be sufficient initially and for many years to come. The limited use of metal salts may eventually be required to reduce the phosphorus levels below the mass loading limitation.

Operability and maintainability considers the level of operational attention, control needed to maintain acceptable performance, frequency and difficulty of maintenance, ability of City staff to perform normal checks, simplicity of technology so that operation can be unattended or staffing is reduced, and the ability of maintenance staff to perform maintenance and move equipment and parts in and out of the area.

Both alternatives have similar levels of operability and maintainability in that the systems' operate with minimal operator attention and maintenance checks are minimal. Alternative 3 does require the removal of the air lifts for annual inspection and periodic replacement that may be considered unwieldy due to the length of the air lifts. Additionally, Alternative 3 does require a continuous metal salt feed that requires the continuous use of a metal salt chemical feed system.

Land use is the assessment of the overall site footprint and the ability to fit the facilities within the confines of the existing site. Both alternatives have a similar footprint and could be contained within a building that fits on the existing site. The height of the filters for Alternative 3 would require a taller building compared to Alternative 2.

References were contacted for the manufacturers considered in Alternative 2 and 3 and the summaries are included in the **Conclusions and Recommendations** section. In addition, an assessment on whether the technology has a proven, successful track record when applied in the same manner as proposed for the City was considered. There have been several published pilot study reports for Alternative 2. The internal pilot study data for Aqua-Aerobic is included in **Appendix B**.

ECONOMIC EVALUATION OF SCREENED PHOSPHORUS REMOVAL ALTERNATIVES

The Phase I capital costs presented are comparative planning-level opinion of construction costs based on conceptual sizing, including preliminary layouts of major structures and rough sizing of critical equipment. Capital costs are in 2014 dollars and operating costs are projected through 2034. Estimates of this type can be expected to vary from 50 percent less than to 30 percent more than the actual final project costs.

Estimated operation and maintenance (O&M) costs were developed for labor, energy, chemicals, and maintenance items. O&M costs were estimated using the following unit costs.

Table 7
O&M Unit Costs for Phosphorus Removal Alternatives

Cost Item	Units	Value
Labor (Including Fringes)	$/hr	$68.00
Electrical Power	$/kWh	$0.08
Ferric Chloride	$/gallon	$3.08

Notes:
1. Polymer and alkalinity costs not included until required dose and specific chemical is determined.
2. Ferric chloride selected as metal salt for O&M evaluation purposes only. Specific metal salt to be used will be determined during the pilot study.
kWh = killowatt hour

Table 8
Economic Evaluation of Phase I Phosphorus Removal Alternatives 2 and 3

	Process	Manufacturer/ Equipment	Equipment Proposal	Total Constructed Cost	O&M
2	Cloth Media Filtration	Aqua-Aerobic AquaDisk	$190,000	$2,100,000	$112,000
3a	Continuous Backwash Granular Media Filter	Blue Water Technologies	$375,000	$2,000,000	$107,000
3b	Continuous Backwash Granular Media Filter	Parkson Dynasand	$1,067,000	$4,100,000	$118,000

The O&M costs presented in **Table 8** assume chemical use for 7 months out the year which is the worst case scenario. It is likely that chemicals will not be required for cloth media filtration initially; however, this will need to be confirmed from the water quality data after the WWTF process has been stabilized.

Based on the information shown in **Table 8**, the following observations are made.

- Alternatives 2 and 3a (Blue Water Technologies) have similar capital and operational costs.
- The equipment proposal price for Alternative 2 is lower compared to Alternative 3a & 3b but the addition of a flocculation tank to Alternative 2 and supplementary feed systems has increased the total constructed costs.

CONCLUSIONS AND RECOMMENDATIONS

As part of the tertiary treatment alternatives evaluation, phone interviews were conducted to verify the performance of Kruger, Inc.'s Hydrotech Discfilter, Aqua-Aerobic's AquaDisk, and Blue Water Technologies Blue Pro systems. All technologies received favorable reviews concerning equipment expectations, operation and maintenance, and meeting permit limits.

Taking into consideration both the non-economic and economic evaluations, the following conclusion was made.

Alternative 2, cloth media filtration, was the preferred alternative. The AquaDisk units have the lowest unit cost per MGD and thus provide more value.

The disk filtration system will be housed in a pre-manufactured steel building that will be located northwest of the existing solids handling building. The building will be sized for the 20-year flow, will be heated, and will include HVAC. A rapid mixing and flocculation/coagulation tank will be located upstream of the disk filtration system. The tank dimensions are 12 feet by 8 feet by 10 feet. The building will include a chemical room to house the chemical feed and storage systems and a separate electrical room. The filter room will be large enough to accommodate a second treatment train for Phase II that will include a flocculation/coagulation tank and filtration unit for future installation as influent flows increase to a maximum day of 2.6 MGD.

An influent lift station will pump the effluent from the secondary clarifier to the phosphorus removal process. The capacity influent lift station will be a peak flow of 1.3 mgd for Phase I. Phase I will include the installation of two pumps; each pump will be capable of 600 gpm. Additionally, the tertiary treatment system will be bypassed so that the effluent from the secondary clarifiers will be sent to the UV disinfection system if the tertiary system is offline for maintenance or equipment issues or during a power outage. Review of the City's electrical purveyor's records indicate that power outages are very infrequent and short in duration. **Appendix C** presents the updated flow diagram and hydraulic profile that includes the recommended tertiary treatment system.

The solids generated from the backwashing of the disc filters will be sent to the belt filter press for processes. **Table 9** presents the additional loading to the belt filter press under average and maximum day scenarios. A range is provided based on the results of the pilot study.

Table 9
Solids Generated from Disk Filter Backwashing

	Average Day			Max Day	
Year	Solids to be Dewatered from WWTF Process (dry lbs/day)	Solids Generated from Cloth Filtration Min. (lbs/day)	Solids Generated from Cloth Filtration Max (lbs/day)	Solids Generated from Cloth Filtration Min. (lbs/day)	Solids Generated from Cloth Filtration Max (lbs/day)
2015	937	83	135	179	293
2035	1,875	166	271	359	586

Table 10 presents the construction costs included in the selected tertiary treatment system construction for Phase I.

Table 10
Cloth Media Filtration Planning-Level Construction Cost Estimate – Phase I

Item No.	Description	Matl Units	Quantity	Total Cost (2014 $)
1	**Equipment Proposal**	**LS**	**1**	**$285,000**
2	**Site and Utilities**	**LS**	**1**	**$135,000**
	Utilities	LF	625	$125,000
	Site	LS	1	$10,000
3	**Building for Tertiary Equipment**	**LS**	**1**	**$271,000**
	Pre-engineered steel bldg	SF	2,600	$260,000
	Misc. Structural (5%)	LS	1	$10,400
4	**Flocculation Tank**	**LS**	**1**	**$380,000**
	Tank with Mixer and Mounting	LS	1	$375,000
	Misc. Mechanical	LS	1	$5,000
5	**Duplex Lift Station**	**LS**	**1**	**$95,000**
	Lift Station Complete	LS	1	$85,000
	Influent Mag. Meter	EA	1	$10,000
6	**Reject Handling**	**LS**	**1**	**$64,500**
	Pipes to Evap. Pond	LF	215	$32,250
	Pipes to IPPS (no chemicals)	LF	215	$32,250
7	**Chemical Feed System**	**LS**	**1**	**$269,000**
	Metallic Salt Dosing System	LS	1	$26,250
	Metallic Salt Product Tank	LS	1	$46,800
	Polymer Makedown System	LS	1	$18,025
	Alkalinity Feed System	LS	1	$102,000
	Rapid Mixer	LS	1	$75,000
8	**Electrical**	**LS**	**1**	**$72,000**
9	**Telemetry and Control**	**LS**	**1**	**$36,000**
	Subtotal Construction Costs			**$1,608,000**
	Contingency		20%	$321,600
	Sales Tax		8.2%	$131,856
	TOTAL Capital Construction Cost			**$2,100,000**

As previously noted, the City is only able to fund a portion of the Phase I tertiary treatment system with the USDA Rural Development remaining funds. It is anticipated that the City will be able to fund 34-percent of the total costs presented in **Table 10**. This percentage includes the procurement of the treatment equipment and the procurement and installation of the building (**Table 11**). The site utilities, lift station, flocculation tank, chemical feed and storage system, electrical, telemetry and control improvements will be funded at a later date by the City.

Table 11
Cloth Media Filtration Planning-Level Construction Cost Estimate – Phase I Partial

Item No.	Description	Matl Units	Quantity	Total Cost (2014 $)
1	**Equipment Proposal**	**LS**	**1**	**$285,000**
2	**Building for Tertiary Equipment**	**LS**	**1**	**$271,000**
	Subtotal Construction Costs			**$556,000**
	Contingency		20%	$111,200
	Sales Tax		8.2%	$45,592
	TOTAL Capital Construction Cost			**$713,000**

A preliminary site layout and equipment and mechanical layout for the recommended alternative are shown in **Figures 2** and **3,** respectively, for the Phase I improvements.

Figure 2
Cloth Media Filtration (Alternative 2) Preliminary Site Layout

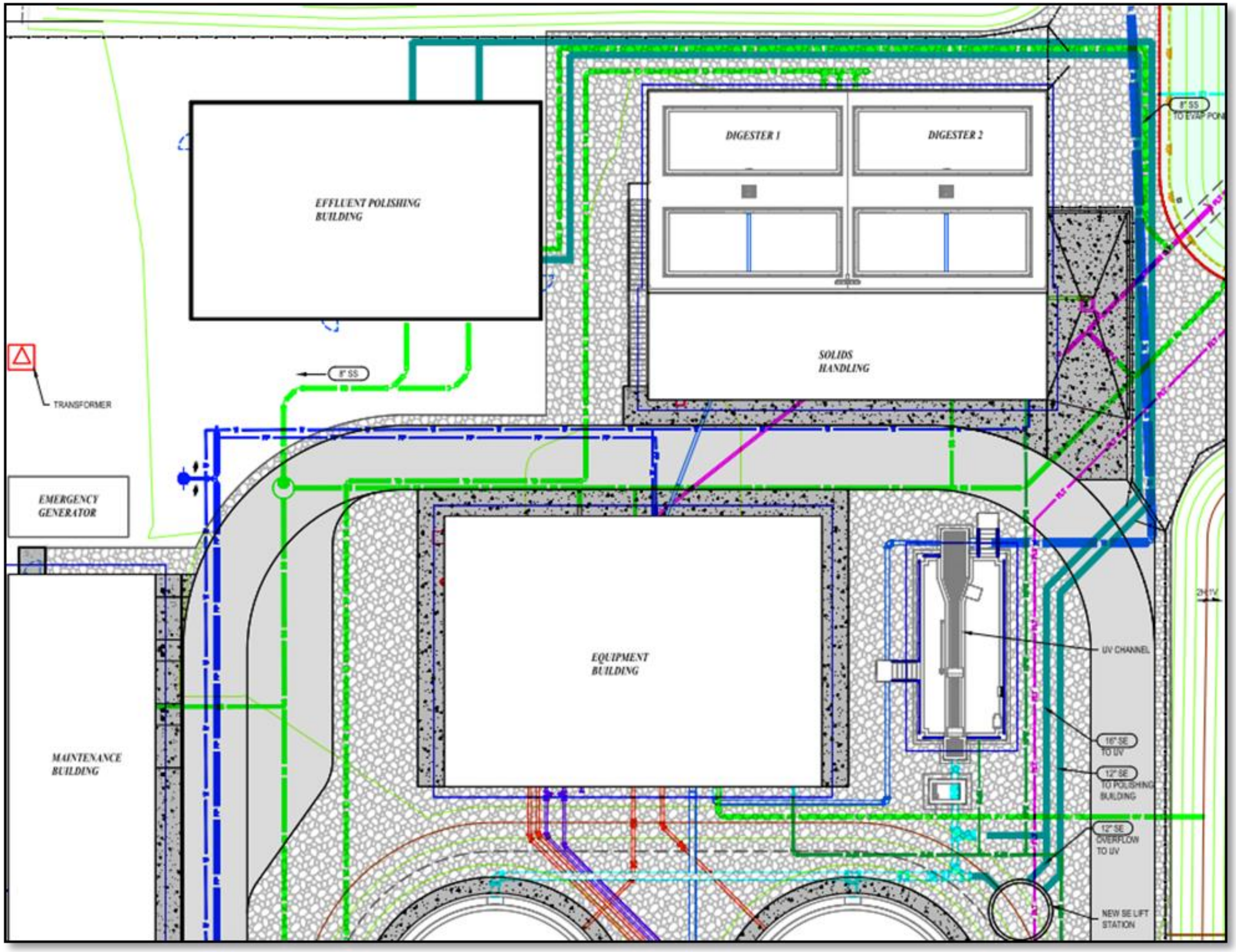
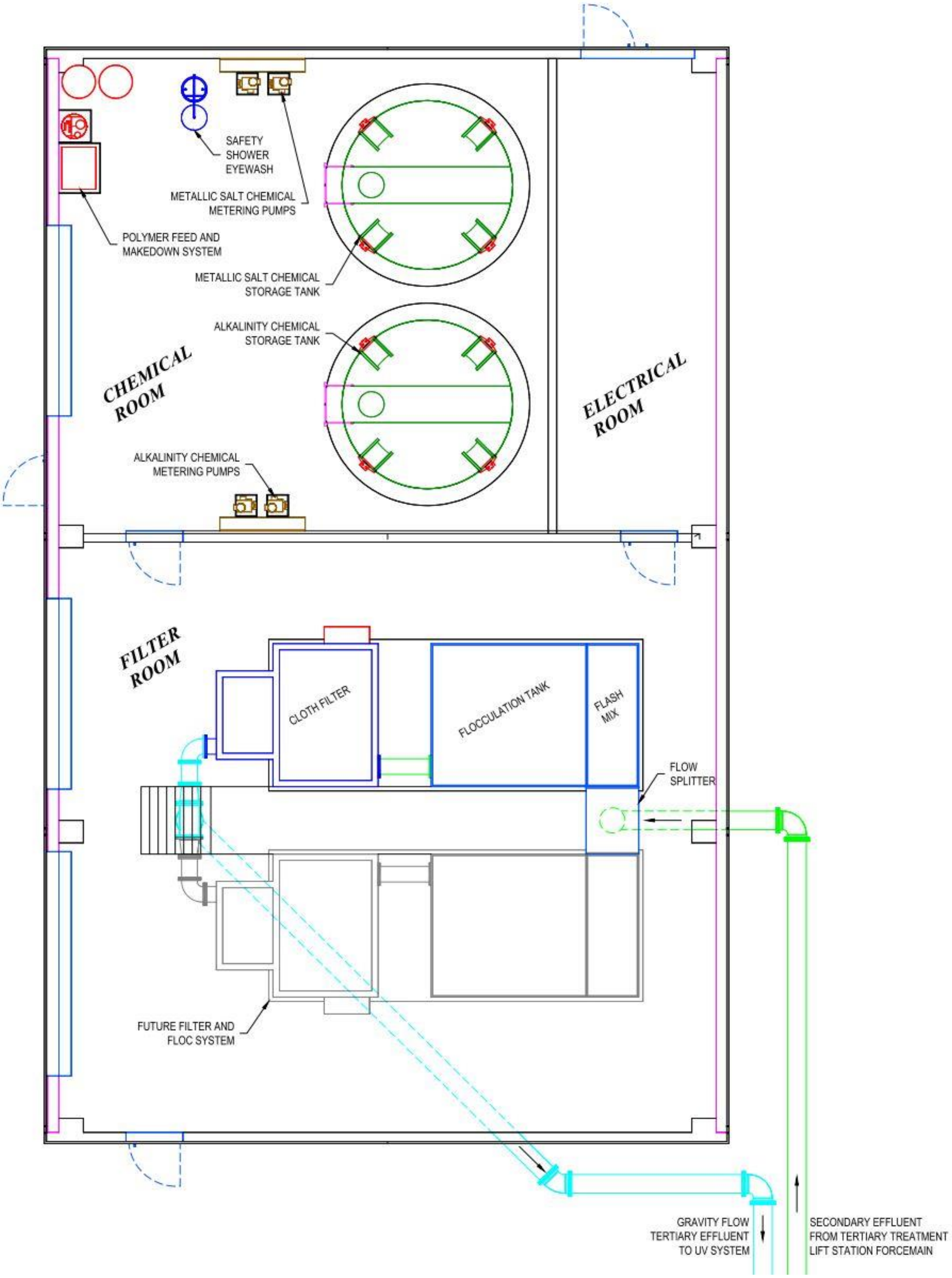


Figure 3
Cloth Media Filtration (Alternative 2) Equipment and Mechanical Layout



Summary of Filtration Pilot Study Results

Testing was conducted at the City's WWTF from February 23 to March 19, 2015, to evaluate the performance of the Aqua-Aerobic Systems, Inc., (AASI) OptiFiber PES-14® Cloth Media Filter System for treating secondary clarifier effluent from the City's WWTF. A report of the results and findings for this filtration pilot study was prepared by AASI, and copy of the report is included in **Appendix D**.

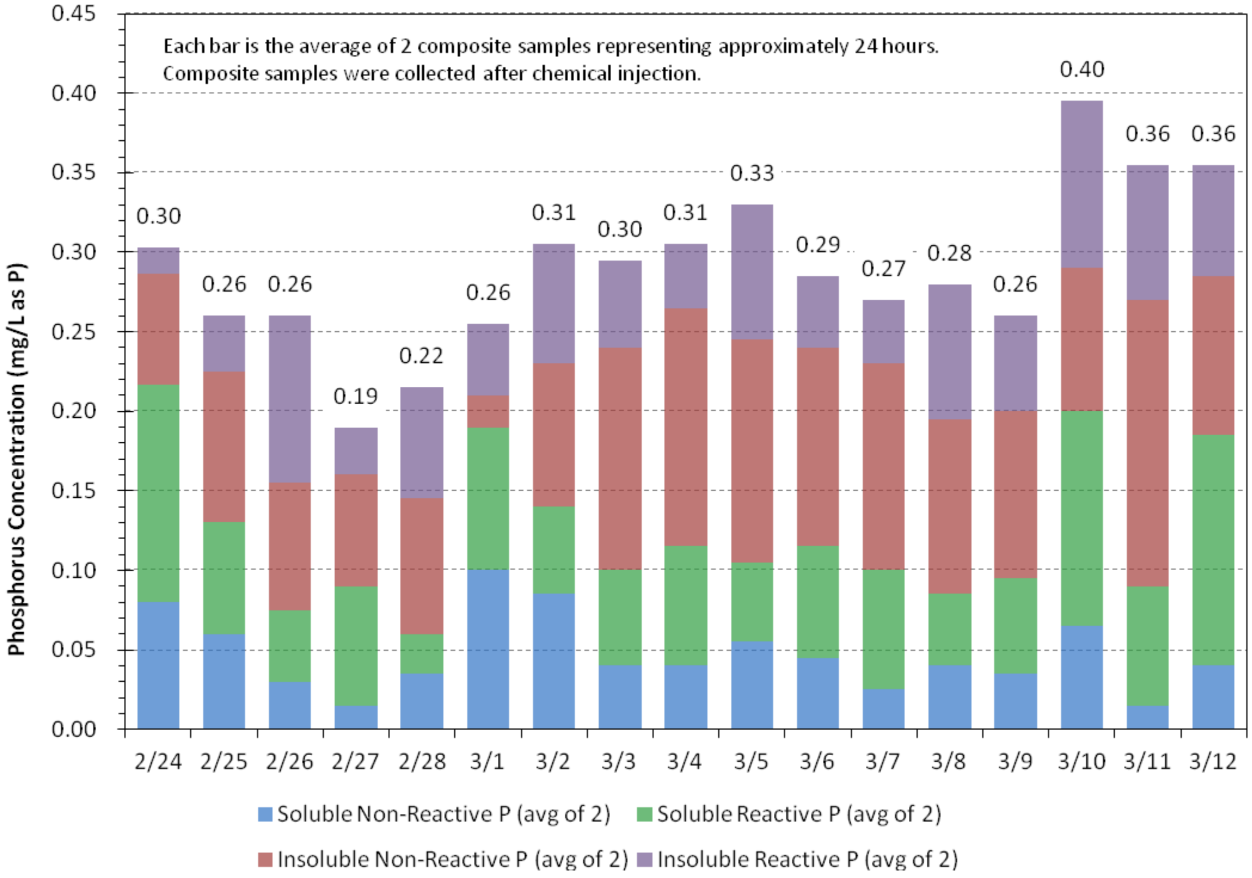
The AquaDisk Pilot System successfully reduced total phosphorus in the secondary effluent stream to less than 0.09 mg/L phosphorus as may be required at the ultimate design flow to meet the TMDL mass loading limit of 0.64 kg/day (Figure 10 of **Appendix D**). This was accomplished using alum and an anionic polymer for pretreatment. The chemical pretreatment operating conditions which were used to achieve the lowest phosphorus concentrations obtained during the pilot study were as follows:

- Alum doses greater than or equal to 70 mg/L as alum.
- Polyacrylamide polymer (20 percent anionic charge) at doses of 0.50 to 0.75 parts per million (ppm) as volumetric product.

Further optimization of the chemical usage to achieve low phospherus levels was beyond the scope of this pilot study. However, findings indicate that further optimization may be possible in the future if and when chemical additions and filtration are needed to meet the TMDL mass loading limit. Such further optimization could reduce chemical usage and waste volumes. A significant fraction of the effluent total phosphorus was measured by the analytical methods as being soluble and reactive. This would suggest that adjustments to the metal salt dose or pH adjustment would allow for more effective precipitation of the soluble phosphate. However, as discussed in greater detail below, the results of recent research funded by the Water Environment Research Foundation (Li, et al, 2015, and Li and Brett, 2014) demonstrates that the differentiation between soluble reactive phosphorus and other forms of particulate and non-reactive phosphorus is more complex that had been previously understood. More importantly, in terms of the water quality impacts of treatment plant effluent on receiving waters, these studies focused on the bioavailability of the various phosphorus species. The complete citations for these two Water Environment Research Foundation (WERF) studies, together with the Abstracts for each report, are included in **Appendix E**. The complete reports can be obtained from WERF.

The phosphorus speciation in the filter pilot influent (Secondary Effluent from the Cashmere EBPR WWTF) samples is summarized in **Figure 4**.

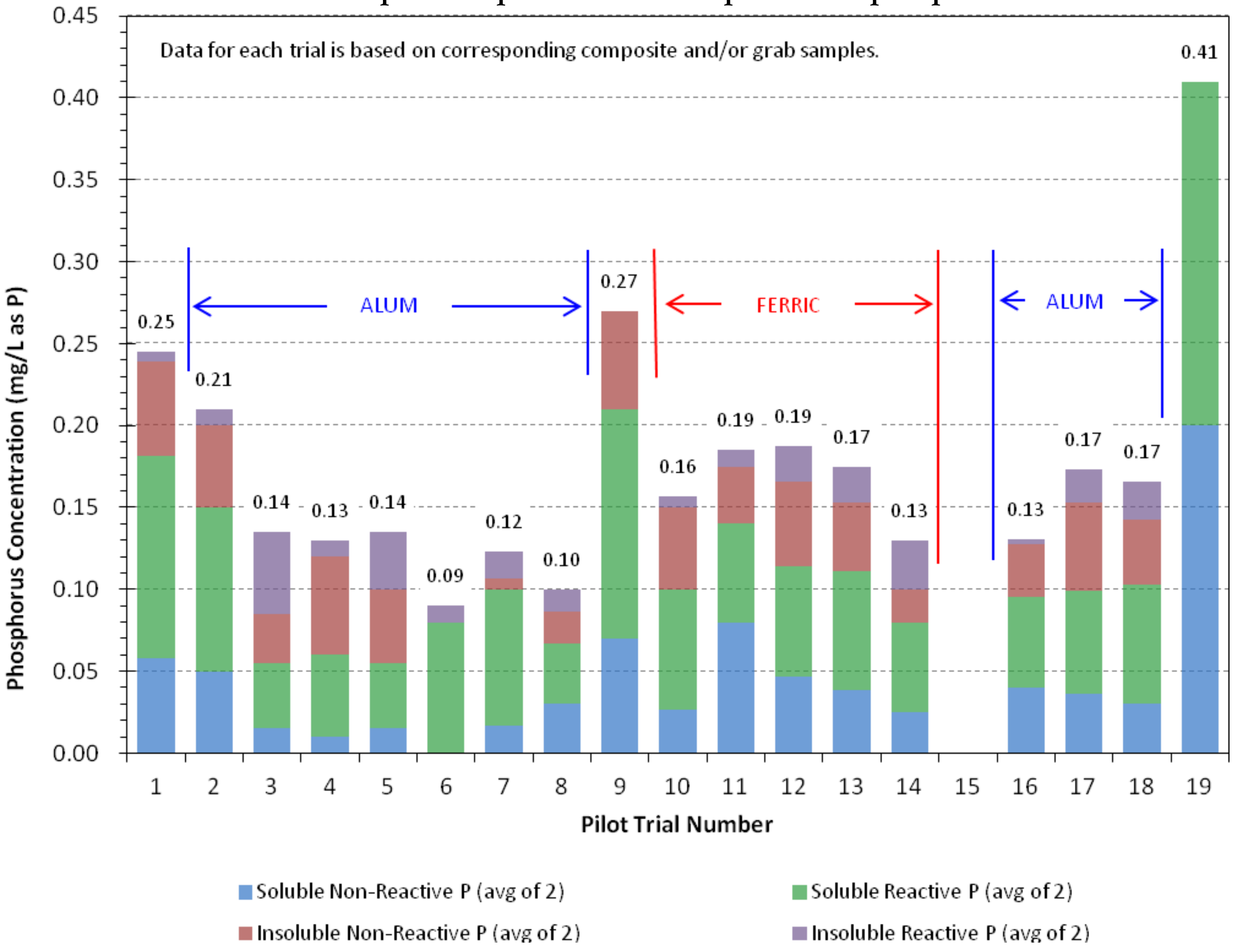
Figure 4
Pilot Filter Influent Phosphorus Species from Composite Samples per 24-hour Period



As can be seen in the data presented in **Figure 4**, the EBPR treatment systems is getting excellent phosphorus removal without any filtration or chemical treatment with secondary effluent composite sample phosphorus concentrations as low as 0.19 mg/L.

The phosphorus speciation in the filter pilot effluent samples is summarized in **Figure 5**.

Figure 5
Pilot Filter Effluent Phosphorus Species from Composite Samples per 24-hour Period



The results of the filter pilot study conducted at the Cashmere WWTP confirm that EBPR together with chemical addition and filtration can achieve low levels of effluent P.

However, the results of the WERF studies suggest that the effluent total reactive phosphorus (TRP) concentration has the strongest statistical association with the total effluent bioavailable phosphorus (BAP) concentration and that the average total BAP to TRP ratio is 0.61 plus or minus 0.24 (about 61 percent). The authors state that the results of this work should encourage water quality modelers determining TMDLs to consider the importance of BAP when assessing the likely ecological impacts of municipal nutrient removal facility effluent discharges.

The WERF study results also indicate that the bioavailability and phosphorus species composition varies with the nutrient removal process and that in most cases a large portion (greater than 50 percent) of the effluent phosphorus was recalcitrant to algal growth. The research also characterized the bioavailability of a variety of well-defined phosphorus containing compounds. These results clearly showed the operationally defined phosphorus classification scheme from classic chemical methods is problematic. Algal phosphorus uptake experiments also suggest that phosphorus species with high bioavailability, including some organic phosphorus species, are unlikely to persist in natural surface waters because their uptake kinetics are very rapid. These results further suggest recalcitrant phosphorus compounds, such as humic-metal-phosphorus complexes, phytic acid and/or apatite may be the dominant components of the recalcitrant dissolved phosphorus in effluents identified in these and other studies.

Some of the important benefits of this recent WERF research as it relates to the City and other municipal treatment plants is that it:

- Provides a more scientific method for setting WWTF discharge permit limitations for effluent phosphorus based on actual algae bioavailability;
- Provides a basis to avoid unnecessarily high chemical use and reduce operation costs, sludge production, and greenhouse gas footprint for wastewater treatment; and
- Shows the classic soluble reactive phosphorus (SRP) chemical characterization is a poor predictor of the bioavailability of phosphorus containing compounds.

The recommendations of the WERF reports are consistent with and supportive of the approach that the City has taken to maximize the use of sustainable biological phosphorus removal and minimize the use of chemicals to achieve water quality improvement objectives in the Wenatchee River. In addition to the high costs and increase greenhouse gas footprint associated with chemical use, the residuals from chemical treatment with metal salts when returned to the activated sludge treatment process in side streams will interfere with the EBPR process. This becomes a vicious cycle leading to increased dependence on the use of chemicals for phosphorus removal.

The decision of whether or not the addition of chemicals should be based on a holistic assessment of impacts and measureable water quality benefits as part of an adaptive implementation approach to implementation of the Wenatchee River TMDL.

APPENDIX A

EFFLUENT PHOSPHORUS SCENARIOS

SCENARIO 1

Month		P (kg/day)	AAF (mgd)	P at AAF (mg/L)
March	Week 1	2.50	0.6	1.100
		2.50	0.6	1.100
	Week 2	0.64	0.6	0.282
		0.64	0.6	0.282
	Week 3	0.64	0.6	0.282
		0.64	0.6	0.282
	Week 4	0.64	0.6	0.282
		0.64	0.6	0.282
March Average		**1.10**	0.6	0.486
April	Week 1	0.20	0.6	0.090
		0.20	0.6	0.090
	Week 2	0.20	0.6	0.090
		0.20	0.6	0.090
	Week 3	0.20	0.6	0.090
		0.20	0.6	0.090
	Week 4	0.20	0.6	0.090
		0.20	0.6	0.090
April Average		**0.20**	0.6	0.090
May	Week 1	0.64	0.6	0.282
		0.64	0.6	0.282
	Week 2	0.50	0.6	0.220
		0.50	0.6	0.220
	Week 3	0.64	0.6	0.282
		0.64	0.6	0.282
	Week 4	0.64	0.6	0.282
		0.64	0.6	0.282
May Average		**0.61**		
Seasonal Average		***0.638***		

SCENARIO 2

Month		P (kg/day)	AAF (mgd)	P at AAF (mg/L)
March	Week 1	2.50	0.6	1.100
		2.50	0.6	1.100
	Week 2	0.64	0.6	0.282
		0.64	0.6	0.282
	Week 3	0.64	0.6	0.282
		0.64	0.6	0.282
	Week 4	0.64	0.6	0.282
		0.64	0.6	0.282
March Average		**1.10**	0.6	0.486
April	Week 1	0.41	0.6	0.181
		0.41	0.6	0.181
	Week 2	0.41	0.6	0.181
		0.41	0.6	0.181
	Week 3	0.41	0.6	0.181
		0.41	0.6	0.181
	Week 4	0.41	0.6	0.181
		0.41	0.6	0.181
April Average		**0.41**	0.6	0.181
May	Week 1	0.41	0.6	0.181
		0.41	0.6	0.181
	Week 2	0.41	0.6	0.181
		0.41	0.6	0.181
	Week 3	0.41	0.6	0.181
		0.41	0.6	0.181
	Week 4	0.41	0.6	0.181
		0.41	0.6	0.181
May Average		**0.41**		
Seasonal Average		***0.642***		

APPENDIX B

ALTERNATIVES 2 AND 3
PILOT STUDY INFORMATION

AQUA-AEROBIC SYSTEMS, INC.
Partnering for Solutions

Ultra Low Total Phosphorus Pilot Studies

Aqua-Aerobic Systems Inc. conducted a series of three pilot studies in preparation for ultra low total phosphorus permits across the country. The goal of these studies was to demonstrate the ability of cloth media filtration to meet stringent effluent total phosphorus permits. The following document summarizes the findings.

November 2013 Pilot Study

The first site tested is facing a future effluent total phosphorus limit of 0.075 mg P/L. The current configuration includes both biological and chemical phosphorus removal upstream of the filters. Filter influent total phosphorus varied between 0.25 and 0.56 mg P/L. The effluent total phosphorus was consistently below the 0.075 mg P/L target. The alum dose was maintained at 4.1 mg Al^{3+}/L. Polymer dosages were varied between 0.5 and 0.75 mg/L.

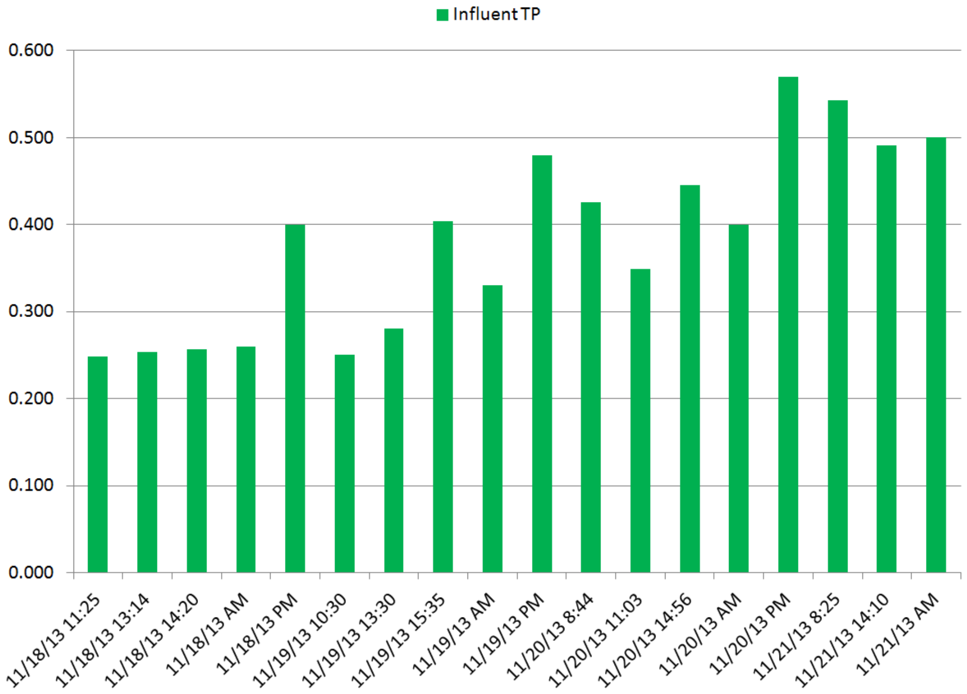


Figure 1: November 2013 Pilot Study Filter Influent Total Phosphorus

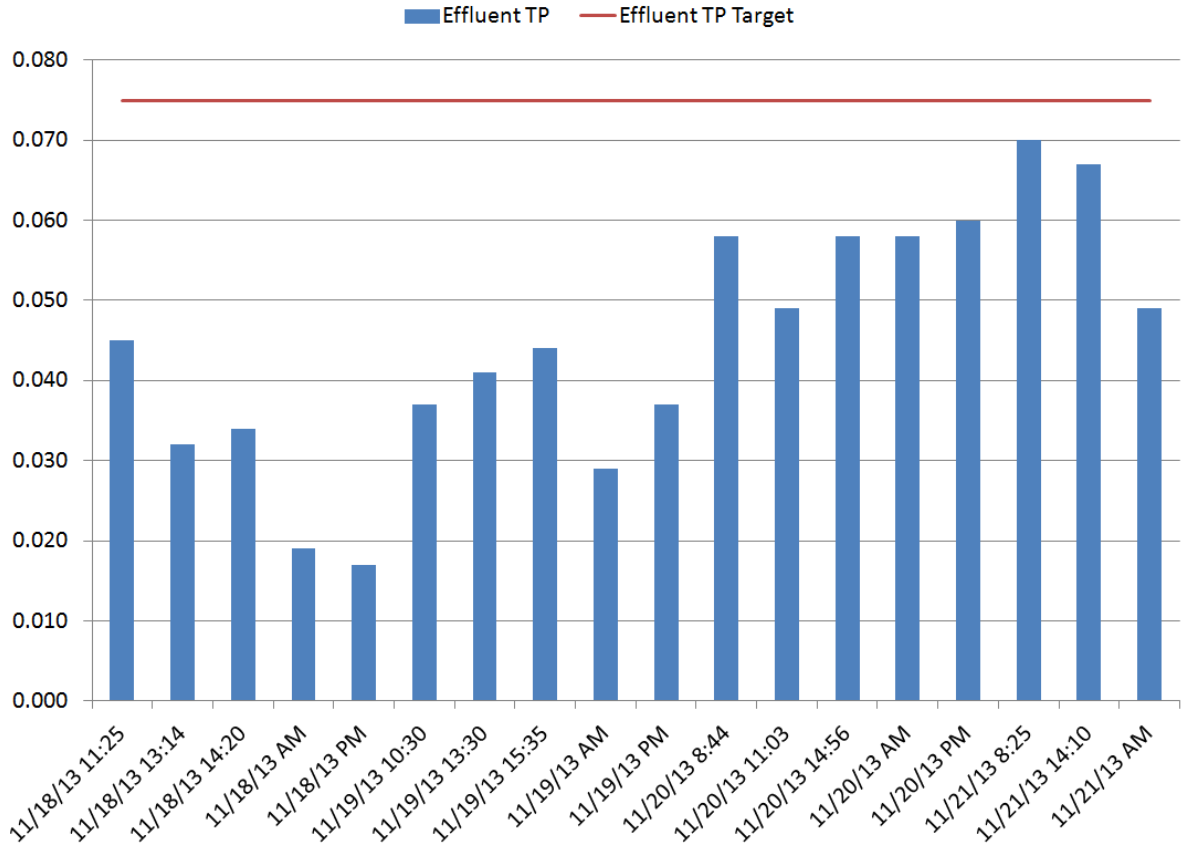


Figure 2: November 2013 Pilot Study Filter Effluent Total Phosphorus

December 2013 Pilot Study

The second plant tested also faces a future effluent total phosphorus permit of 0.075 mg/L. The current phosphorus removal configuration includes chemical phosphorus removal upstream of sand filters. The filter influent total phosphorus ranged from 0.38 to 0.89 mg P/L throughout the pilot study. A test of the phosphorus speciation was conducted before testing, which indicated that there was a high fraction of soluble, non-reactive phosphorus in the wastewater. To address this concern, the influent and effluent phosphorus speciation was monitored throughout the study. The effluent total phosphorus ranged from 0.058 to 0.074 mg P/L. The ferric chloride dose was between 0.95 and 1.5 mg Fe^{3+}/L. Polymer doses were varied between 0.75 and 1.0 mg/L.

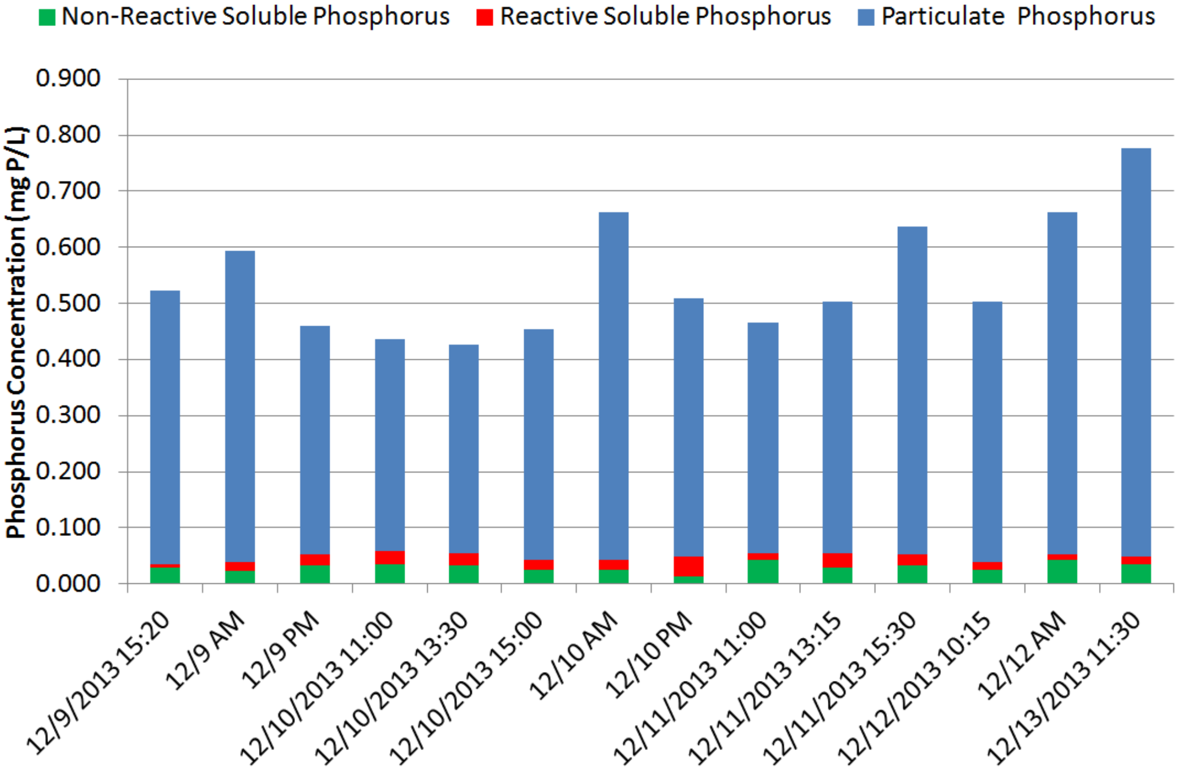


Figure 3: December 2013 Pilot Study Filter Influent Phosphorus Speciation

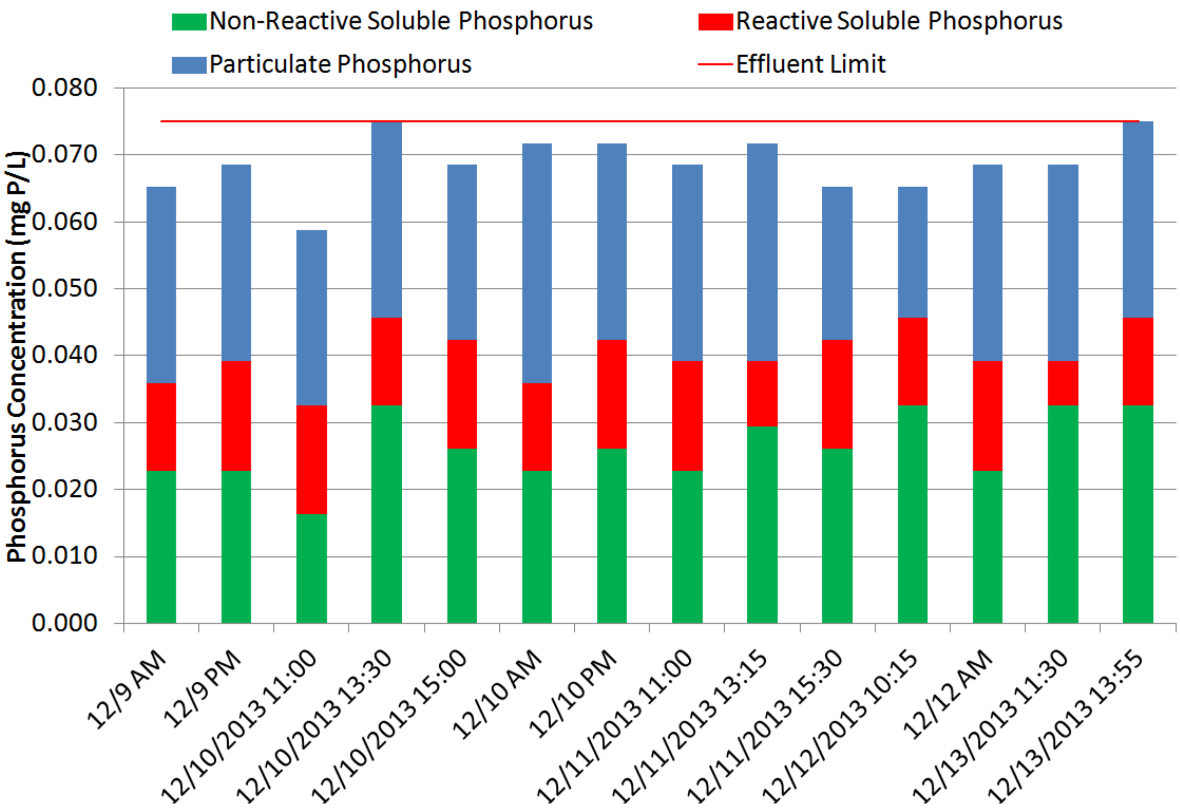


Figure 4 : December 2013 Pilot Study Filter Effluent Phosphorus Speciation

January 2014 Pilot Study

The third plant tested is also facing a future effluent total phosphorus permit of 0.075 mg/L. The current phosphorus removal configuration includes a biological and chemical phosphorus removal process. The filter influent total phosphorus ranged from 0.17 to 0.28 mg P/L throughout the pilot study. The effluent total phosphorus ranged from 0.02 to 0.075 mg P/L. The Fe+3:P molar ratios ranged from 13.7:1 to 25.7:1, averaging 19.7:1. The polymer dose was maintained at 0.25 mg/L.

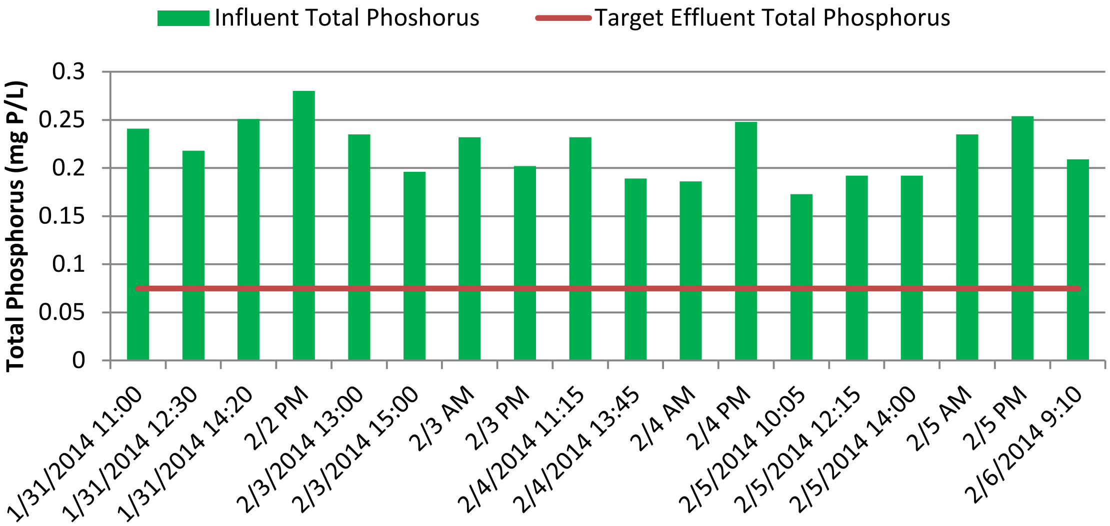


Figure 5: January Pilot Study Filter Influent Total Phosphorus

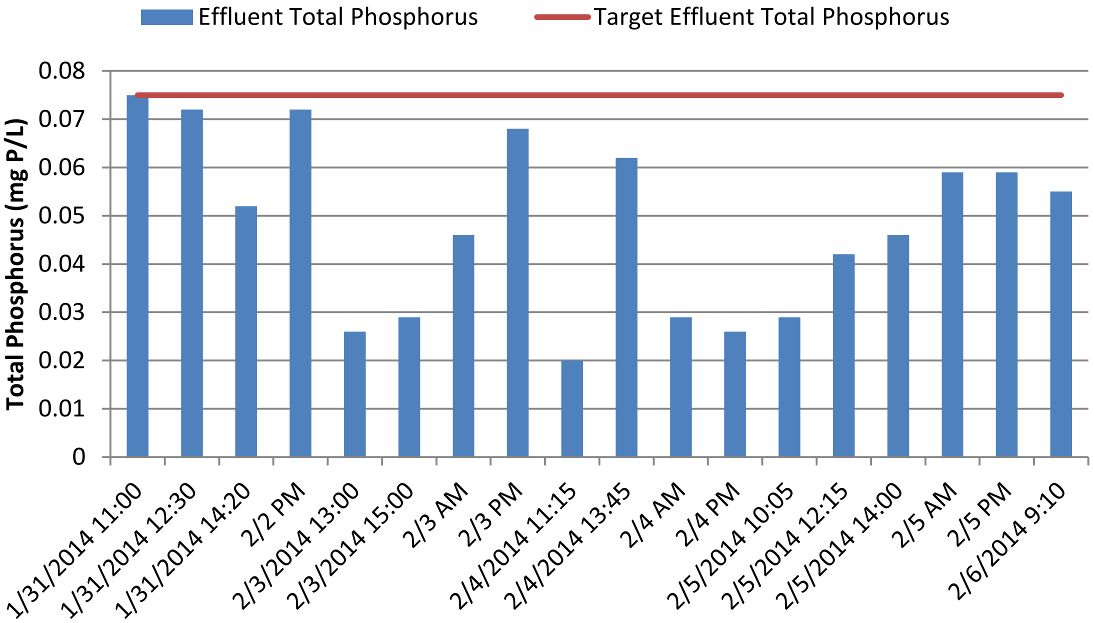


Figure 6: January 2014 Pilot Study Filter Effluent Total Phosphorus

BLUE PRO® CASE STUDY - PLUMMER WWTP, ID

Equipment:	Centra-flo® Gravity Sand Filter with Blue PRO® Four (4) Model CF-64
System Size	0.35 MGD average flow
Deliverable:	Less than 0.05 mg/L total phosphorus
Installation Date:	Start-up in September 2010
Locaton:	Plummer WWTP, Idaho

Low Level Phosphorus Removal

The new Plummer WWTP replaced an old lagoon plant for a small town. Upon startup, the plant is achieving <0.050 mg/L total phosphorus with a chemical dose of only 10 mg/L iron for the entire plant.

Plummer, Idaho arrived at a total phosphorus limit of <0.050 mg/L to protect water quality in the river that flows through town, and makes its way into Lake Coeur d'Alene. This low phosphorus discharge concentration was agreed upon through cooperation with the United States Environmental Protection Agency (EPA), the Idaho Department of Environmental Quality, and the local Coeur d'Alene Tribe. The entire Lake Coeur d'Alene, Idaho and Spokane River, Washington watershed area is a region heavily impacted by nutrient loading, particularly phosphorus from both point and non-point sources. The same impact can be seen in the Grand River and Lake Simcoe Watersheds.

A view of the Centra-flo® filters from below

Blue PRO® filter system, featuring Blue Water's custom air panel

System Design:

The new WWTP is a packaged biological nutrient removal (BNR) plant, with sequencing aeration and continuous clarification, including an anaerobic selector. The secondary system is intended to lower phosphorus to <1 mg/L biologically. This is followed by tertiary reactive filtration for phosphorus removal and UV disinfection. Final future design flow for the plant is 0.315 MGD.

The tertiary reactive filtration system consists of two continuous backwash, upflow filters with hydrous ferric oxide (HFO) coated sand for adsorption of phosphorus arranged in series. The reject streams from both filters are recycled to the secondary system that allows for the uptake of phosphorus by the excess adsorptive capacity leftover in the HFO waste particulates. The final fate of the HFO particulates is in the waste solids.

Performance testing at the plant was complete in October 2010, with results at 0.020-0.024 mg/L total phosphorus. Additionally, 24-hour composite testing for 7 consecutive days produced an average result of 0.036 mg/L total phosphorus. As plant operations stabilize the effluent concentration is expected to drop further.

In the reactive filtration system, ferric sulfate or ferric chloride is dosed in front of the filters to allow the continuous regeneration of the HFO coated sand. At Plummer, this iron dose is 6 mg/L as Fe in the first filter, and 4 mg/L as Fe in the second filter. Besides this 10 mg/L Fe, there is no other phosphorus removal chemical dosed in the system, and no pH adjustment is necessary.

BLUE WATER TECHNOLOGIES

Phosphorus Removal Achieved with Capital Affordability

Lincoln WWTP, Lincoln, Arkansas, USA

CHALLENGE

To deliver a filtration system that is easy to operate, affordable and achieves the city's phosphorus limits efficiently.

ENGINEER

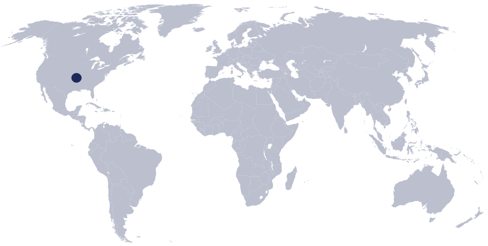
McClelland Consulting Engineers

RESULTS

The City of Lincoln received a 0.5 MGD average flow Blue PRO® system (with a 2.3 MGD peak flow) with a deliverable of 0.1 mg/L total phosphorus.

PRODUCT

Blue PRO® System



BACKGROUND

Phosphorus Removal

Lincoln is located in Washington County in the northwest corner of Arkansas. Its population was 2,249 at the 2010 census.

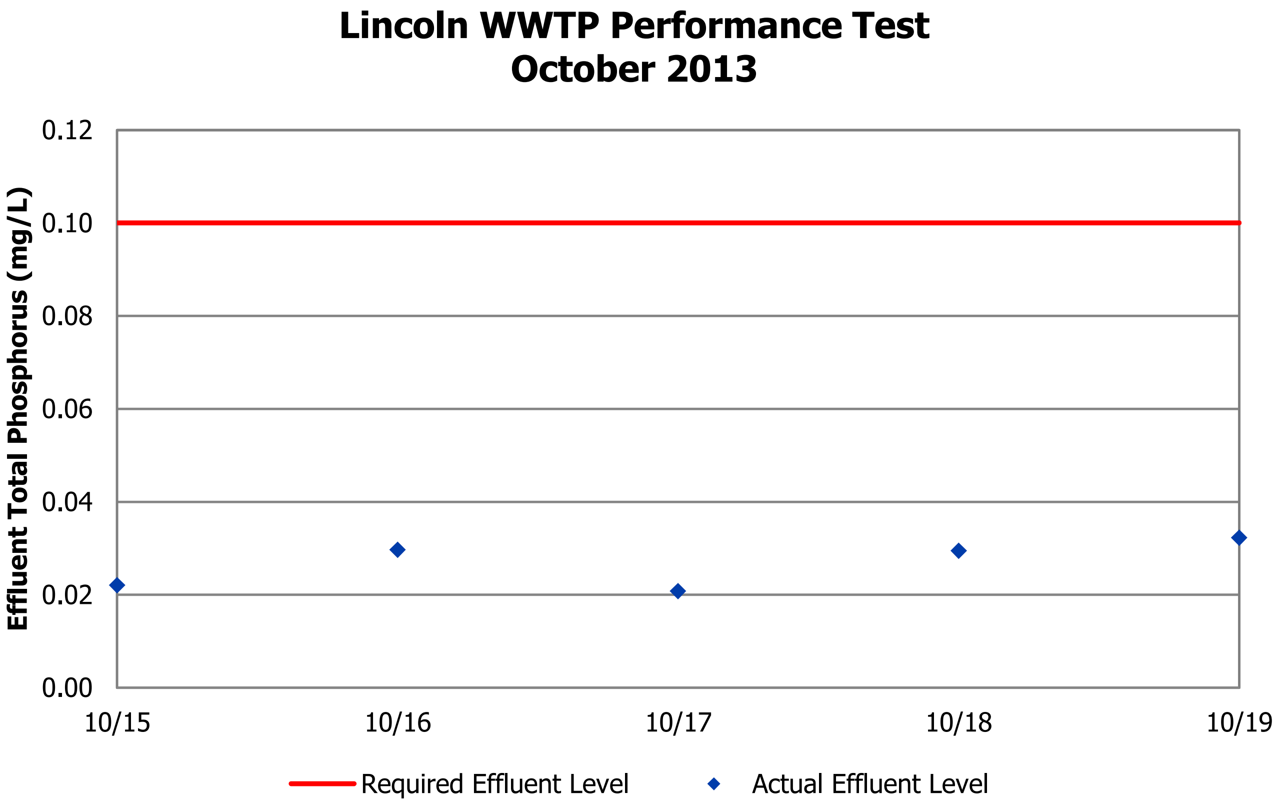
The Blue PRO® system was chosen for the City of Lincoln's wastewater treatment plant to meet a reduced and more stringent phosphorus requirement for discharge. McClelland piloted treatment while documenting treatment capabilities and technology lifecycle costs. The Blue PRO® system was the appropriate solution for the City of Lincoln, and provided the most flexibility for future needs. The Blue PRO® tertiary reactive filtration system consists of continuous backwash, upflow filters with hydrous ferric oxide (HFO) coated media for adsorption of phosphorus. The Blue PRO® system was selected for the project based on ease of operation, phosphorus results at pilot scale, capital affordability and minimized operating expense.

Six Model CF-64, 0.5 MGD average flow, 2.3 MGD peak flow phosphorus removal system at the Lincoln WWTP

System Design

The single-pass Blue PRO® system features six CF-64 vessels, and is very effective at meeting current treatment requirements. Potential future alterations to the discharge permit were considered through system design, and this technology platform provides an effective means of minimizing costly upgrades as discharge permits evolve. For example, the Blue PRO® process removes many dissolved metals, and these filters have detention time capacity for denitrification by adding a Blue NITE® control system.

CASE STUDY: Lincoln WWTP, Lincoln, Arkansas, USA



The Blue PRO® system air control panels

An influent flow splitting box evenly distributes flow to the treatment system

Results

An extensive system performance test was completed in October 2013. During this test period with the plant operating within Blue Water's design, residual total phosphorus in 24-hour composite samples averaged 0.027 mg/L. Single samples measured as low as 0.021 mg/L. Orthophosphate was never measured above 0.013 mg/L for the entire performance test.

BLUE WATER
TECHNOLOGIES

| 888.710.2583 |
| sales@bluewater-technologies.com |
| www.bluewater-technologies.com |

CASE STUDY

BLUE WATER
TECHNOLOGIES

Phosphorus Removal Achieved with Capital Affordability

Georgetown WWTP, Georgetown, Colorado, USA

CHALLENGE

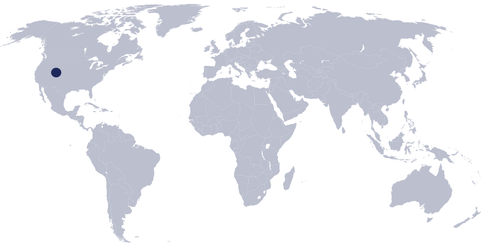
To deliver a filtration system that is easy to operate, affordable and achieves the city's phosphorus and zinc limits for wastewater efficiently.

RESULTS

The City of Georgetown received a 0.88 MGD avg. flow system (1.2 MGD peak flow) with a deliverable of 0.3 mg/L total phosphorus and 0.2 mg/L zinc.

PRODUCT

Blue PRO®
System



BACKGROUND

Phosphorus Removal

The Blue PRO® system was chosen for the wastewater treatment plant in Georgetown, Colorado as the only viable option to simultaneously overcome the city's challenges with both phosphorus and zinc. Georgetown is located within a historical mining district, and the wastewater plant experiences high influxes of zinc and cadmium in addition to the typical challenges regarding phosphorus in sewage treatment. The Blue PRO® tertiary reactive filtration system consists of continuous backwash, upflow filters with hydrous ferric oxide (HFO) coated media for adsorption of phosphorus and zinc. The Blue PRO® system was selected for the project based on ease of operation, pilot performance results, capital affordability and minimized O&M expense.

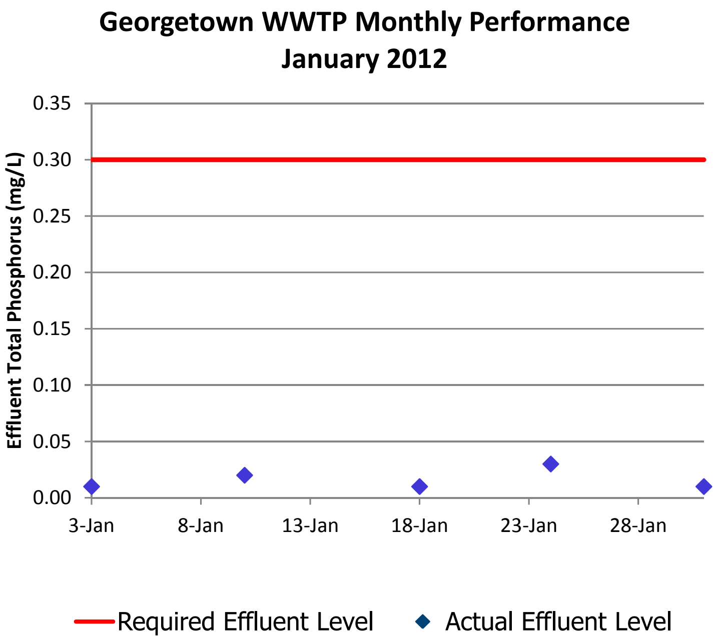
The building was erected during plant expansion and Blue PRO® filter installation.

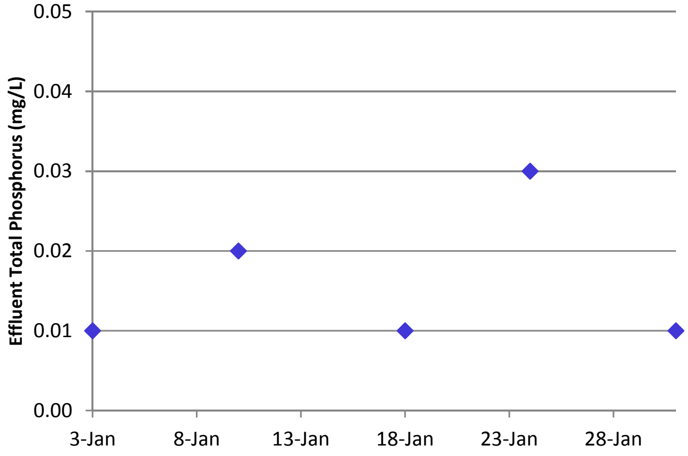
System Design

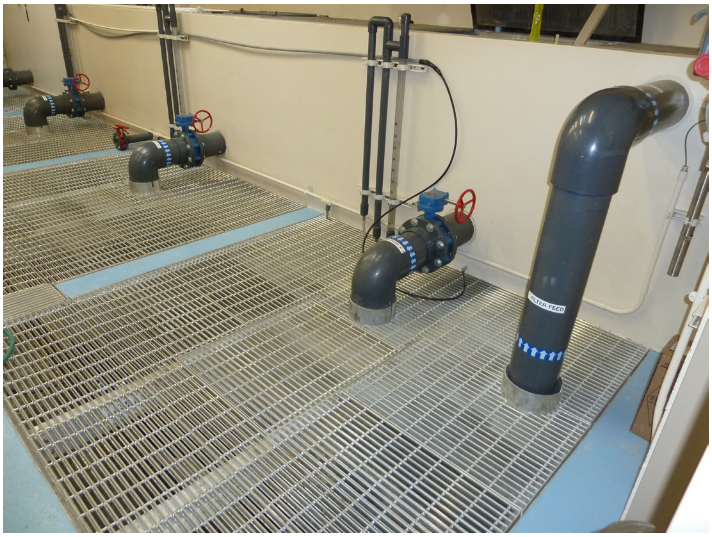
The single-stage Blue PRO® system features three CF-64 cells installed in concrete. Concrete for a fourth cell was installed for future lifecycle needs of the facility. With the system operating at 8,500 feet in elevation, the filters were enclosed in a building for freeze protection.

ZINC & PHOSPHORUS REMOVAL

Georgetown WWTP, Georgetown, Colorado, USA







Convenient in-ground installation of the Blue PRO® filters in Georgetown.

Results

A performance test was completed after system commissioning in May 2011. Per the performance specification with the plant operating within Blue Water's design, residual phosphorus and zinc in 24-hour composite samples met all performance criteria. Over the first year of operation this single-stage Blue PRO® system has managed as low as 0.01 mg/L P and 0.085 mg/L Zinc.

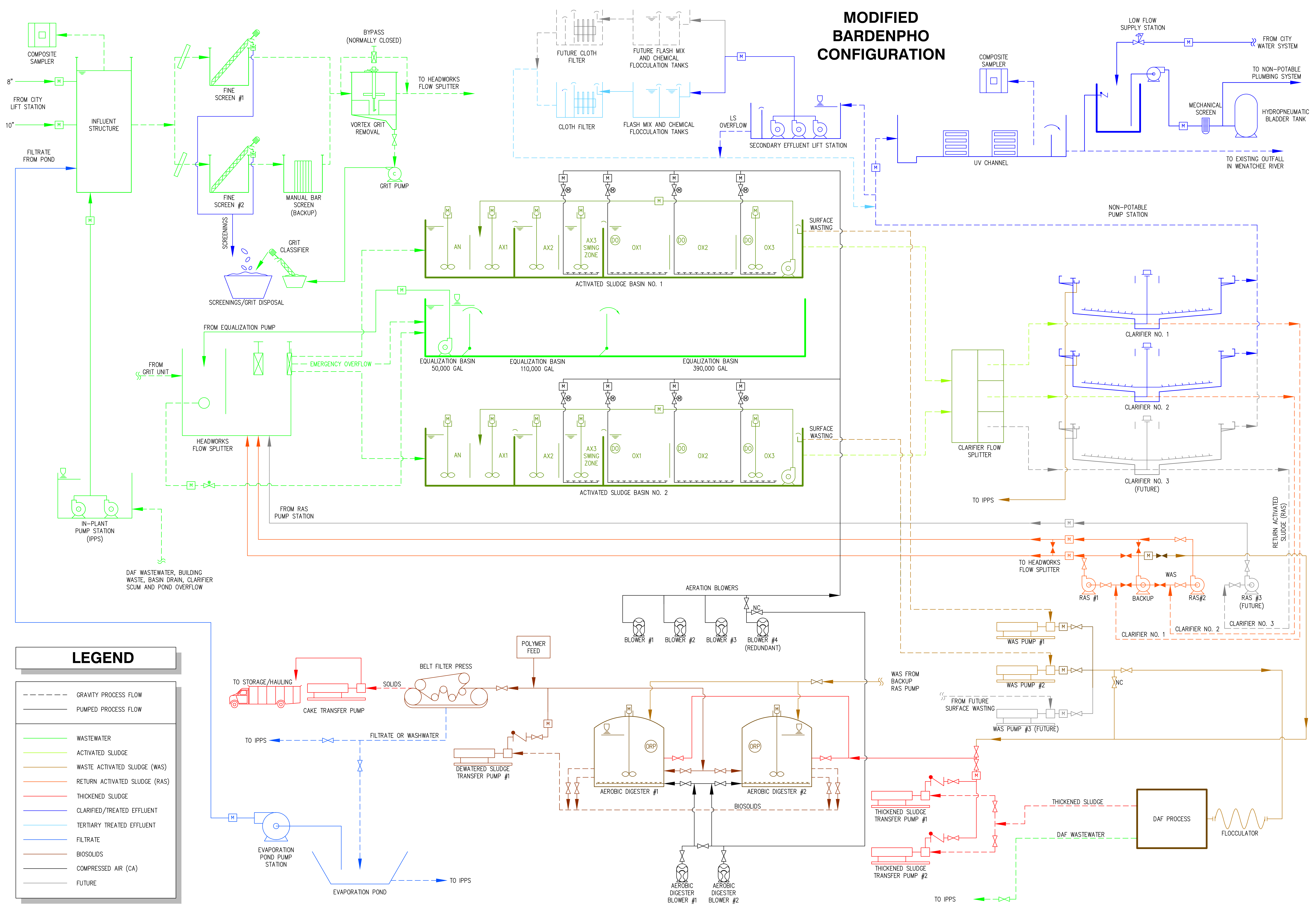
Concrete CF-64 cell prior to being charged with media.

BLUE WATER
TECHNOLOGIES

| 888.710.2583 |
| sales@bluewater-technologies.com |
| www.bluewater-technologies.com |

APPENDIX C

UPDATED FLOW DIAGRAM AND HYDRAULIC PROFILE



RICHARD L. BALLARD 32878

TONY V. PARDI 26978

RH2 ENGINEERS PLANNERS SCIENTISTS

RH2 ENGINEERING, INC.
www.rh2.com 1.800.720.8052
BOTHELL, WA
22722 29th Drive SE, Suite 210

CITY OF CASHMERE
WASTEWATER TREATMENT
FACILITY UPGRADES - PHASE 2

AREA 8 - TERTIARY TREATMENT

PRELIMINARY

PROCESS SCHEMATIC

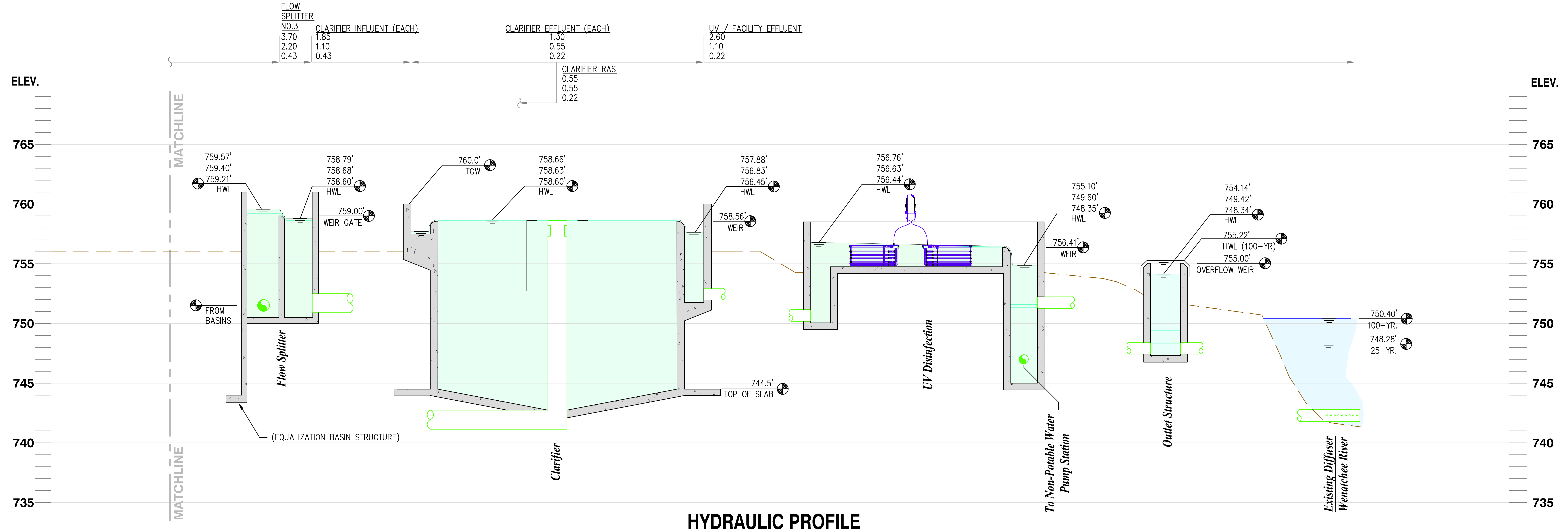
ENGINEER: ETS
REVIEWED: DJM
SAVE DATE: Nov 17, 2014
PLOT DATE: Nov 17, 2014
CLIENT: CA
FILENAME: CAWWTF-D-8G03.DWG
JOB NO.: 210-089

REVISIONS

NO.	DATE	DESCRIPTION	BY	REVIEW

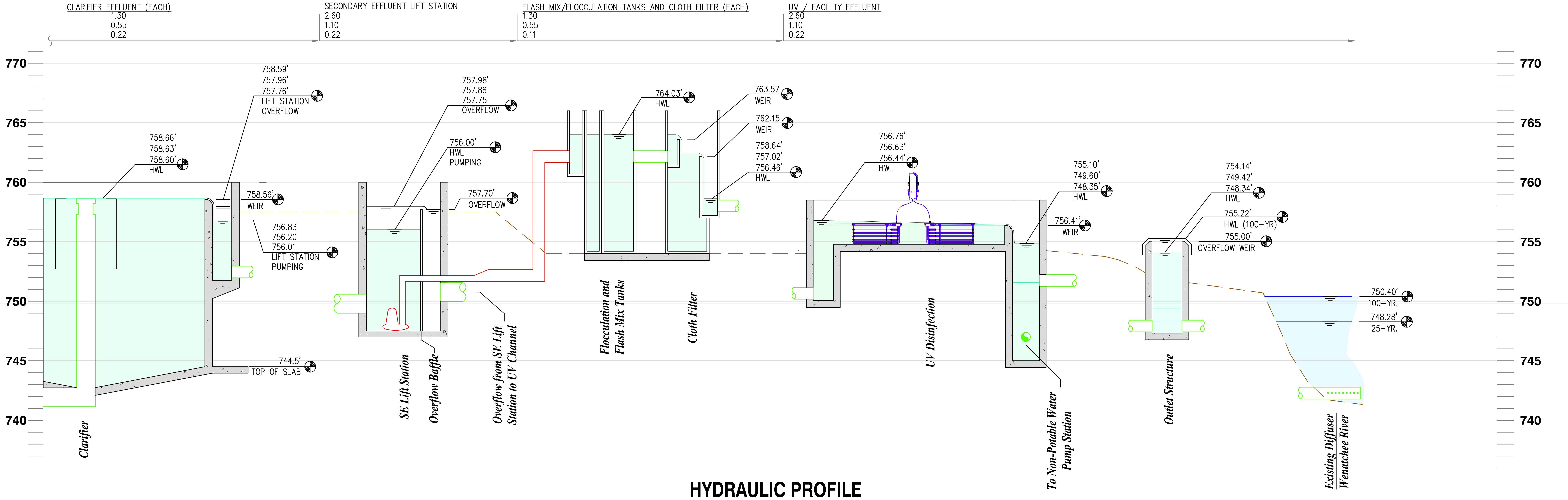
SCALE: SHOWN
0" 1" 2"
DRAWING IS FULL SCALE WHEN BAR MEASURES 2"

DWG NO.: G801
SHEET NO.: ----
YY



HYDRAULIC PROFILE
(WITHOUT TERTIARY TREATMENT)

H: NTS; V: 1" = 5'



HYDRAULIC PROFILE
(WITH TERTIARY TREATMENT)

H: NTS; V: 1" = 5'

ELEVATION LEGEND

754.14' ← MAXIMUM*
749.42' ← AVERAGE
748.34' ← MINIMUM
HWL

VERTICAL DATUM = NAVD88

*NOTE: PEAK FLOW THROUGH HEADWORKS UP TO EQUALIZATION BASIN DIVERSION MAY EXCEED MAXIMUM FLOW THROUGH REST OF PLANT. WHERE TWO MAXIMUM WATER SURFACE ELEVATIONS ARE LISTED AT THE HEADWORKS, THE FIRST ELEVATION IS BASED ON A PEAK FLOW OF 3.46 MGD THROUGH THE HEADWORKS. THE SECOND ELEVATION IS BASED ON A MAXIMUM PLANT FLOW OF 2.64 MGD.

GENERAL NOTES:

1. WATER SURFACE ELEVATIONS SHOWN THROUGHOUT THE PLANS MAY DIFFER SLIGHTLY FROM THOSE SHOWN ON THE HYDRAULIC PROFILE. ELEVATIONS SHOWN ON THE HYDRAULIC PROFILE ARE BASED ON FINAL DESIGN. WATER SURFACE ELEVATIONS SHOWN ON ALL OTHER PLANS ARE APPROXIMATE AND SHOULD BE TREATED AS SUCH.

RICHARD L. BALLARD
32878

TONY V. PARDI
26978

RH2
ENGINEERS
PLANNERS
SCIENTISTS
RH2 ENGINEERING, INC.
www.rh2.com 1.800.720.8052
BOTHELL, WA
22722 29th Drive SE, Suite 210

CITY OF CASHMERE
WASTEWATER TREATMENT
FACILITY UPGRADES - PHASE 2

PRELIMINARY

AREA 8 - TERTIARY TREATMENT
HYDRAULIC PROFILE

ENGINEER: ETS	SAVE DATE: Nov 17, 2014	CLIENT: CA	JOB NO.: 210-089
REVIEWED: DJM	PLOT DATE: Nov 17, 2014	FILENAME: CAWWTF-D-8G01.DWG	

REVISIONS

NO.	DATE	DESCRIPTION	BY	REVIEW

SCALE: SHOWN
0" 1" 2"
DRAWING IS FULL SCALE WHEN BAR MEASURES 2"

DWG NO.: G802
SHEET NO.: ----
YY

APPENDIX D

CASHMERE PILOT STUDY REPORT

AQUA-AEROBIC SYSTEMS, INC.
Partnering for Solutions

Evaluation of OptiFiber PES-14® Cloth Media Filtration for Treating Secondary Clarifier Effluent

Full-Scale Filtration Study

Testing Conducted at:

Cashmere Wastewater Treatment Plant
Cashmere, WA

February 23 – March 19, 2015

Printed on 4/16/2015

Table of Contents

List of Tables

List of Figures

EXECUTIVE SUMMARY

The Cashmere Waste Water Treatment Plant (WWTP), located in Cashmere WA, discharges effluent from its new enhanced biological phosphorus removal (EPBR) treatment plant to the Wenatchee River. A Total Maximum Daily Load (TMDL) study was completed by the Washington State Department of Ecology in 2009 which established a waste load allocation of 0.64 kg/day of total phosphorus (TP). At the maximum design flow of 1.88 MGD, as stipulated in the TMDL study, the 0.64 kg/day load allocation corresponds to 0.090 mg/L. The City of Cashmere is in the process of purchasing a chemical feed system, flocculation basin and one AquaDisk® Cloth Media Filter as needed to meet the future effluent phosphorus requirements. The filtration system would be upstream of the WWTP UV disinfection system, and the filtration system must not negatively affect UV operation. Aqua-Aerobic Systems, Inc.'s (AASI) OptiFiber PES-14® cloth filtration media is designed to achieve consistently low effluent particle-associated phosphorus concentrations. From February 23 – March 12, 2015 a single-disk Aqua MiniDisk® cloth media filter was tested at the Cashmere WWTP to quantify the effluent total phosphorus concentration under various chemical dosing strategies. Data from this study will allow for better prediction of the chemical dosages and operating costs required to meet future total phosphorus effluent objectives as low as 0.09 mg/L as P at the maximum design flow of 1.88 MGD as measured by laboratory analysis of composite samples.

Secondary clarified effluent, representative of typical operating conditions, served as the filter's feed water. Effluent quality was evaluated primarily based on TP; however, total suspended solids (TSS), turbidity, total soluble phosphorus, and total and soluble orthophosphate were also monitored.

RH2 Engineering, Inc. provided oversight on behalf of the City of Cashmere. AASI contracted Blueleaf, Inc. to provide field engineering services, to operate the pilot system, perform onsite water quality analyses, collect data and write the pilot report. Blueleaf is an impartial pilot engineering company that provides piloting services, and is not affiliated with any vendors or products. Cascade Analytical of Wenatchee Washington provided certified laboratory services.

FINDINGS

The AquaDisk Pilot System demonstrated the ability to reduce total phosphorus in the secondary effluent stream to less than 0.09 mg/L P. This was accomplished using alum and an anionic polymer for pretreatment. Effective chemical pretreatment operating conditions were:

- Alum doses ≥70 mg/L as alum.
- Polyacrylamide polymer (20% anionic charge) at doses of 0.50 to 0.75 ppm as volumetric product.

The scope of this study did not include further optimization of the chemicals which might be possible when operating the filtration system to achieve low total phosphorus levels in the filtered effluent. However, findings indicate that future optimization may be helpful in targeting even lower levels of effluent P or reducing chemical usage and waste volumes. A large fraction of the effluent total phosphorus was soluble and reactive, which would indicate that adjustments to the metal salt dose or pH adjustment would allow for more effective precipitation of the soluble phosphate.

1.0 INTRODUCTION

1.1 PROCESS DESCRIPTION

The pilot trailer is equipped with a single-disk Aqua MiniDisk filter having an available filter area of 11 ft^2. The completely submerged disk is divided into two equal segments and is fitted with OptiFiber® PES-14 cloth filtration media. There are three modes of operation: filtration, backwash, and solids removal from the bottom of the tank. Unlike many other filtration devices, filtration in the MiniDisk continues during the backwash and solids removal events.

For this pilot study, secondary clarifier effluent was pumped to the pilot unit. Coagulants and polymers were introduced into the feed piping prior to an in-line static mixer. After rapid mixing, flow was then discharged into a flocculation chamber and then to the filter tank. The flocculation basin volume was set to 250 gallons, which corresponds to a 6.4 minute HRT under average flow conditions. This HRT was selected to match the full scale flocculation tank design and is consistent with the manufacturer's recommendations on flocculation tank sizing. The flow was filtered by gravity through the cloth media, which removed solids by retaining them on the surface and within the depth of pile fabric medium. Backwash events were automatically initiated at an approximate 12-inch differential measured within the filter tank. The backwash mechanism cleaned the cloth by drawing a small amount of filtrate through a backwash shoe assembly. Deposited solids were removed from the bottom of the tank and discharged into an on-site retention pond.

Influent and effluent turbidity values were monitored continuously using two (2) GLI low range process turbidimeters. Influent flow was monitored using a Krohne IFC020D magnetic flow meter. Backwash flow was monitored using an ABB Model 10D1475 magnetic flow meter. Influent and effluent orthophosphate concentrations were monitored via two ChemScan® mini oP (ortho-phosphate) analyzers. The unit is PLC-controlled and is equipped with an electronic logging system for data acquisition.

1.2 CHEMICAL PRETREATMENT

Table 1 summarizes the properties of the coagulants used during the pilot study, and Table 2 summarizes the properties of the polymers. The methods for calculating the various chemical parameters are detailed in the following sections.

Table 1: Coagulant Properties

Parameter	Coagulant	
	Alum	Ferric Chloride
General molecular formula	$Al_2(SO_4)_3 \cdot 14H_2O$ (dry)	$FeCl_3$ (liquid)
Product	General Chemical Alum	Kemiron Standard Grade
Stock strength (bulk product by weight)	48.5% alum	42% $FeCl_3$
Specific Gravity (bulk product at 20°C)	1.335	1.40
pH	3.5	2.0
Alumina concentration (bulk product)	8.3%	Not applicable
Average molecular weight	594.4 g/mol alum	162.5 g/mol $FeCl_3$

Metal ion atomic weight	26.98 g/mol Al^{3+}	55.85 g/mol Fe^{3+}
Metal ion concentration (bulk product)	4.41% Al^{3+}	13.8% Fe^{3+}

Table 2: Polymer Properties

Polymer	Description
Polydyne EMA 20 PWG	Anionic polyacrylamide emulsion, 20% anionic charge
Polydyne EM 532 PWG	Anionic polyacrylamide emulsion, 20% anionic charge

Dose as Volumetric Product (ppmvp)

The method for calculating the chemical dose in terms of the volumetric product concentration is shown below. The units are parts per million as volumetric product (ppmvp). The volumetric calculation is independent of terms related to mass, e.g. specific gravity, density, or weight percentage. "Product" refers to the commercial chemical stock. Only polymer doses are reported herein as ppmvp (coagulant doses are reported as mass concentrations in units of mg/L). Polymers were obtained as emulsions, and diluted with water at a ratio of 1/100 (1% solution) to produce chemical feed stock for the pilot system.

$$Volumetric\ product\ dose\ (ppmvp) = \left[\frac{(R)(D)}{(Q)(3875.4\ ml/gal)}\right] x\ 10^6$$

Where: R = chemical feed rate (ml/minute)
D = feed stock dilution (D = 1% for polymer feed stocks)
Q = influent flow rate (gpm)

Dose as Mass Concentrations (mg/L)

The method for calculating the chemical dose in terms of the mass concentration is shown below. The units are milligrams per liter (mg/L). The specific gravity and stock strength refer to the commercial bulk product properties, i.e. 48.5% alum and 42% ferric chloride. Coagulants were fed neat, without dilution, therefore the dilution term (D) is equal to 1.

$$Dose\ (mg/L) = \left[\frac{(R)(D)(Strength)(SG)}{(Q)(3875.4\ ml/gal)}\right] x\ 10^6$$

Where: R = chemical feed rate (ml/minute)
D = feed stock dilution, if applicable (dimensionless fraction, coagulants were not diluted)
Strength = stock strength of bulk product (weight based percentage)
SG = specific gravity of bulk product
Q = influent flow rate (gpm)

The above equation was used only for coagulants. The following notes apply:

1. The coagulants (alum and ferric) were not diluted, therefore the value of *D* in the above equation would be one (1).
2. The stock strength (48.5%) for alum was based upon the weight percentage of dry hydrated aluminum sulfate in the bulk liquid product ($Al_2(SO_4)_3 \cdot 14H_2O$). Alum concentrations are therefore reported on a dry basis.

Product Usage (gal/MG)

Product usage values are identical to volumetric product doses, but the units are in terms of the gallons of bulk product applied per million gallons of treated water (gal/MG). This is useful for projecting chemical volumes and costs.

$$Product\ Usage\ (gal/MG) = \left[\frac{(R)(D)}{(Q)(3875.4\ )}\right] x\ 10^6$$

Where: R = chemical feed rate (ml/minute)
D = feed stock dilution, if applicable (dimensionless fraction)
Q = influent flow rate (gpm)

Metal Ion Mass Ratios (mg M^{3+} per mg TP)

Mass ratios were calculated using a Total P concentration of 0.298 mg/L. This was the average influent TP for the entire pilot study, based upon all of the field analyses: average influent TP = 0.298 ±0.062 mg/L, based on 58 data (field analyses), ranging from min 0.13 mg/L to max 0.49 mg/L). Coagulant doses remained constant for each individual trial, while the influent TP concentrations varied, meaning that the actual mass ratios would have varied with varying influent TP.

The atomic weight of aluminum is 26.98 g/mol. The molecular weight of alum (hydrated aluminum sulfate) is 594.39 g/mol. There are 2 aluminum atoms per aluminum sulfate molecule. The concentration of aluminum ion is calculated from the alum dose as:

$$C_{Al}\ (mg/L) = \left[\frac{2\ x\ 26.98}{594.39}\right] x\ (alum\ dose) = 0.091\ x\ alum\ dose$$

The atomic weight of iron is 55.85 g/mol. The molecular weight of $FeCl_3$ (ferric chloride) is 162.2 g/mol. There is 1 iron atom per ferric chloride molecule. The concentration of ferric ion is calculated from the ferric chloride dose as:

$$C_{Fe}\ (mg/L) = \left[\frac{55.85}{162.2}\right] x\ (FeCl_3\ dose) = 0.344\ x\ ferric\ dose$$

The mass ratio of either metal ion (C_{Al} or C_{Fe}) to Total Phosphorus is calculated as:

$$Mass\ ratio\ (mg{:}mg) = \frac{metal\ ion\ concentration}{average\ TP\ concentration} = \frac{C_M}{0.298}$$

Metal Ion Molar Ratios (mol M^{3+} per mol TP)

Molar ratios were calculated using a Total P concentration of 0.298 mg/L (the average influent TP for the entire pilot study by field analyses). The average TP molar concentration was calculated using the atomic weight of phosphorus (30.97 g/mol) as follows:

$$TP\ (molar) = \frac{0.298\ \ mg/L}{30.97\ x\ 10^3\ \ mg/mol} = 9.64\ \ \mu mol/L$$

The atomic weight of aluminum is 26.98 g/mol. The atomic weight of iron is 55.85 g/mol. The metal ion molar concentrations (Al^{3+} or Fe^{3+}) in units of micro moles per liter (µmol/L) were calculated as:

$$Al^{3+}\ (\mu mol/L) = \frac{1000\ \cdot\ C_{Al}}{26.98}$$

$$Fe^{3+}\ (\mu mol/L) = \frac{1000\ \cdot\ C_{Fe}}{55.85}$$

In the above equations, *C* indicates the mass concentration of either Al^{3+} or Fe^{3+} as calculated in the preceding section. The molar ratio of either the aluminum or ferric metal ion (M^{3+}) was calculated as:

$$Metal\ ion\ molar\ ratio\ = \frac{M^{3+}\ (\mu mol/L)}{TP\ (\mu mol/L)}$$

1.3 OPERATING CONDITIONS

Table 3 summarizes the operating conditions for each of the pilot trials. Figure 1 plots the coagulant doses (left vertical scale) and polymer doses (right vertical scale) by date. A total of 19 trials were conducted. Each trial used a unique combination of operating conditions, including:

- Coagulant type (alum, ferric chloride, or none).
- Coagulant dose (reported in mg/L of either alum or ferric chloride).
- Polymer type (EMA 20 PWG, EM 532 or none).
- Polymer dose (reported in ppmvp of the product).
- Influent flow rate (18 trials at 39 gpm, 1 trial at 70 gpm).

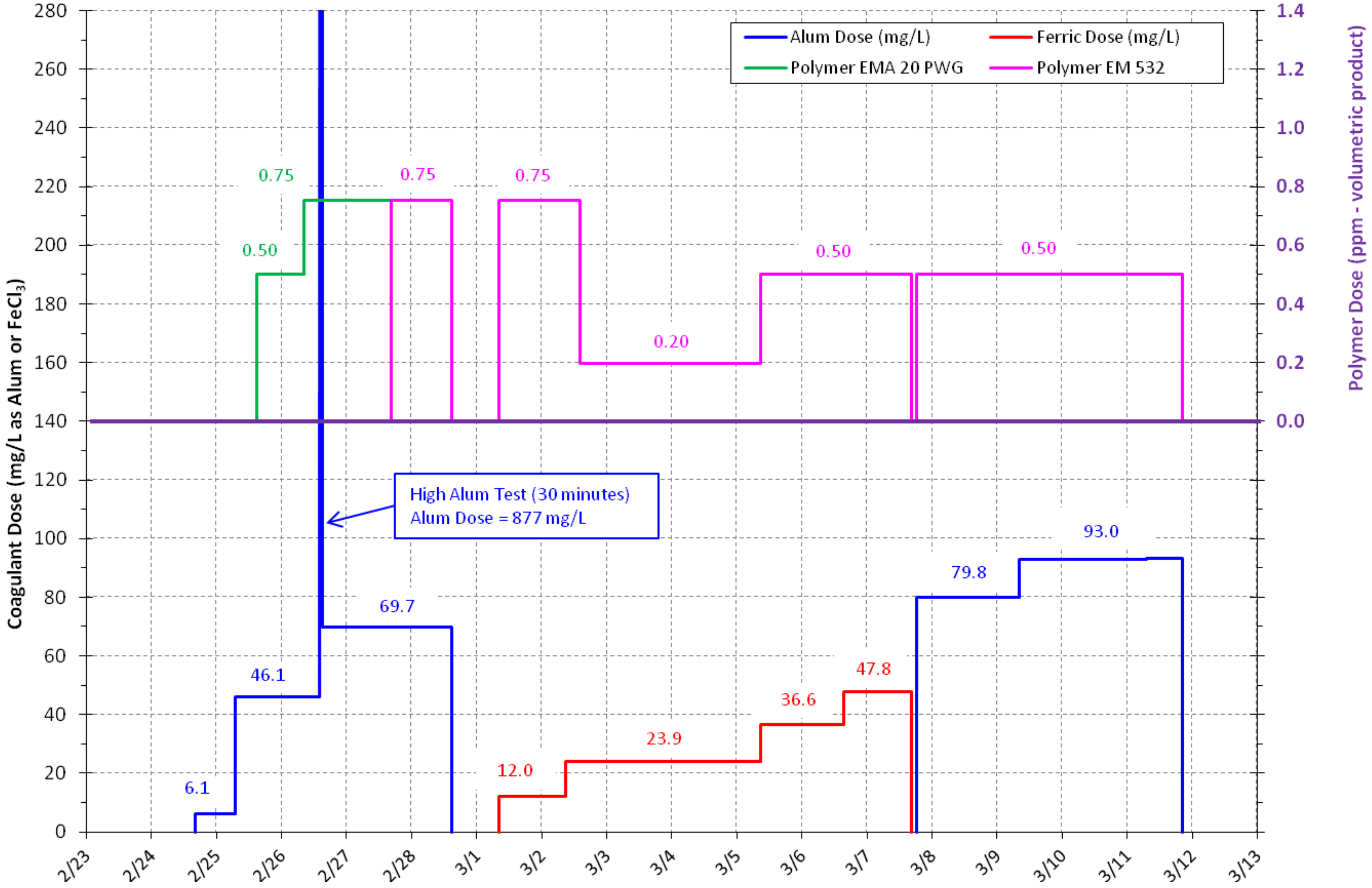
The columns in Table 3 are as follows:

(1) Trial number: sequential from 1 to 19.
(2) Sample numbers: ID numbers for corresponding water quality samples (field and laboratory).
(3) Start time: starting time for trial, when chemical and flow changes were initiated.
(4) End time: end time for trial.
(5) Duration: hours of operation.
(6) Flow: influent flow as recorded by the pilot system influent mag meter. This is not the through-put, because it does not subtract the backwash and solids wasting flows.
(7) HLR: hydraulic loading rate, calculated as FLOW ÷ 11 ft^2 (the surface area of the filter disc).
(8) HRT: hydraulic retention time, calculated as 250 gallons ÷ FLOW.
(9) Coagulant type.
(10) Coagulant usage: calculated per Section 1.2.
(11) Coagulant dose: calculated per Section 1.2.
(12) Molar ratio: ratio of coagulant metal ion (Al^{3+} or Fe^{3+}) to avg. influent TP, per Section 1.2.
(13) Polymer type.
(14) Polymer dose: calculated per Section 1.2.

Table 3: Summary of Filter Operating Conditions

(1)	(2)	Date and Time Data			Hydraulic Data			Coagulant Data				Polymer Data	
Trial No.	Sample Numbers	(3) Start Time	(4) End Time	(5) Duration (hours)	(6) Flow (gpm)	(7) HLR (gpm/ft^2)	(8) HRT (min)	(9) Coag. Type	(10) Usage (gal/MG)	(11) Dose (mg/L)	(12) Molar Ratio	(13) Polymer Type	(14) Dose (ppmvp)
1	1 – 15	2/23 - 10:00	2/24 - 16:00	30.0	39	3.25	6.4	None				None	
2	16 – 17	2/24 - 16:00	2/25 - 07:00	15.0	39	3.25	6.4	Alum	9.50	6.1	2.1	None	
3	18 – 22	2/25 - 07:00	2/25 - 15:00	8.0	39	3.25	6.4	Alum	71.1	46.1	16.1	None	
4	23 – 24	2/25 - 15:00	2/26 - 08:10	17.2	39	3.25	6.4	Alum	71.1	46.1	16.1	20	0.50
5	25 – 29	2/26 - 08:10	2/26 - 14:00	5.8	39	3.25	6.4	Alum	71.1	46.1	16.1	20	0.75
6	30	2/26 - 14:30	2/26 - 15:00	0.5	39	3.25	6.4	Alum	1355	877	307	20	0.75
7	31 – 37	2/26 - 15:00	2/27 – 16:30	22.5	39	3.25	6.4	Alum	108	69.7	24.4	20	0.75
8	38 – 44	2/27 – 16:30	2/28 - 15:00	22.5	39	3.25	6.4	Alum	108	69.7	24.4	532	0.75
9	45 – 46	2/28 - 15:00	3/01 - 08:10	17.2	39	3.25	6.4	None				None	
10	47 – 53	3/01 - 08:10	3/02 - 08:45	24.6	39	3.25	6.4	$FeCl_3$	20.3	12.0	7.3	532	0.75
11	54 – 58	3/02 - 08:45	3/02 - 14:00	5.3	39	3.25	6.4	$FeCl_3$	40.6	23.9	14.6	532	0.75
12	59 – 74	3/02 - 14:00	3/05 - 08:40	66.7	39	3.25	6.4	$FeCl_3$	40.6	23.9	14.6	532	0.20
13	75 – 90	3/05 - 08:40	3/06 - 15:30	30.8	39	3.25	6.4	$FeCl_3$	62.3	36.6	22.3	532	0.50
14	91 – 99	3/06 - 15:30	3/07 - 16:15	24.8	39	3.25	6.4	$FeCl_3$	81.3	47.8	29.1	532	0.50
15	–	3/07 - 16:15	3/07 - 18:15	2.0	39	3.25	6.4	None				None	
16	100 – 108	3/07 - 18:15	3/09 - 08:00	37.8	39	3.25	6.4	Alum	128	82.9	29.0	532	0.50
17	109 – 122	3/09 - 08:00	3/11 - 07:00	47.0	39	3.25	6.4	Alum	144	93.0	32.5	532	0.50
18	123 – 132	3/11 - 07:00	3/11 - 20:30	13.5	70	5.83	3.6	Alum	143.8	93.1	32.6	532	0.50
19	133 – 135	3/11 - 20:30	3/12 - 09:20	12.8	39	3.25	6.4	None				None	

Figure 1: Chemical Dose Data (by date)



1.4 WATER QUALITY SAMPLING

Water quality samples were collected for analysis (1) by field methods in the onsite AASI pilot system field laboratory, and (2) by laboratory methods at a certified laboratory, Cascade Analytical (Wenatchee, WA).

Grab samples were collected at minimum once daily. Two composite samples were typically collected per 24 hour period as follows:

- Day Composite (DC): typically 09:00 through 15:00
- Night Composite (NC): typically 17:00 through 07:00

Composite samples were collected on a timed basis in 200 ml increments at 30 minute intervals. The pilot system flow rate and chemical dosing were constant during each individual trial, therefore it was not necessary for composite samples to be flow based. Composite samples were split for analysis by both field and laboratory methods. Grab samples were typically analyzed only by field methods. Table 4 summarizes sample collection.

Table 4: Water Quality Sampling Points

Sample		Collection Point	Notes
1	Influent, pre-chemical injection	Influent sample port	Grab samples only
2	Influent, post-chemical	Filter basin	Composite samples
3	Effluent (filtrate)	Effluent weir	Both grabs and composites

1.5 FIELD ANALYSES

Phosphorus Analyses

All phosphorus data are reported in units of mg/L as phosphorus (P). It is important to note that concentrations are not reported in terms of orthophosphate, which has a molecular weight approximately 3 times greater than phosphorus.

Table 5: Phosphorus Species Analysis and Calculation

Phosphorus Species (P)		Analysis or Calculation
(A)	Total Phosphorus	Direct analysis, unfiltered and digested
(B)	Reactive Phosphorus	Direct analysis, unfiltered, undigested
(C)	Soluble Total Phosphorus	Direct analysis, filtered and digested
(D)	Soluble Reactive Phosphorus	Direct analysis, filtered, undigested
(E)	Insoluble Total Phosphorus	A – C
(F)	Insoluble Reactive Phosphorus	B – C
(G)	Soluble Non-reactive Phosphorus	C – D
(H)	Non-Reactive Phosphorus	A – B
(J)	Insoluble Non-reactive Phosphorus	G - H

QA/QC

Distilled water blanks were analyzed daily for Total Phosphorus and Reactive Phosphorus, by field methods. The data are summarized in Table 6, and the statistics of the data are summarized in Table 7. The mean Total P concentration for all blanks was 0.020 ±0.0097 mg/L P, and the mean Reactive P concentration for blanks was 0.012 ±0.0063 mg/L P.

Figure 2 shows histograms of the distribution of Total P and Reactive P data.

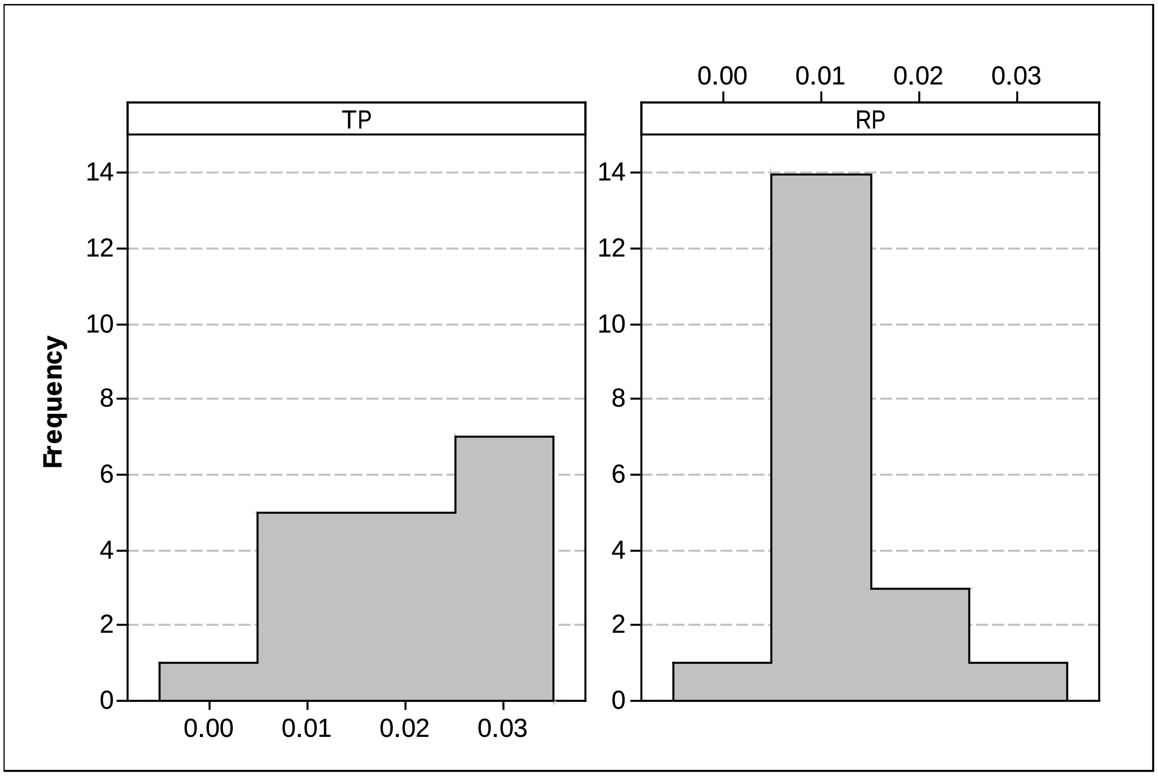
Table 6: Phosphorus Blanks Data

Date (2015)	Total P (mg/L as P)	Reactive P (mg/L as P)
2/23	0.02	0.01
2/23	0.02	0.02
2/24	0.03	0.03
2/25	0.01	0.02
2/26	0.00	0.00
2/27	0.01	0.01
2/28	0.01	0.02
3/01	0.01	0.01
3/02	0.01	0.01
3/03	0.02	0.01
3/04	0.03	0.01
3/05	0.03	0.01
3/06	0.03	0.01
3/07	0.02	0.01
3/08	0.02	0.01
3/09	0.03	0.01
3/10		0.01
3/11	0.03	0.01
3/12	0.03	0.01

Table 7: Statistics of Phosphorus Blanks Analyses

Parameter	Method	Mean ± std. dev.	Min - Max	Data Count (n)
Total P	Hach 8190 PhosVer 3	0.020 ± 0.0097	0.00 – 0.03	18
Reactive P	Hach 8048 PhosVer 3	0.012 ± 0.0063	0.00 – 0.03	19

Figure 2: Histogram of Phosphorus Blanks (mg/L P)



Composite samples were split for analysis by both field and laboratory methods. Data pairs for Total Phosphorus were analyzed by paired t-tests. The data were grouped according to Influent and Effluent samples.

Effluent Data:

The mean difference in TP for field versus lab analyses was 0.038 ± 0.046 mg/L P, based on 27 split samples. All of the differences were positive, indicating that the field method was conservative, and consistently yielded results that were greater than the laboratory method (SM 4500P-D Stannous Chloride Method, colorimetric method using molybdophosphoric acid). This suggests that actual TP concentrations for effluent samples were typically 0.038 mg/L less than indicated by the field method (Hach method 8190 PhosVer 3).

Results for: FIELD vs LAB (2)

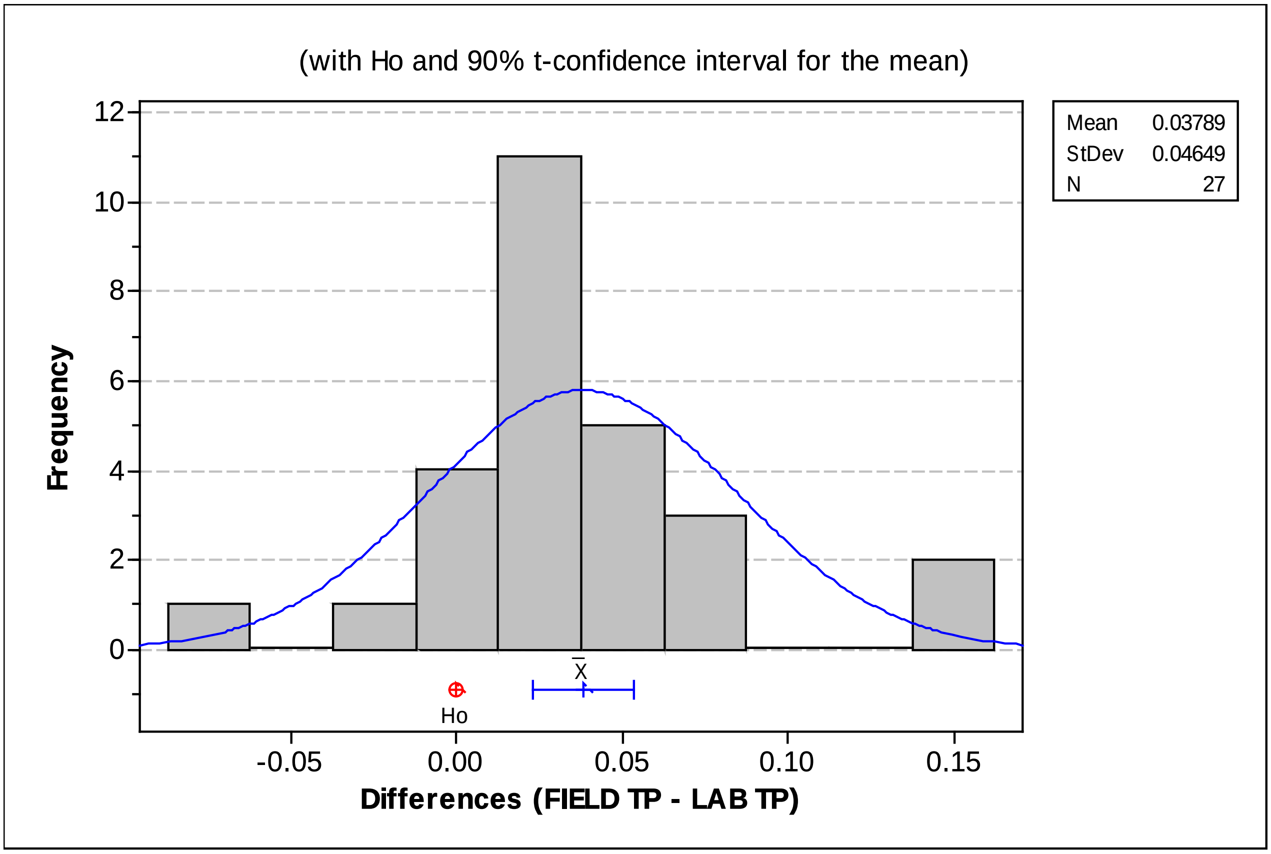
Paired T-Test and CI: FIELD EFF TP, LAB EFF TP

```
Paired T for FIELD EFF TP - LAB EFF TP

                N      Mean        StDev       SE Mean
FIELD EFF TP   27      0.1674       0.0621     0.0119
LAB EFF TP     27      0.1295       0.0634     0.0122
Difference     27      0.03789     0.04649     0.00895


90% CI for mean difference: (0.02263, 0.05315)
T-Test of mean difference = 0 (vs not = 0): T-Value = 4.23  P-Value = 0.000
```

Figure 3: Histogram of Differences for Effluent Samples



Influent Data:

The mean difference in TP for field versus lab analyses of influent composite samples was 0.005 ± 0.061 mg/L P, based on 27 split samples.

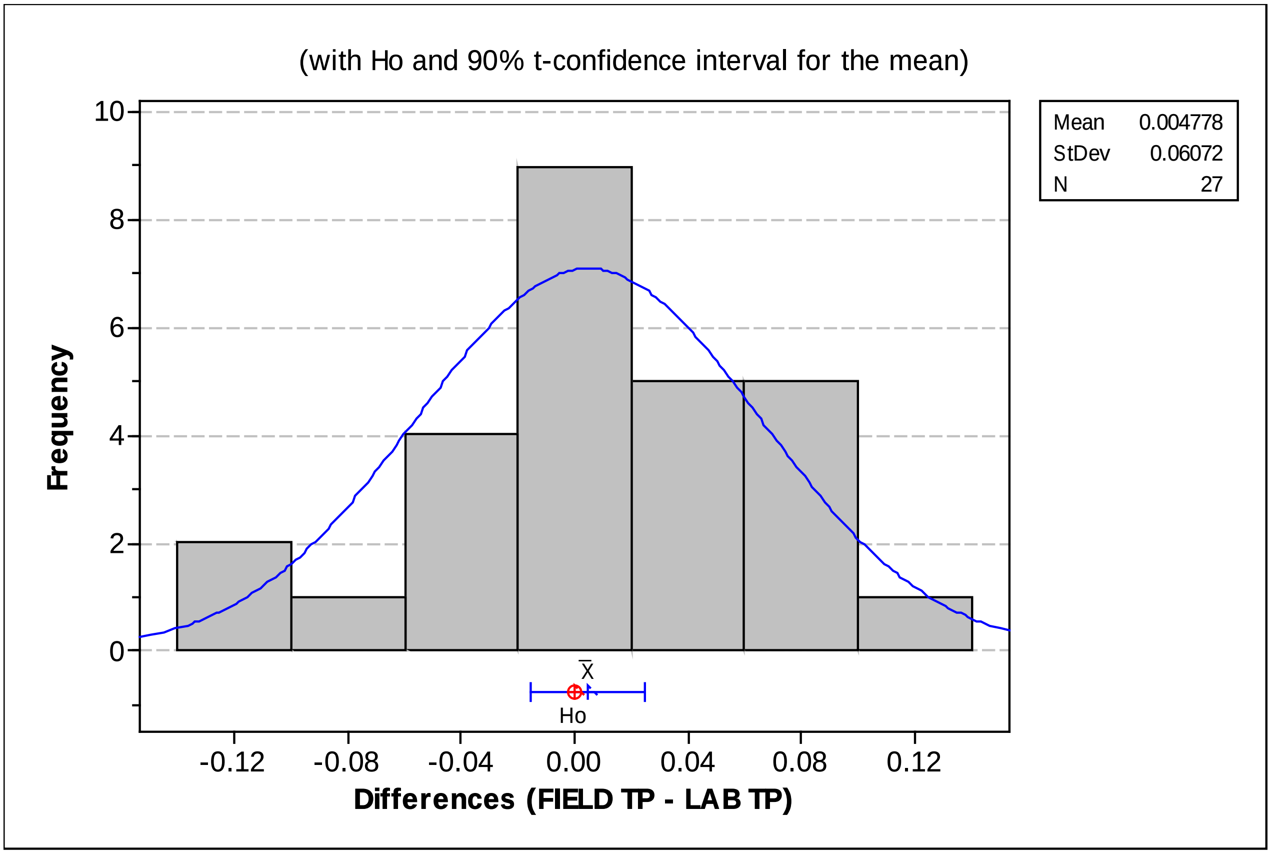
Paired T-Test and CI: FIELD INF TP, LAB INF TP

```
Paired T for FIELD INF TP - LAB INF TP

              N      Mean      StDev     SE Mean
FIELD INF TP  27     0.2889    0.0756    0.0146
LAB INF TP    27     0.2841    0.0536    0.0103
Difference    27     0.0048    0.0607    0.0117


90% CI for mean difference: (-0.0152, 0.0247)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.41  P-Value = 0.686
```

Figure 4: Histogram of Differences for Influent Samples



2.0 FINDINGS

2.1 INFLUENT PHOSPHORUS

Figure 5 plots the phosphorus data for influent grab samples collected prior to chemical addition. Grab samples were analyzed by field methods only. Total phosphorus (blue) typically varied between approximately 0.25 and 0.40 mg/L P, with a generally increasing trend in the latter half of the pilot study period. The increasing trend is indicated by the linear regression line.

Figure 5: Influent Grab Samples Total Phosphorus (Field Analysis)

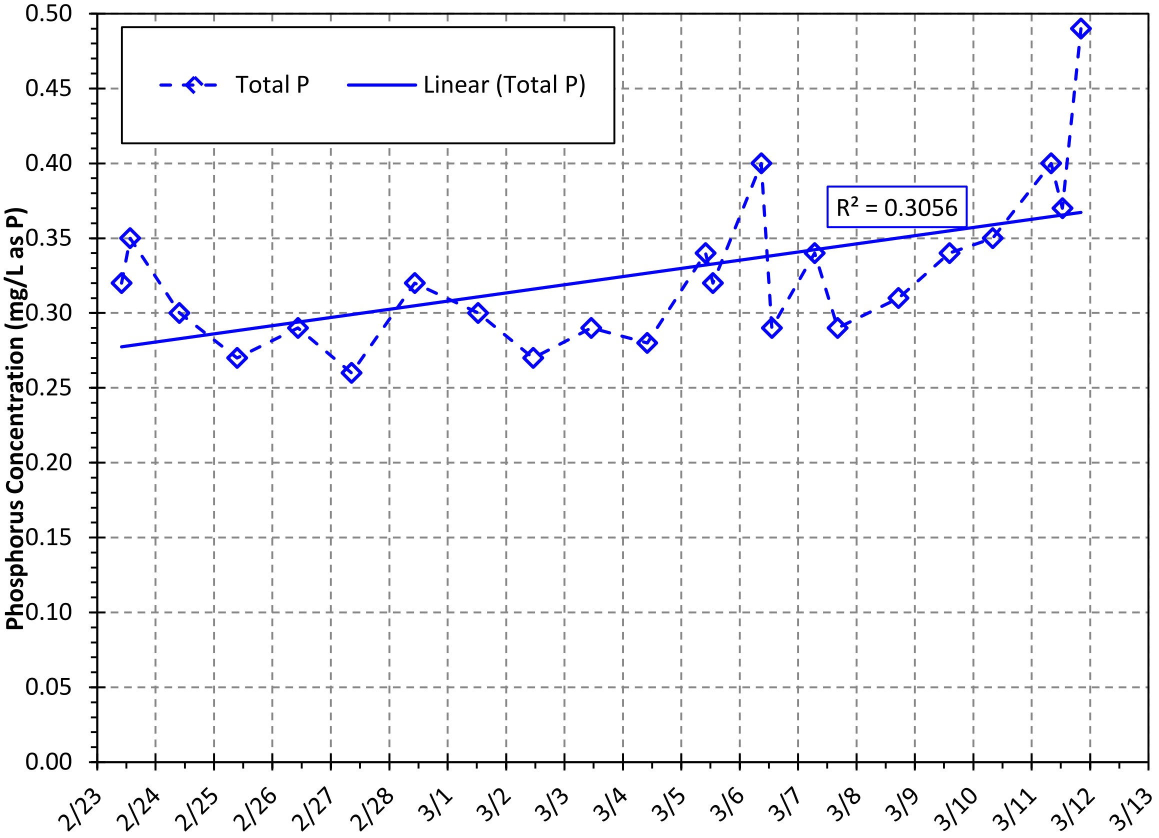
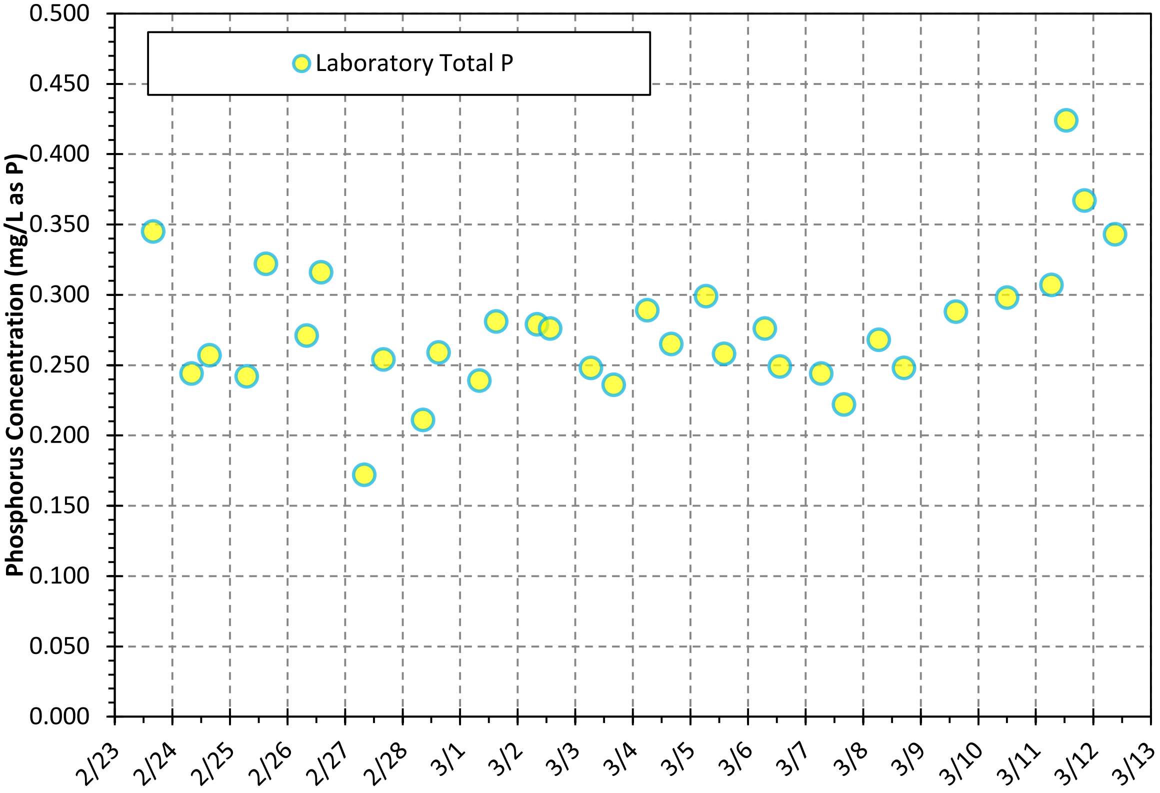


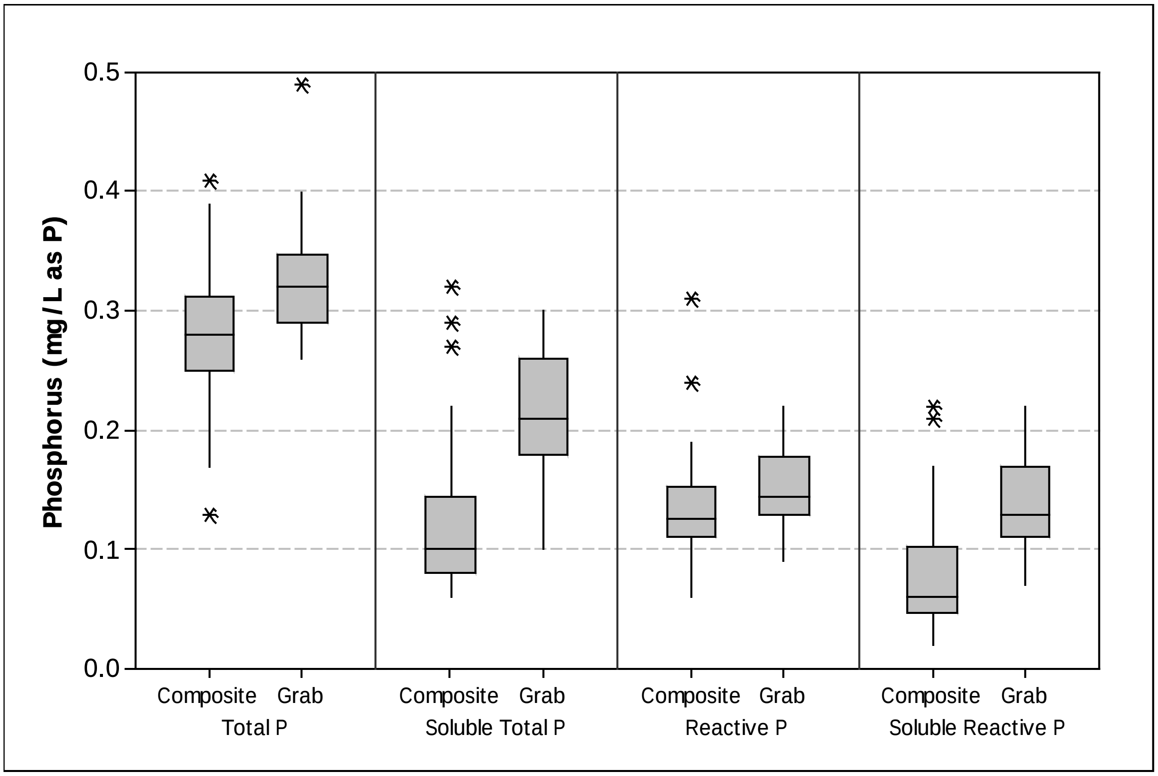
Figure 6 plots the phosphorus data for influent composite samples. Composite samples were analyzed by both field and laboratory methods for total P, and by field methods for soluble total P, reactive P, and soluble reactive P. Total phosphorus by field analysis (blue) typically varied between approximately 0.15 and 0.40 mg/L P, with a generally upward trend, indicated by the linear regression line. Laboratory total P data was similar to field total P data.

Figure 6: Influent Composite Samples Total Phosphorus



Phosphorus data for influent grab samples were typically greater than data for composite samples. Figure 7 shows boxplots of the field influent phosphorus data grouped according to to species and sample type (grab or composite). For each species, the median grab sample P was greater than the median composite P.

Figure 7: Boxplots of Influent Phosphorus Data By Field Analyses



2.2 PHOSPHORUS SPECIES CALCULATED FROM FIELD ANALYSIS

The figure below represents the speciation of total phosphorus into reactive and non-reactive components. The reactive and non-reactive components are further speciated into soluble and insoluble components. The sum of the components will equal Total P.

Reactive P	Soluble Reactive P	**Total P**
	Insoluble Reactive P	
Non-Reactive P	Soluble Non-Reactive P	
	Insoluble Non-Reactive P	

Figure 8 summarizes the phosphorus speciation of influent composite samples for the entire pilot study period, based on field data. The influent composite samples were collected after chemical pretreatment. Each bar represents the average of 2 composite samples that were collected within a

period of approximately 24 hours. Typically, the day composite ran from 09:00 to 15:00, and the night composite from 18:00 to 07:00.

- The bars corresponding to 2/24, 3/1, 3/7 and 3/12 were from trials that did not use chemicals (neither coagulant or polymer).
- Soluble non-reactive P varied from 0.02 to 0.10 mg/L. This is the most difficult species to remove since it does not tend to react or precipitate to form filterable particles.
- The sum of the soluble species (soluble non-reactive P plus soluble reactive P) varied from 0.06 to 0.22 mg/L. The soluble reactive species can be treated and removed only if the proper chemistry exists to cause it to react to form filterable particles. Ideally, the soluble reactive P would be greatly reduced in the pretreated water, and converted to insoluble species.
- The figure plots data from composite samples that were collected after chemical injection and coagulation, directly from the filter basin. A large percentage of total P remains as soluble reactive P, which suggests that the pretreatment chemistry was not optimal for filtration.
- The insoluble species (insoluble non-reactive P and insoluble reactive P) are particulate, and should be effectively removed by direct filtration with a nominal filter size of 5 microns.

Figure 8: Influent Phosphorus Species from Composite Samples per 24 Hour Period

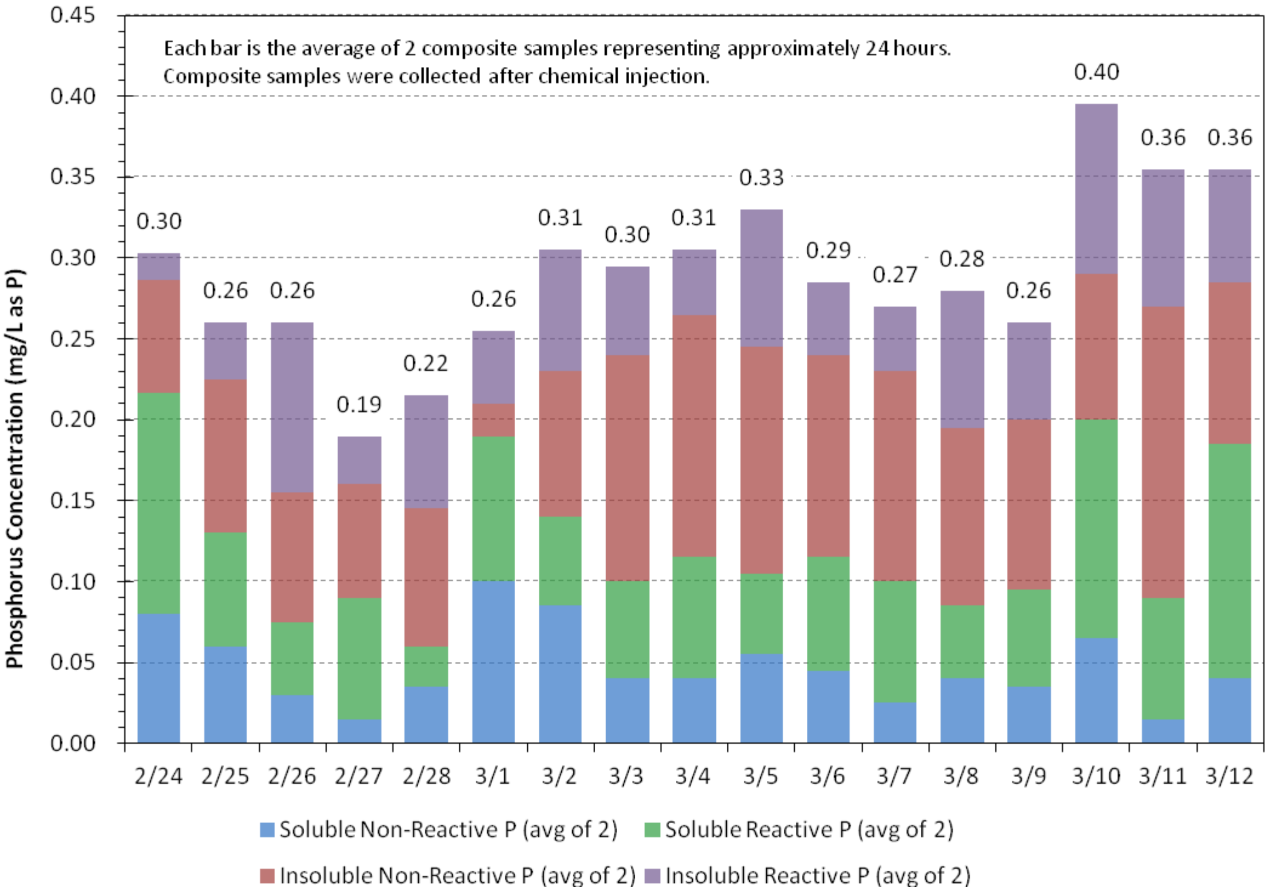
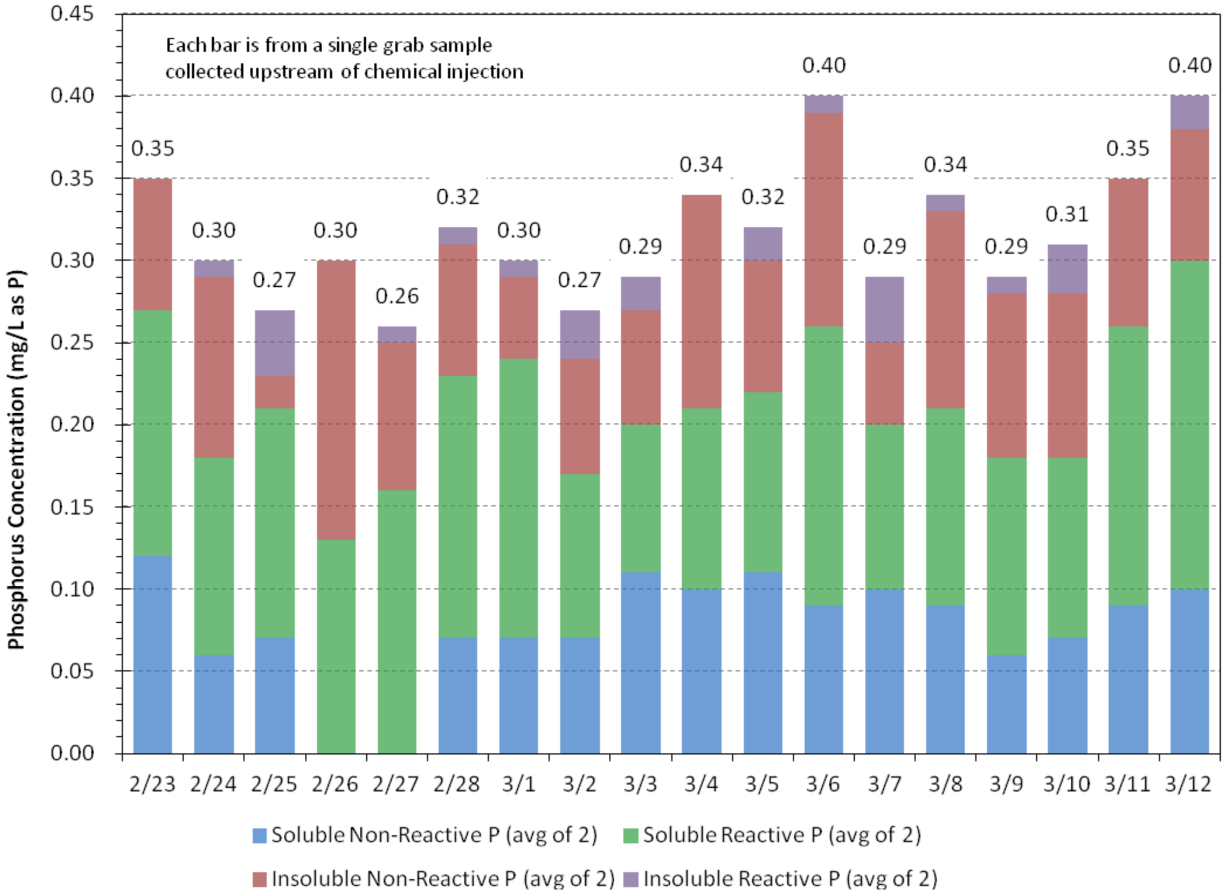


Figure 9 summarizes the phosphorus speciation of influent grab samples for the entire pilot study period, based on field data. Each bar represents a single grab sample. Typically, grab samples were collected between approximately 10:00 and 15:00.

- Grab samples were collected before chemical pretreatment, and represent the “raw” secondary clarified influent to the pilot system.
- Compared to the composite speciation data (post chemical), the sum of the soluble components in the grab samples (pre-chemical) compose a greater percentage of total P.
- Compared to the composite speciation data (post chemical), the insoluble reactive P in the grab samples (pre-chemical) is only a minor component of total P.
- The comparison of the pre-chemical grab samples to the post-chemical composite samples indicates that coagulation successfully converted soluble species to insoluble species, but that substantial fractions of total P did not form filterable particulates, and remained as soluble species.

Figure 9: Bar Chart of Influent Phosphorus Species from Grab Samples



2.3 EFFLUENT PHOSPHORUS

Figure 10 plots effluent total phosphorus data for effluent composite samples. The figure also shows influent total P for composite samples. Effluent TP concentrations appeared to be affected by influent TP. Laboratory TP data were below the project goal of 0.09 mg/L P during periods corresponding to effective operations. These periods had molar ratios of metal salt to phosphorus of > 20:1 and pH < 7.5. The pilot system flow rate and hydraulic loading rate were constant for 17 of 18 trials, which suggests that effective performance (defined as TP < 0.09 mg/L) was mainly a function of chemical pretreatment.

Figure 10: Effluent Phosphorus Data for Composite Samples

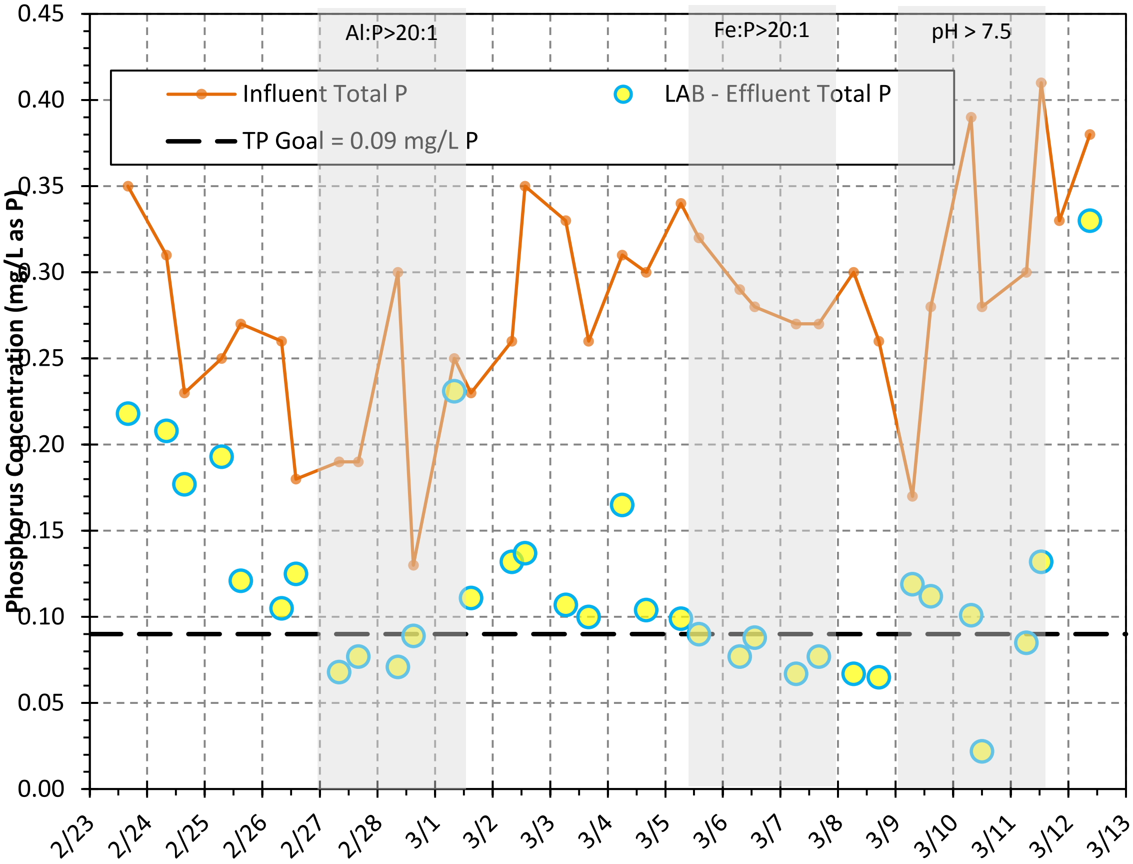


Figure 12 plots effluent speciation by trial number. The coagulants used are indicated (coagulant doses and polymer doses are not indicated). The figure indicates that a significant component of soluble reactive phosphorus remained (green) even during the best performing trials. This suggests that the chemical pretreatment was not optimal. Improved pretreatment could potentially reduce the reactive P component and produce lower effluent total phosphorus.

Figure 12: Effluent Phosphorus Species by Trial Number

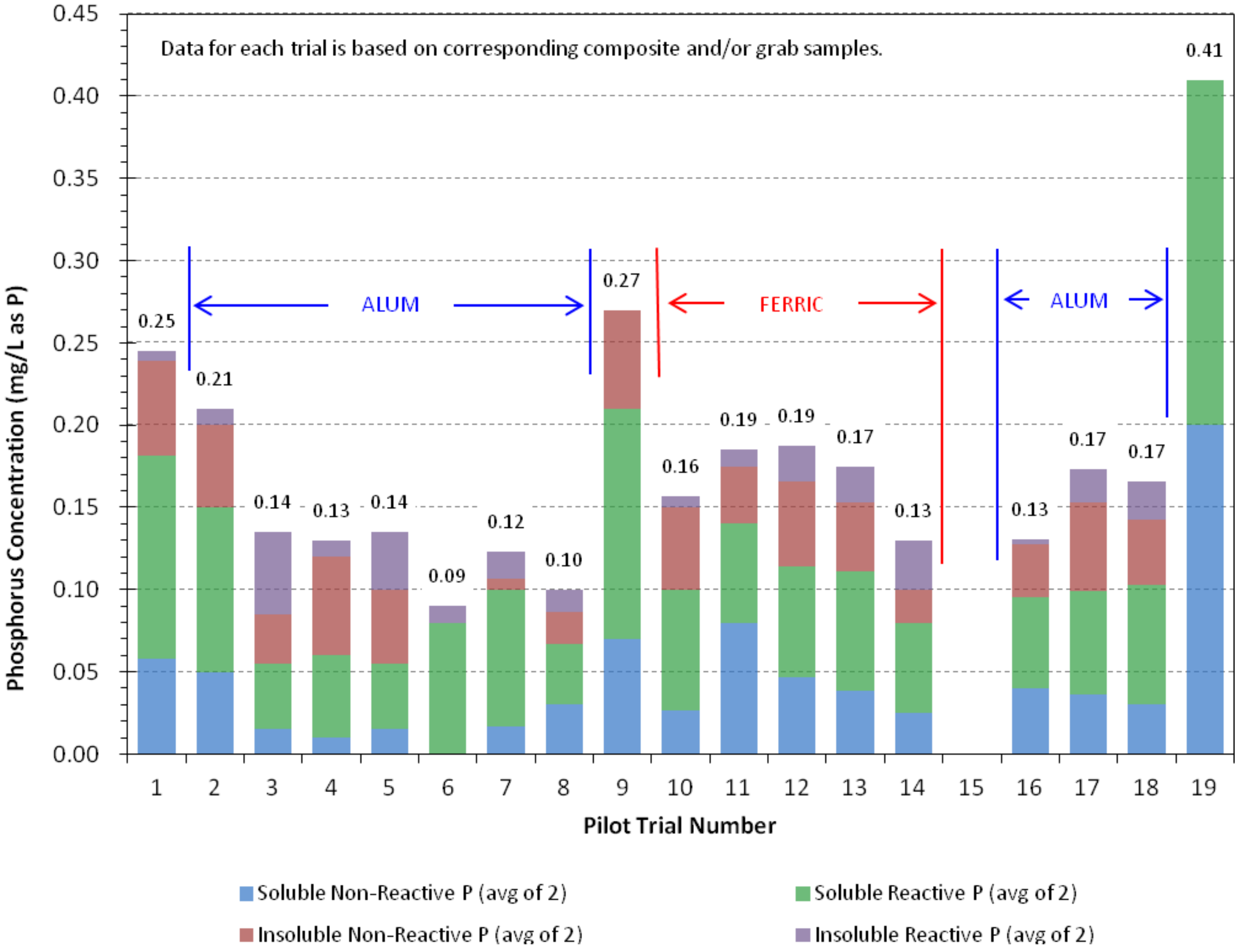


Figure 13 shows boxplots of laboratory influent and effluent data by trial. Figure 14 shows individual values plots of the same effluent laboratory TP data. These lots indicate the pilot system produced effluent with TP concentrations that were at or below the goal of 0.09 mg/L P during the following trials:

- Trial 7: alum at 69.7 mg/L, EMA 20 PWG polymer at 0.75 ppmvp, flow = 39 gpm
- Trial 8: alum at 69.7 mg/L, EM 352 PWG polymer at 0.75 ppmvp flow = 39 gpm
- Trial 13: $FeCl_3$ at 36.6 mg/L, EM 532 PWG polymer at 0.50 ppmvp flow = 39 gpm
- Trial 14: $FeCl_3$ at 47.8 mg/L, EM 532 PWG polymer at 0.50 ppmvp flow = 39 gpm
- Trial 16: alum at 82.9 mg/L, EM 532 PWG polymer at 0.50 ppmvp flow = 39 gpm
- Trial 17: alum at 93.0 mg/L, EM 532 PWG polymer at 0.50 ppmvp flow = 39 gpm

Figure 13: Boxplots of Laboratory Influent and Effluent Total P Data by Trial

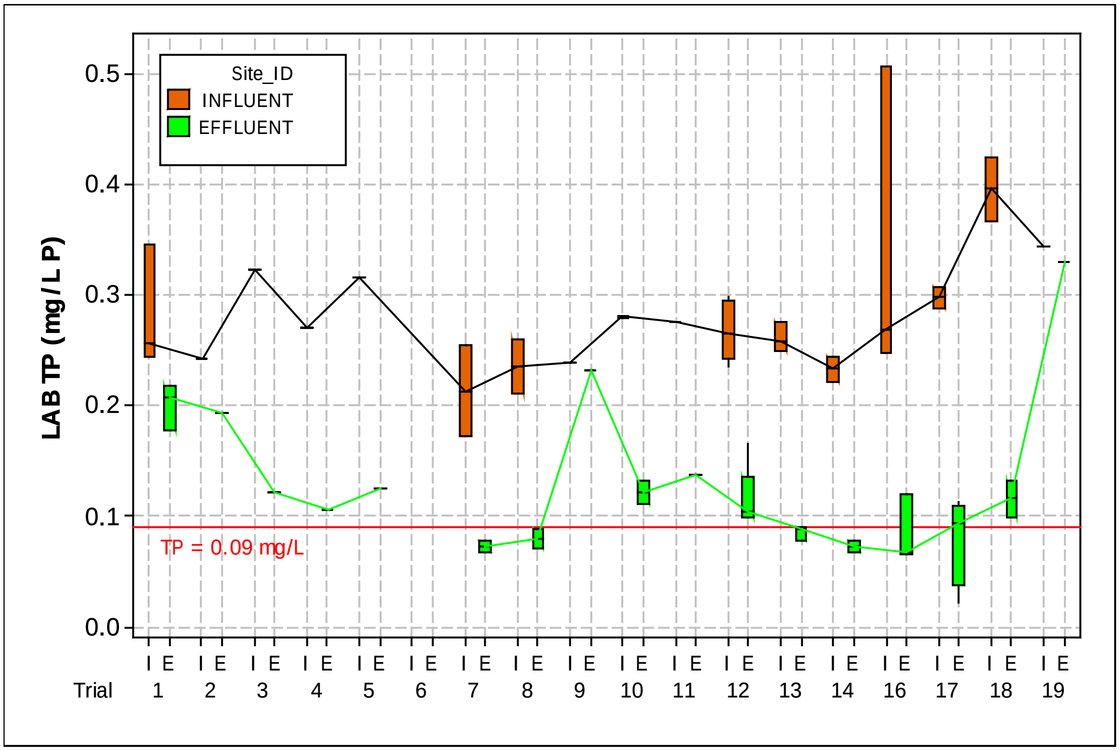
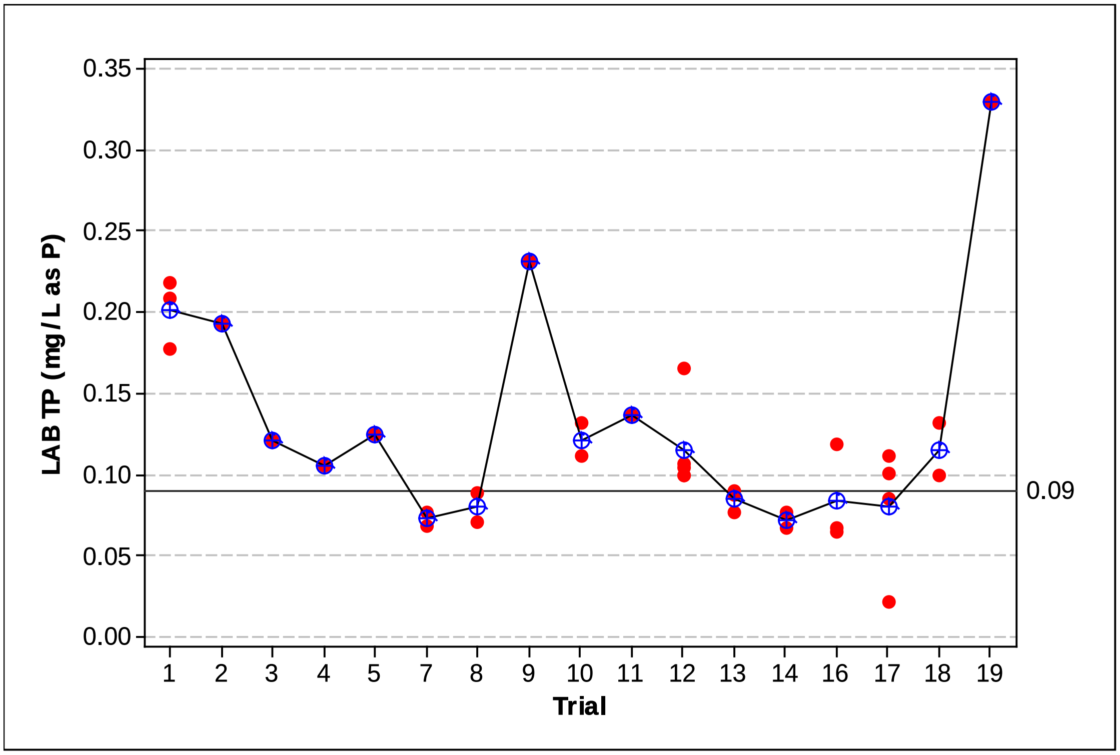


Figure 14: Individual Values Plot of Total Phosphorus by Lab Analysis



2.4 EFFECTIVE OPERATING CONDITIONS

The Field phosphorus data was analyzed (prior to receiving laboratory results) to determine the best performing set of operating conditions that were tested during the pilot study. Table 8 shows the statistics of the *corrected* field TP data. The correction was: corrected TP = field TP – 0.03 mg/L. The correction factor was based upon statistical analysis of laboratory versus field TP data from split samples, using a paired t-test. Only 27 data pairs were available at the time, and they indicated a mean difference of 0.038 mg/L P (Field TP > Lab TP).

The table lists the trials in order of increasing mean TP. The shaded cells indicate trials where the mean TP percent removal was greater than 50%.

Table 8: Trial Rankings Based on Corrected Field Data

Trial	Coagulant		Polymer		Effluent Total P Data (corrected TP)(1)			
	Type	Dose (mg/L)	Type	Dose (ppmvp)	Mean TP ± Std Deviation (mg/L as P)	TP Data (n)	Percent Removal	Removal Ranking
6	**Alum**	**877**	**20**	**0.75**	**0.050**	**1**	no data	no data
7	**Alum**	**70**	**20**	**0.75**	**0.067 ± 0.006**	**3**	**53%**	**5**
8	**Alum**	**70**	**532**	**0.75**	**0.070 ± 0.000**	**3**	**53%**	**7**
16	**Alum**	**83**	**532**	**0.50**	**0.083 ± 0.013**	**4**	**53%**	**6**
14	**Ferric**	**48**	**532**	**0.50**	**0.090 ± 0.014**	**4**	**58%**	**3**
17	Alum	93	532	0.50	0.095 ± 0.023	6	61%	2
4	Alum	46	20	0.50	0.100	1	50%	8
3	Alum	46	None	0	0.105 ± 0.007	2	50%	9
5	Alum	46	20	0.75	0.105 ± 0.007	2	40%	12
18(2)	Alum	93	532	0.50	0.108 ± 0.010	4	67%	1
13	Ferric	37	532	0.50	0.117 ± 0.018	7	54%	4
10	Ferric	12	532	0.75	0.127 ± 0.015	3	39%	13
12	Ferric	24	532	0.20	0.133 ± 0.015	7	45%	11
11	Ferric	24	532	0.75	0.140 ± 0.057	2	46%	10
2	Alum	6.1	None	0	0.180	1	16%	15
1	None	0	None	0	0.202 ± 0.031	6	24%	14
9	None	0	None	0	0.230	1	0%	17
19	None	0	None	0	0.330	1	5%	16
15	None	0	None	0	No data	0	no data	no data

Bold Type indicates Mean TP ≤ 0.090 mg/L
Shaded Cells indicate TP Percent Removal ≥ 50%
(1) Corrected TP = TP by Field Analysis minus 0.03 mg/L
(2) Trial 18 conducted at Flow = 70 gpm; all other trials conducted at 39 gpm.

The table suggests the following:

1. Trials 6, 7, 8, 16: The lowest effluent TP was obtained using alum doses of ≥70 mg/L and polymer at doses of 0.50-0.75 ppmvp (type 20 or 532 polymers).
2. Trials 17, 18: The greatest TP percent removal was obtained using alum at a dose of 93 mg/L and the 532 polymer at a dose of 0.50 ppmvp. These were consistent with the conditions that produced the lowest effluent TP, but did not meet the goal of 0.09 mg/L P.
3. Trial 14: Ferric chloride produced 0.090 mg/L mean effluent TP (4 data) at a dose of 48 mg/L, with a polymer dose of 0.50 ppmvp using the 532 polymer. However, the laboratory data indicates that using ferric caused residual iron in the effluent.
4. Trial 2: The lowest alum dose (6.1 mg/L) produced results comparable to zero coagulant.

Based on the above, the most effective operating conditions appeared to be alum doses greater than 70 mg/L, polymer doses of 0.50 to 0.75 ppmvp (either types 20 or 532), and a flow rate of 39 gpm. These correspond to Trials 7, 8, 16, and 17. Trial 6 was not included owing to the extremely high alum dose (877 mg/L). Ferric trials were not included owing to preliminary laboratory results that indicated high residual iron concentrations in the effluent.

Effluent TP was potentially affected by influent TP, in addition to chemical pretreatment parameters. Figure 14 plots effluent TP versus influent TP data. Both the field data (uncorrected TP) and laboratory data (received as of 3/19/15) are plotted. Both data sets indicate a general trend of increasing effluent TP in response to increasing influent TP, although the R^2 values are low.

Figure 15: Effluent Total P versus Influent Total P (Effective Operations Data)

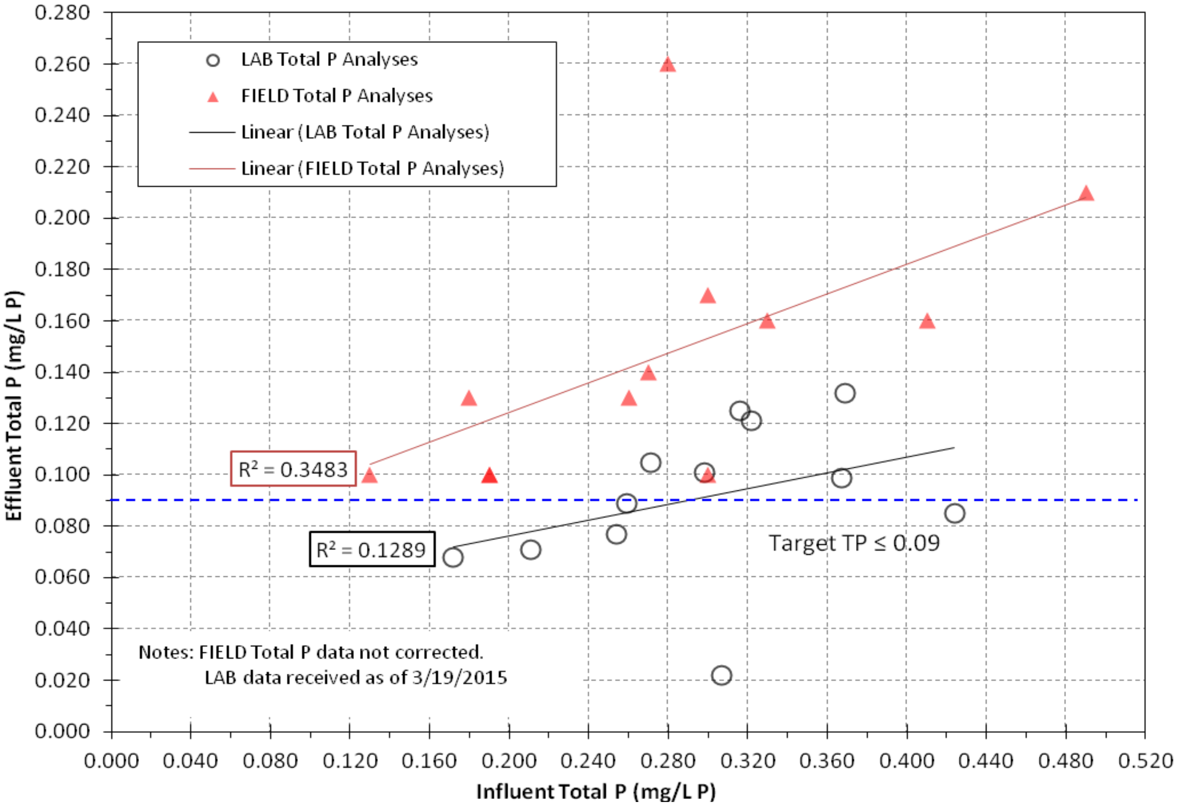
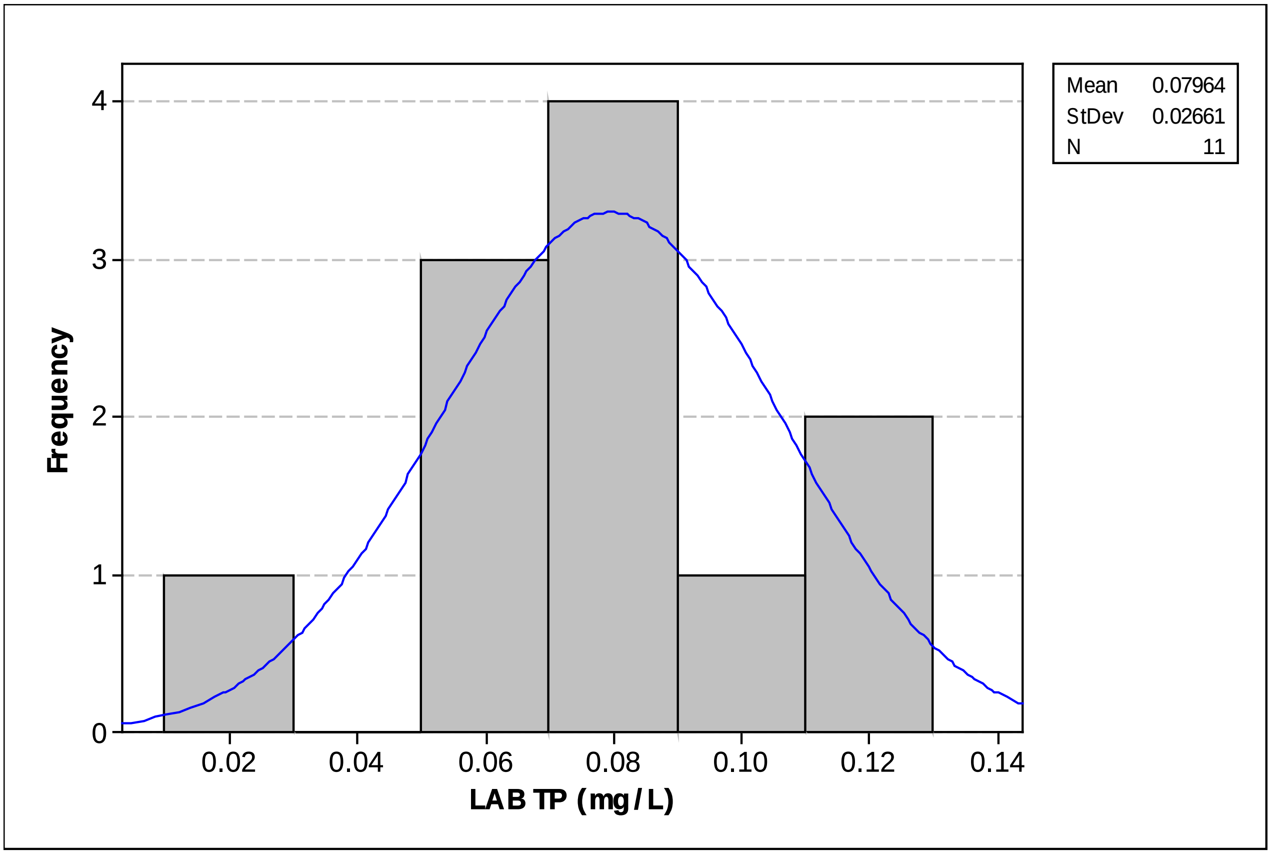


Table 9 summarizes the statistics of the laboratory and field total phosphorus data (results for all corresponding laboratory samples was available for this analysis). The laboratory data show that each all of the individual trials that operated with the effective conditions achieved mean effluent TP concentrations that were below the goal of 0.09 mg/L P. When data from all four trials were combined, the mean effluent TP was 0.080 ±0.027 mg/L P (11 laboratory data). These 4 trials correspond to 130 hours of operation (5.4 days). Figure 16 shows a histogram of the 11 laboratory TP data.

Table 9: Statistics of Total P Data for Effective Operating Conditions

Parameter	Trial	Mean ± Std Deviation (n) (mg/L as P) Laboratory Data	Field Data (uncorrected)
Total P (mg/L P)	7	0.073 ± 0.006 (2)	0.097 ± 0.006 (3)
	8	0.080 ± 0.013 (2)	0.100 ± 0.000 (3)
	16	0.084 ± 0.031 (3)	0.113 ± 0.013 (4)
	17	0.080 ± 0.040 (4)	0.125 ± 0.023 (6)
Total P (mg/L P)	Combined (7, 8, 16, 17)	0.080 ± 0.027 (11)	0.112 ± 0.019 (16)
TSS (mg/L)	Combined (7, 8, 16, 17)	0.080 ± 0.027 (11)	

Figure 16: Histogram of Effluent Total Phosphorus Data by Lab Analysis

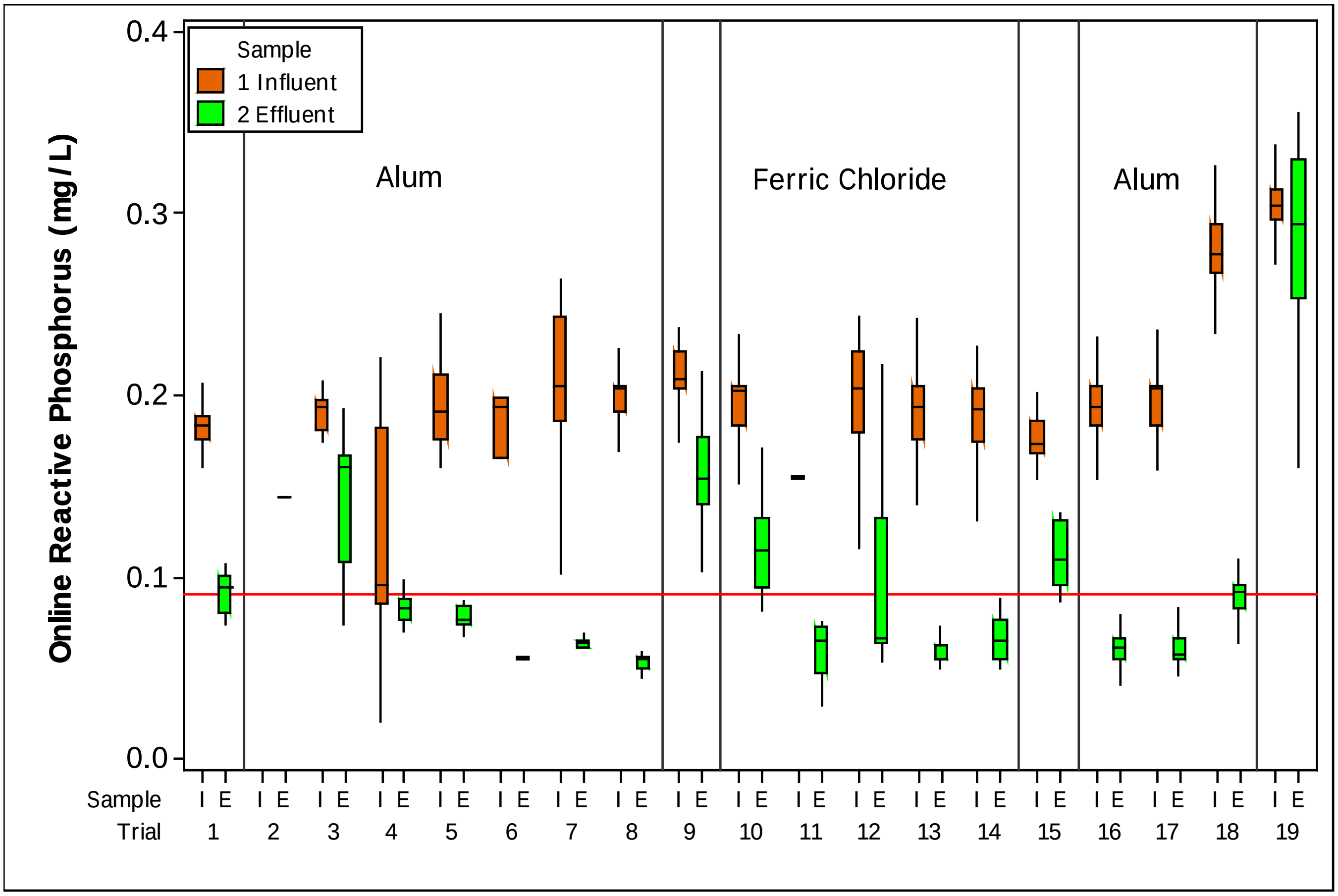


2.5 TRENDING DATA

Online Reactive Phosphorus Trends

Figure 16 shows boxplots of the reactive phosphorus data from the continuous online influent and effluent OP analyzers. The data were recorded in units of mg/L PO_4-P (not PO_4), i.e. as elemental phosphorus. The periods of operation are indicated for alum, ferric chloride, and no coagulant. The red line indicates the goal of 0.09 mg/L total phosphorus for reference, although the analyzers determined only the reactive species.

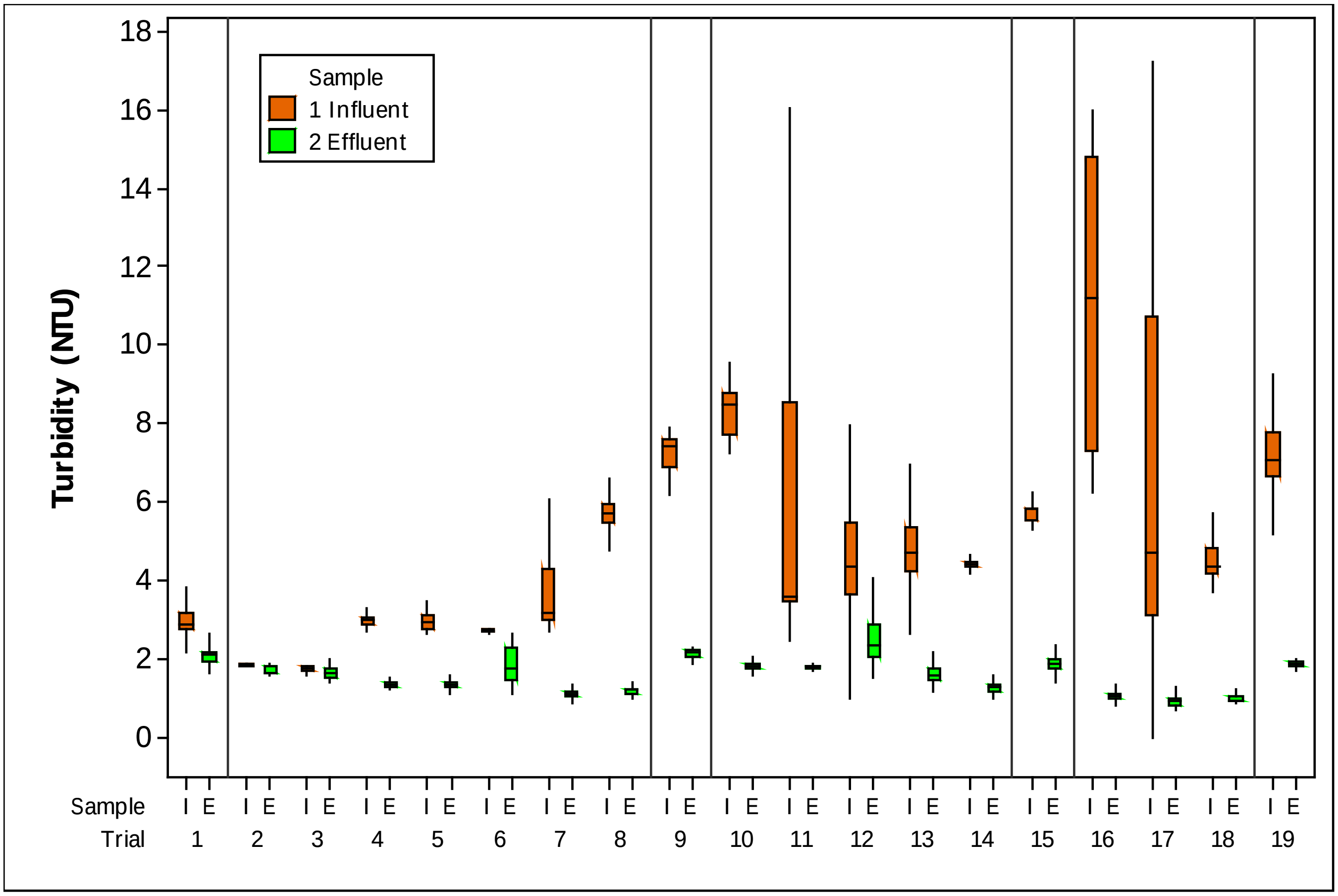
Figure 16: Boxplots of Online Reactive Phosphorus Data



Online Turbidity Trends

Figure 17 shows boxplots of the turbidity data from the continuous online influent and effluent turbidity meters. The data were recorded in units of ntu. The periods of operation are indicated for alum, ferric chloride, and no coagulant (indicated by the vertical lines. The boxplots indicate little variation in effluent turbidity in response to either (1) influent turbidity, or (2) effective phosphorus removal.

Figure 17: Boxplots of Online Turbidity Data



2.6 SOLIDS LOADING RATES AND WASTE VOLUMES

Table 10 summarizes backwash wasting rates and solids wasting rates as a percent of influent flow. Influent flow was 39 gpm for all trials except Trial 18 at 70 gpm. The time between backwash events is indicated in terms of the mean, standard deviation, and number of data (backwash events). Solids wasting occurred after every 5 backwash cycles. The system is designed to backwash in 30 seconds at 29 gpm. The data below represents the actual performance measured by the backwash flow meter. Differences in valve opening, pump ramp up, and pump ramp down times make the volume per backwash slightly different from what would be calculated at 29 gpm for 30 seconds. Coagulants are indicated by the shading, although the coagulant (and polymer) doses varied. The filter media was new at the start of the filter trial, and data for Trials 1 and 2 were possibly not representative of long term performance. Trial 1 was conducted with no coagulant and no polymer. Trial 2 was conducted with a very low alum dose and no polymer. Trials 9, 15 and 19 were also conducted without chemicals.

Table 10: Backwash and Solids Wasting Rates by Trial

	Flow Rates (gpm)			Time between Backwashes (min)	Wasting Rates (% of Influent Flow)		
Trial	Influent	Solids	BW	Mean ± StDev [n]	Backwash (BW)	Solids (SW)	Combined (BW+SW)
1	39	0.98	12.03	57.8 ± 21.0 [25]	1.0	0.3	1.3
2	39	0.29	n/a	n/a	0.0	0.0	0.0
3	39	3.15	n/a	63.6 ± 167.5 [14]	5.7	1.4	7.1
4	39	7.93	13.157	13.0 ± 53.6 [79]	10.5	2.6	13.1
5	39	8.59	8.321	5.1 ± 0.4 [69]	10.9	2.7	13.6
6	39	20.2	21.428	2.3 ± 0.6 [12]	24.1	6.5	30.6
7	39	10.82	13.6	3.4 ± 0.4 [444]	16.3	4.0	20.3
8	39	13.17	10.017	3.1 ± 0.5 [435]	18.3	4.5	22.8
9	39	1.54	15.716	30.5 ± 19.6 [33]	1.8	0.5	2.3
10	39	8.8	14.262	4.8 ± 1.9 [312]	11.7	2.9	14.6
11	39	9.12	13.538	5.0 ± 4.4 [62]	12.0	2.8	14.8
12	39	7.98	11.388	5.0 ± 5.4 [799]	11.6	2.8	14.4
13	39	11.93	12.444	3.2 ± 0.4 [571]	17.3	4.3	21.6
14	39	13.27	12.049	2.9 ± 0.4 [503]	18.8	1.2	20.0
15	39	3.82	15.388	9.2 ± 8.1 [10]	5.3	1.2	6.5
16	39	13.33	13.352	3.0 ± 2.4 [756]	19.1	4.7	23.8
17	39	14.59	12.737	2.6 ± 0.5 [998]	21.5	5.3	26.8
18	70	20.17	17.917	3.1 ± 13.6 [336]	25.8	3.3	29.1
19	39	1.52	9.771	26.6 ± 16.9 [28]	2.1	0.5	2.6

Yellow indicates alum trials (not including Trial 2 at very low alum dose.
Blue indicates ferric chloride trials.
No color indicates no coagulant.

Table 11 summarizes the waste volumes for each trial, for filter backwash (BW) and solids wasting (SW). The backwashes were initiated based on headloss (differential water level across filter cloth). Solids wasting occurred once for every 5 BW cycles. During SW cycles, the settled solids in the filter basin were flushed to waste. BW and SW data were logged by the SCADA. Data included waste flow rates for BW and SW (gpm), total BW and SW volumes (gallons), and cycle counts for BW and SW.

There were no solids analyses of BW or SW samples. The solids concentrations and masses of the combined BW and SW waste stream was estimated in two different ways in the table below:
(1) based on TSS data for the chemically pretreated influent and effluent; (2) based on the theoretical solids loads introduced by the specific chemical pretreatment.

Table 11: Waste Volume and Estimated Solids Mass by Trial

	Influent and Waste Volumes (gallons)			Estimated per TSS Data for Influent and Effluent			Estimated per Chemical Dose Data	
Trial	Influent	BW	SW	Average Waste TSS (mg/L)	TSS Mass Removed (gram)	Removal Rate (lb/MG)	Coagulated Solids (gram)	Removal Rate (lb/MG)
1	69,740	596	150	445	1,257	40		
2	14,356	21	0	1,817	147	23	87	13
3	34,476	1,389	333	388	2,525	161	1,580	101
4	40,061	2,322	592	207	2,288	126	1,912	105
5	13,617	1,487	377	131	925	150	663	107
6	1,150	279	82				1,006	1,928
7	59,637	9,666	2,397	82	3,732	138	4,302	159
8	52,231	9,565	2,348	93	4,180	176	3,767	159
9	39,991	708	184	68	230	13		
10	57,212	6,756	1,689	74	2,368	91	1,874	72
11	11,811	1,330	320	114	713	133	737	138
12	148,722	17,442	4,237	107	8,783	130	8,972	133
13	72,074	12,447	3,082	160	9,419	288	6,712	205
14	58,170	10,969	2,701	137	7,084	268	7,041	267
15	4,562	223	53					
16	88,556	16,413	4,049	117	9,060	226	7,466	186
17	101,396	21,751	5,353	98	10,064	219	9,567	208
18	54,538	14,103	1,802	100	5,996	242	5,151	208
19	29,785	603	160	145	420	31		

Yellow indicates alum trials (not including Trial 2 at very low alum dose.
Blue indicates ferric chloride trials.
No color indicates no coagulant.

The mass values estimated based on TSS and coagulant doses were comparable for most trials. For the alum trials that were most effective in terms of phosphorus removal (Trials 7, 8, 16 and 17) the average combined waste TSS was estimated to range from 82 to 117 mg/L. The removal rates varied from 138 to 226 lb/MG. The calculations for these estimates are detailed below.

Estimated per TSS Data for Influent and Effluent

The mass of TSS wasted was estimated as shown below, for the total combined waste stream (BW + SW). The mass removed is shown in both grams of total mass, and pounds per million gallons treated.

$$TSS\ Mass\ Removed\ (g) = \ [(TSS_{INF}\ x\ V_{INF}) - \ (TSS_{EFF}\ x\ V_{EFF})]x\ \frac{3.7854\ \ L/gal}{1000\ \ mg/g}$$

Where:

TSS_{INF} = median influent TSS for trial (lab analysis of composite samples, mg/L)
V_{INF} = influent volume for trial (gal)
TSS_{EFF} = median effluent TSS for trial (lab analysis of composite samples, mg/L)

V_{EFF} $= V_{INF} – (V_{BW} + V_{SW})$ = net effluent volume for trial (gal)

The average waste TSS was calculated from the TSS mass removed and the combined BW and SW waste volume:

$$Average\ Waste\ TSS\ (mg/L) = \frac{(TSS\ Mass\ in\ grams)\ x\ 1000\ \ mg/L}{(V_{BW} +\ V_{SW})\ x\ 3.7854\ \ L/gal}$$

Estimated per Chemical Dose Data

The mass of solids wasted was estimated from the coagulant and polymer doses using the following assumptions:

1. One mole of alum (molecular mass = 594 g/mol) reacted completely with alkalinity to form two moles of solid aluminum hydroxide (molecular mass = 78 g/mol). The molar mass ratio of aluminum hydroxide to alum was (2 x 78)/594 = 0.2626.
2. One mole of ferric chloride (molecular mass = 162.5 g/mol) reacted completely with alkalinity to form one mole of solid ferric hydroxide (molecular mass = 107 g/mol). The molar mass ratio of ferric hydroxide to ferric chloride was 107/162.5 = 0.6585.
3. Polymer mass was completely removed at a mass concentration equal to the dose. Polymer mass was small compared to coagulant mass.

The mass contributed by each coagulant/polymer combination was calculated as shown below.

$$Alum\ solids\ mass\ (g) = [0.2626(alum\ dose) +\ (poly\ dose)](V_{INF})\ x\ \frac{3.7854\ \ L/gal}{1000\ \ mg/g}$$

$$Ferric\ solids\ mass\ (g) = [0.6585(ferric\ dose) +\ (poly\ dose)](V_{INF})\ x\ \frac{3.7854\ \ L/gal}{1000\ \ mg/g}$$

Gram values were converted to pounds using a factor of 453.592 grams per lb. Removal rates were calculated as:

$$Removal\ Rate\ (lb/MG) = \frac{(solids\ mass, lb)(454\ \ g/lb)}{(influent\ volume, gal)}\ x\ 10^6\ \ gal/MG$$

2.7 TSS DATA

Table 11 summarizes TSS data from laboratory analysis. The data were grouped according to the coagulant used (alum, ferric chloride, or none) regardless of coagulant dose or polymer dose. All influent samples were composite samples. Influent composite samples were collected after chemicals were added, except for trials with coagulant type “None” (in which case there were no pretreatment chemicals). Effluent composite samples were collected from the cloth filter effluent weir.

Table 11: Total Suspended Solids Data by Laboratory Analyses

	Mean ± Std. Deviation (min – max) [number of data]	
Coagulant (Trials)	Influent (post-chemical)	Effluent
Alum (Trials 2-8, 16-18)	**25.4** ± 7.7 (5.0 – 34.0) [16]	**4.8** ± 1.5 (2.3 – 7.0) [16]
Ferric Chloride (Trials 10-14)	**23.7** ± 10.4 (10.0 – 40.0) [13]	**2.3** ± 1.1 (1.0 – 4.7) [13]
None (Trials 1, 9, 15, 19)	**5.2** ± 2.7 * (2.5 – 9.0) [4]	**1.1** ± 0.1 (1.0 – 1.2) [4]
Effective Operations Alum > 70 mg/L (Combined 7, 8, 16, 17)	**27.8** ± 5.6 (14.0 – 34.0) [12]	**4.8** ± 1.4 (2.3 – 7.0) [12]

* Untreated pilot system influent (secondary clarifier effluent)

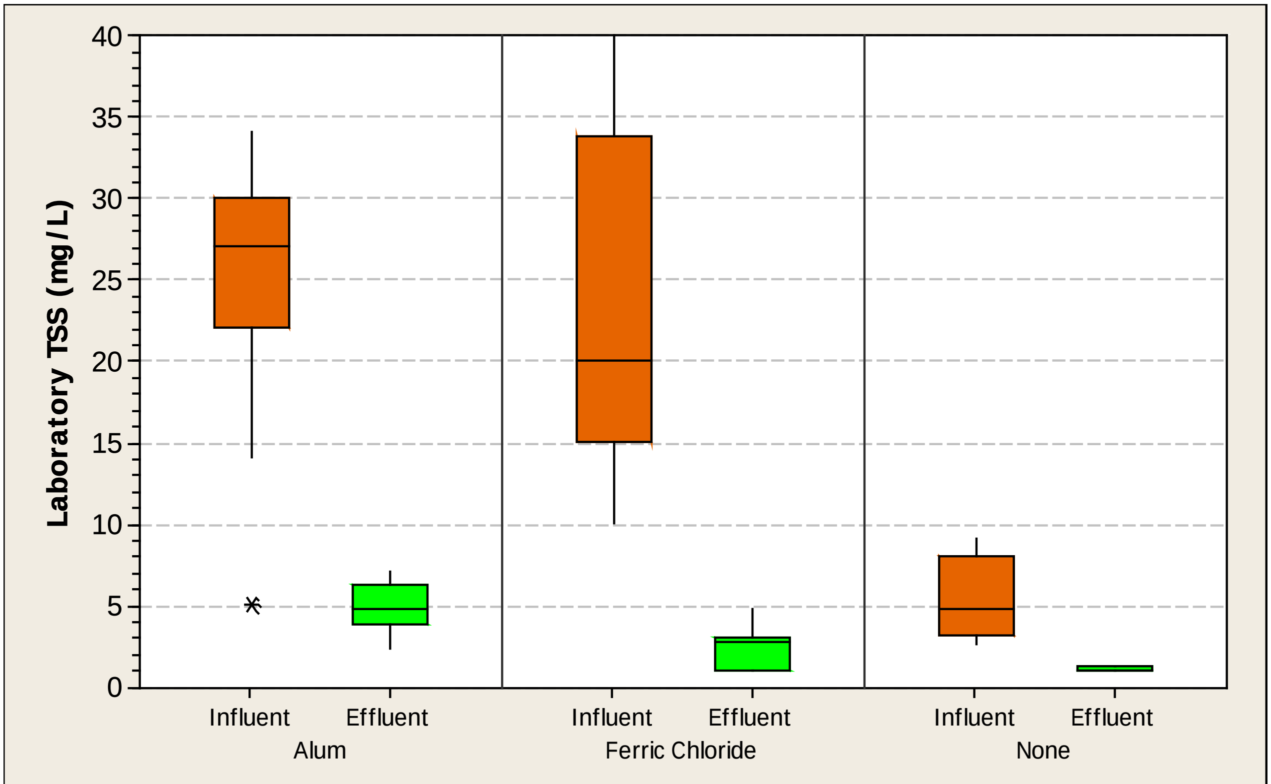
The table also shows the statistics of the data corresponding to the effective operating conditions using alum (Trials 7, 8, 16 and 17) are shown.

The data corresponding to “None” indicate the TSS of the pilot system influent without any chemical addition (i.e. the secondary clarifier effluent). The mean influent TSS without chemical addition was 5.2 ± 2.7 mg/L. The mean TSS was reduced to 1.1 ± 0.1 mg/L after filtration, even without chemical pretreatment. This indicates approximately 79% removal of influent TSS by simple filtration with the cloth media (4 data pairs).

The data corresponding to treatment with ferric chloride indicated that the mean TSS of the pretreated influent was increased to 23.7 ± 10.4 mg/L. The mean TSS of the filtered effluent was reduced to 1.1 ± 0.1 mg/L. This indicated approximately 95% removal of the pretreated influent TSS. The data corresponding to treatment with alum for the “effective operations” trials indicate that the mean TSS of the pretreated influent was increased to 27.8 ± 5.6 mg/L. The mean TSS of the filtered effluent was reduced to 4.8 ± 1.4 mg/L (equal to the mean for all alum trials combined). This indicated approximately 83% removal of the pretreated influent TSS.

Figure 18 shows boxplots for the influent and effluent TSS data according to coagulant type.

Figure 18: Boxplots of TSS Data vs. Sample Site and Coagulant Type

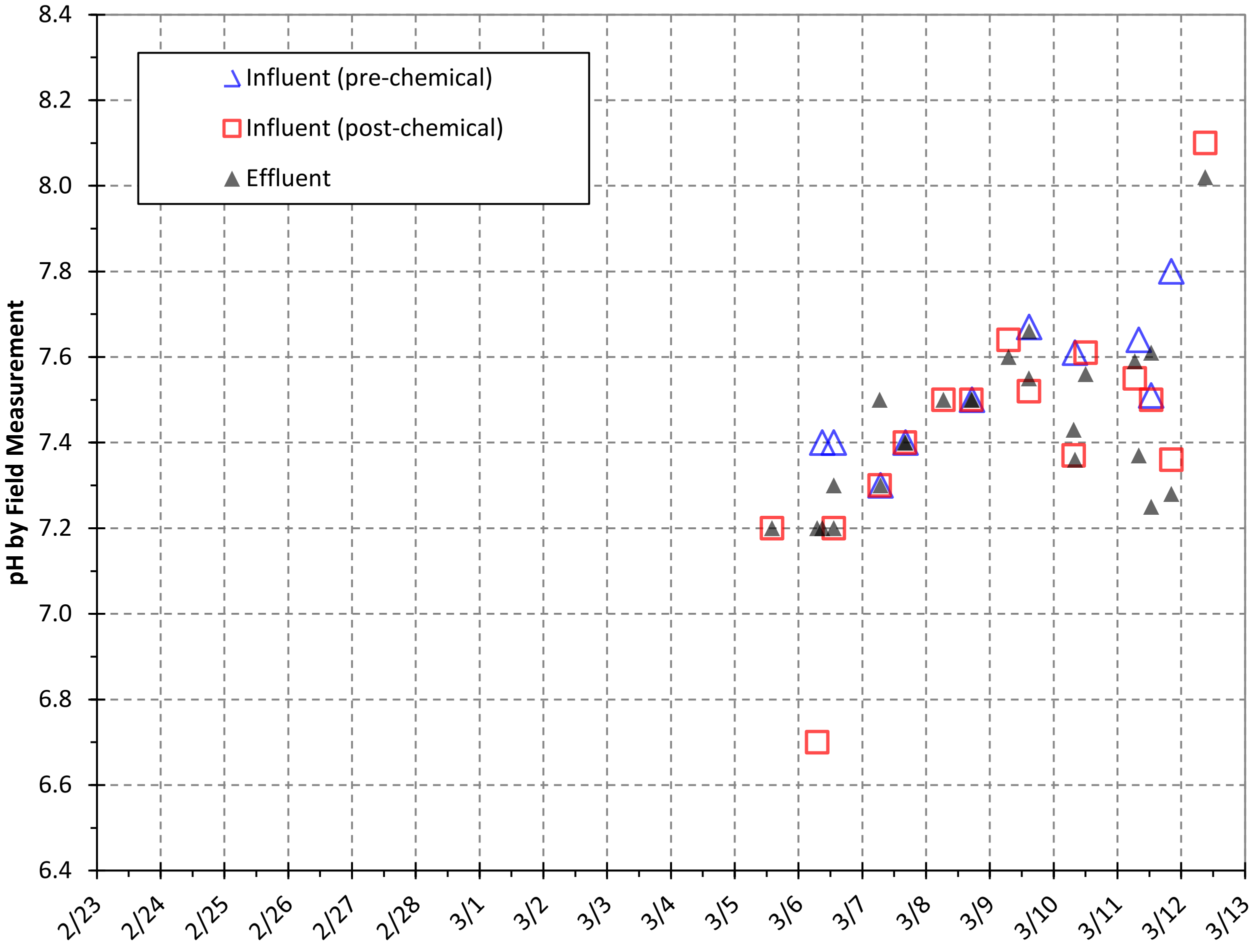


1. All samples were composites.
2. Influent samples were post-chemical treatment.

2.8 pH DATA

The pH data from the pilot study were limited owing to equipment malfunction. The original inline turbidity probe failed, and a replacement probe also failed. Subsequently, pH measurements were taken of the daily water quality samples of (1) the pilot influent before chemical pretreatment, (2) the chemically treated influent, and (3) the filter effluent. Figure 18 plots the pH data by date, for the pilot influent before chemical pretreatment, the influent after chemical pretreatment, and the effluent. The plot indicates that pH was increasing over the last week of the pilot study.

Figure 18: pH Data



pH data from the 3 sample sites were compared by a one-way analysis of variance (ANOVA). The output is shown below. The mean pH values were:

- Influent (pre-chemical): mean pH = 7.65 ±0.105
- Influent (post-chemical): mean pH = 7.58 ±0.233
- Effluent: mean pH = 7.52 ±0.209

Figure 19 shows boxplots of the three data sets (center marks and connecting lines indicate the means). The plot suggests that pH decreased after addition of coagulant, and also decreased after filtration. Generally, the pH of coagulation and flocculation was 7.4 – 7.8. The pH for optimal alum coagulation is typically 6.0 - 6.5.

One-way ANOVA: pH_Hach versus Site ID

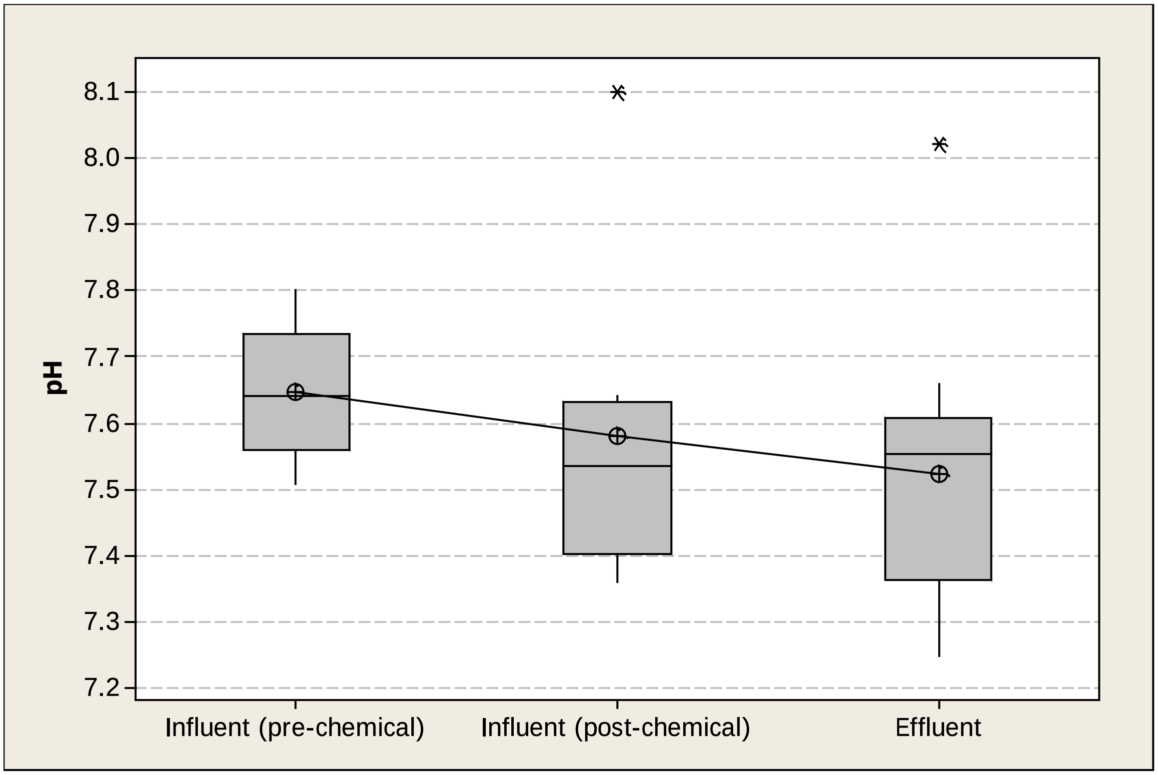
```
Source       DF      SS      MS     F      P
Site ID      2      0.0557  0.0279  0.68  0.517
Error        22     0.9005  0.0409
Total        24     0.9562

S = 0.2023   R-Sq = 5.83%   R-Sq(adj) = 0.00%


                           Individual 90% CIs For Mean Based on
                           Pooled StDev
Level   N    Mean   StDev  --------+---------+---------+---------+-
1       5  7.6460  0.1050         (---------------*---------------)
2       8  7.5812  0.2325     (-----------*-----------)
3      12  7.5233  0.2085  (---------*---------)
                           --------+---------+---------+---------+-
                                7.50      7.60      7.70      7.80

Pooled StDev = 0.2023
```

Figure 19: Boxplots of pH Data



Discussion, phosphorus removal with alum coagulation

In simplified terms, alum coagulation is intended to precipitate dissolved species of phosphorus to form solid particulates, in particular aluminum phosphate ($AlPO_4$). Alum coagulation is pH dependent, and different removal mechanisms dominate at different pH levels. The mean pH of the Cashmere secondary effluent (pilot influent) was approximately 7.5, which likely favored formation of aluminum hydroxide over aluminum phosphate, especially since the influent wastewater alkalinity was high (343 mg/L as $CaCO_3$ based on 1 field measurement). This might explain the high molar ratios that were required for effective phosphorus removal. Molar ratios of aluminum ion to influent total P (Al^{3+}:TP) ranged from 24.4 to 32.5 for effective operations (Trials 7, 8, 16 and 17).

It is possible that lower pH might provide more efficient precipitation of soluble phosphorus species, which would allow lower coagulant doses and more efficient filter performance in terms of both effluent water quality, and backwash wasting percentages.

Alternative coagulants might allow more efficient phosphorus removal within the pH range that was observed during the period from 3/5 through 3/12/15. Alternatives would include polyaluminum chloride (PACl) and aluminum chlorohydrate (ACH). PACl and ACH typically have higher pH levels for minimum solubility than alum, and can potentially produce floc with greater positive surface charge than alum. Floc with high positivity could potentially have greater adsorptive capacity for phosphate species.

Iron Data

Several laboratory composite samples were analyzed for iron, to evaluate whether the use of ferric chloride increased residual total Fe concentrations in the effluent. The data are shown in Table 11. The laboratory analyzed iron by EPA Method 200.7, and the reporting limit was 9.7 µg/L (0.0097 mg/L). Figure 20 shows boxplots of all iron data grouped according to sample site and chemical pretreatment.

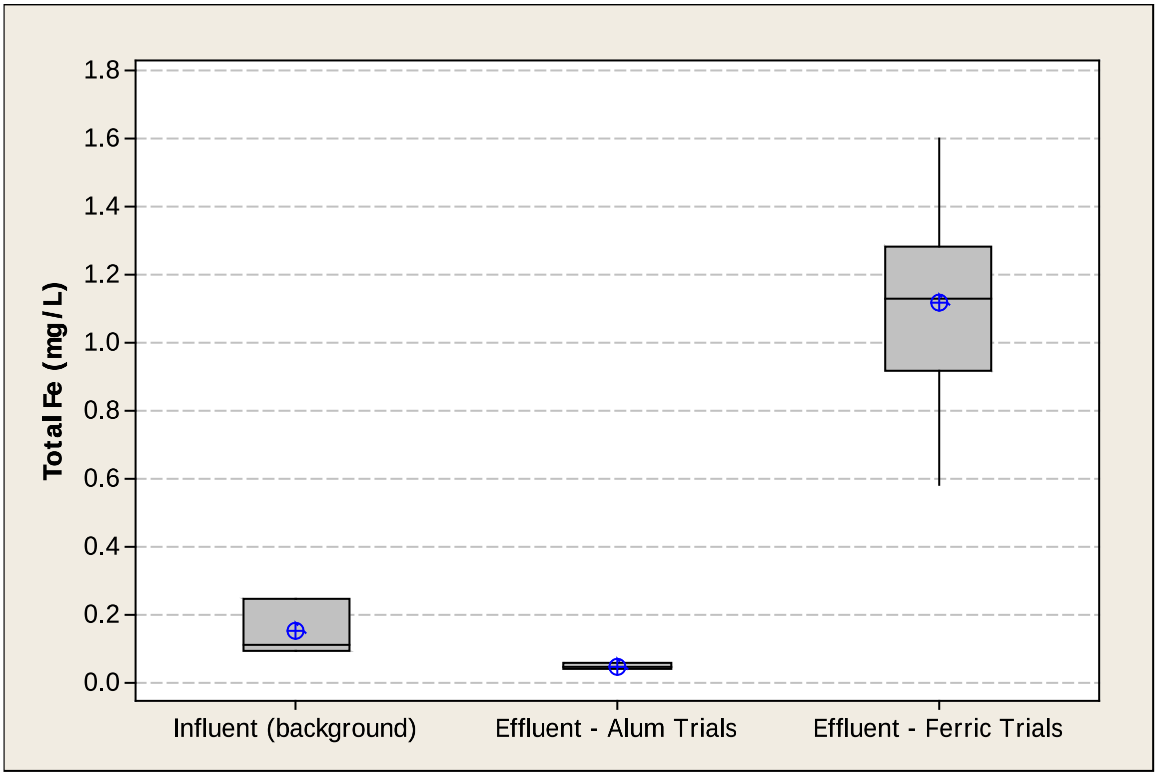
Background iron concentrations in the pilot influent ranged from 0.093 to 0.248 mg/L total Fe, based on 3 influent data (these were pretreated with 89.2 mg/L alum with negligible iron content). Effluent iron concentrations when operating with alum 0.0398 and 0.0555 mg/L based on 2 data. The available data suggest that alum coagulation followed by filtration reduced background iron concentrations.

Effluent iron concentrations were analyzed during Trials 12, 13 and 14 while operating the pilot system with ferric chloride doses ranging from 23.9 to 47.8 mg/L as FeCl3. Effluent iron concentrations ranged from 0.585 to 1.600 mg/L total Fe (10 data). The use of ferric chloride substantially increased effluent iron concentrations.

Table 11: Total Iron Data by Laboratory Analysis

Sample Site	Trial	Coagulant Type	Coagulant Dose (mg/L)	Sample ID	Total Fe (mg/L)
Influent (post-chemical)	16	Alum	82.9	100 102 107	0.2480 0.1100 0.0930
Effluent	16	Alum	82.9	101 103	0.0555 0.0398
Effluent	12	$FeCl_3$	23.9	60 65 67 69 74	0.9250 1.1600 0.5850 1.1000 1.0400
	13	$FeCl_3$	36.6	79 83 88	1.2800 0.9000 1.2700
	14	$FeCl_3$	47.8	92 97	1.3000 1.6000

Figure 20: Boxplots of Total Iron Data (mg/L total Fe)



		Sample Collection Data						Data by Field Analysis (AASI Field Laboratory)											Data by LAB Analysis (Cascade Analytical)		
WQ ID No.	Trial No.	Collection Time	Composite Start Time	Composite Duration (hrs)	Sample Type	Site ID	Sample Collection Site	Total P	Soluble Total P	Reactive P	Soluble Reactive P	Insoluble Total P	Insoluble Reactive P	Soluble Non-reactive P	Non-reactive P	Insoluble Non-reactive P	Turbidity (ntu)	pH	TSS (mg/L)	Total P (mg/L P)	Total Fe (mg/L)
1	1	2/23 - 10:00			Grab	1	Influent (pre-chemical)	0.32	0.24	0.12	0.13										
2	1	2/23 - 10:00			Grab	3	Effluent	0.19	0.27	0.12	0.12										
3	1	2/23 - 10:00			Grab	4	Blank	0.02		0.01											
4	1	2/23 - 13:30			Grab	1	Influent (pre-chemical)	0.35	0.27	0.15	0.15	0.08	0.00	0.12	0.20	0.08					
5	1	2/23 - 13:30			Grab	3	Effluent	0.24	0.17	0.12	0.13	0.07	0.00	0.04	0.12	0.08					
6	1	2/23 - 13:30			Grab	4	Blank	0.02		0.02											
7	1	2/23 - 16:00	2/23 - 09:00	7	Composite	2	Influent (filter basin)	0.35	0.22	0.16	0.14	0.13	0.02	0.08	0.19	0.11			9.0	0.345	
8	1	2/23 - 16:00	2/23 - 09:00	7	Composite	3	Effluent	0.28	0.20	0.12	0.13	0.08	0.00	0.07	0.16	0.09			1.2	0.218	
9	1	2/24 - 08:00	2/23 - 16:00	16	Composite	2	Influent (filter basin)	0.31	0.29	0.15	0.17	0.02	0.00	0.12	0.16	0.04				0.244	
10	1	2/24 - 08:00	2/23 - 16:00	16	Composite	3	Effluent	0.24	0.21	0.14	0.11	0.03	0.03	0.10	0.10	0.00				0.208	
11	1	2/24 - 09:45			Grab	1	Influent (pre-chemical)	0.30	0.18	0.13	0.12	0.12	0.01	0.06	0.17	0.11					
12	1	2/24 - 09:45			Grab	3	Effluent	0.23	0.17	0.15	0.15	0.06	0.00	0.02	0.08	0.06					
13	1	2/24 - 09:45			Grab	4	Blank	0.03		0.03											
14	1	2/24 - 15:30	2/24 - 08:00	7.5	Composite	2	Influent (filter basin)	0.23	0.14	0.13	0.10	0.09	0.03	0.04	0.10	0.06			4.7	0.257	
15	1	2/24 - 15:30	2/24 - 08:00	7.5	Composite	3	Effluent	0.21	0.16	0.09	0.10	0.05	0.00	0.06	0.12	0.06			<1.0	0.177	
16	2	2/25 - 07:00	2/24 - 19:00	12	Composite	2	Influent (filter basin)	0.25	0.18	0.14	0.11	0.07	0.03	0.07	0.11	0.04			5.0	0.242	
17	2	2/25 - 07:00	2/24 - 19:00	12	Composite	3	Effluent	0.21	0.15	0.11	0.10	0.06	0.01	0.05	0.10	0.05			2.3	0.193	
18	3	2/25 - 09:30			Grab	1	Influent (pre-chemical)	0.27	0.21	0.18	0.14	0.06	0.04	0.07	0.09	0.02					
19	3	2/25 - 09:30			Grab	3	Effluent	0.13	0.07	0.10	0.04	0.06	0.06	0.03	0.03	0.00					
20	3	2/25 - 09:30			Grab	4	Blank	0.01		0.02											
21	3	2/25 - 15:00	2/25 - 08:30	6.5	Composite	2	Influent (filter basin)	0.27	0.08	0.07	0.03	0.19	0.04	0.05	0.20	0.15			26.0	0.322	
22	3	2/25 - 15:00	2/25 - 08:30	6.5	Composite	3	Effluent	0.14	0.01	0.08	0.04	0.13	0.04	0.00	0.06	0.06			7.0	0.121	
23	4	2/26 - 08:00	2/25 - 17:00	15	Composite	2	Influent (filter basin)	0.26	0.08	0.13	0.03	0.18	0.10	0.05	0.13	0.08			20.0	0.271	
24	4	2/26 - 08:00	2/25 - 17:00	15	Composite	3	Effluent	0.13	0.06	0.06	0.05	0.07	0.01	0.01	0.07	0.06			5.3	0.105	
25	5	2/26 - 10:30			Grab	1	Influent (pre-chemical)	0.29		0.12	0.13	0.29	0.00	0.00	0.17	0.17					
26	5	2/26 - 10:30			Grab	3	Effluent	0.14	0.06	0.08	0.03	0.08	0.05	0.03	0.06	0.03					
27	5	2/26 - 10:30			Grab	4	Blank	0.00		0.00											
28	5	2/26 - 14:00	2/26 - 10:00	4	Composite	2	Influent (filter basin)	0.18	0.07	0.17	0.06	0.11	0.11	0.01	0.01				22.0	0.316	
29	5	2/26 - 14:00	2/26 - 10:00	4	Composite	3	Effluent	0.13	0.05	0.07	0.05	0.08	0.02	0.00	0.06	0.06			4.7	0.125	
30	6	2/26 - 14:45			Grab	3	Effluent	0.08	0.05	0.09	0.08	0.03	0.01	0.00	0.00	0.00					
31	7	2/27 - 08:00	2/26 - 16:00	16	Composite	2	Influent (filter basin)	0.19	0.07	0.11	0.11	0.12	0.00	0.00	0.08	0.08			14.0	0.172	
32	7	2/27 - 08:00	2/26 - 16:00	16	Composite	3	Effluent	0.10	0.08	0.10	0.06	0.02	0.04	0.02	0.00	0.00			4.7	0.068	
33	7	2/27 - 08:30			Grab	1	Influent (pre-chemical)	0.26	0.16	0.17	0.16	0.10	0.01	0.00	0.09	0.09					
34	7	2/27 - 08:30			Grab	3	Effluent	0.09	0.06	0.15	0.15	0.03	0.00	0.00	0.00	0.00					
35	7	2/27 - 08:30			Grab	4	Blank	0.01		0.01											
36	7	2/27 - 16:00	2/27 - 09:00	7	Composite	2	Influent (filter basin)	0.19	0.07	0.10	0.04	0.12	0.06	0.03	0.09	0.06			26.0	0.254	
37	7	2/27 - 16:00	2/27 - 09:00	7	Composite	3	Effluent	0.10	0.07	0.05	0.04	0.03	0.01	0.03	0.05	0.02			4.0	0.077	
38	8	2/28 - 08:30	2/27 - 16:30	16	Composite	2	Influent (filter basin)	0.30	0.06	0.11	0.02	0.24	0.09	0.04	0.19	0.15			22.0	0.211	
39	8	2/28 - 08:30	2/27 - 16:30	16	Composite	3	Effluent	0.10	0.08	0.04	0.03	0.02	0.01	0.05	0.06	0.01			3.3	0.071	
40	8	2/28 - 10:30			Grab	1	Influent (pre-chemical)	0.32	0.23	0.17	0.16	0.09	0.01	0.07	0.15	0.08					
41	8	2/28 - 10:30			Grab	3	Effluent	0.10	0.06	0.06	0.04	0.04	0.02	0.02	0.04	0.02					
42	8	2/28 - 10:30			Grab	4	Blank	0.01		0.02											
43	8	2/28 - 15:00	2/28 - 09:00	6	Composite	2	Influent (filter basin)	0.13	0.06	0.08	0.03	0.07	0.05	0.03	0.05	0.02			28.0	0.259	
44	8	2/28 - 15:00	2/28 - 09:00	6	Composite	3	Effluent	0.10	0.06	0.05	0.04	0.04	0.01	0.02	0.05	0.03			6.7	0.089	
45	9	3/01 - 08:00	2/28 - 17:00	15	Composite	2	Influent (filter basin)	0.25	0.19	0.16	0.12	0.06	0.04	0.07	0.09	0.02			2.5	0.239	
46	9	3/01 - 08:00	2/28 - 17:00	15	Composite	3	Effluent	0.26	0.21	0.13	0.14	0.05		0.07	0.13	0.06			<1.0	0.231	
47	10	3/01 - 12:30			Grab	1	Influent (pre-chemical)	0.30	0.24	0.18	0.17	0.06	0.01	0.07	0.12	0.05					
48	10	3/01 - 12:30			Grab	3	Effluent	0.14	0.09	0.06	0.06	0.05	0.00	0.03	0.08	0.05					
49	10	3/01 - 12:30			Grab	4	Blank	0.01		0.01											
50	10	3/01 - 15:00	3/01 - 10:00	5	Composite	2	Influent (filter basin)	0.23	0.19	0.11	0.06	0.04	0.05	0.13	0.12				14.0	0.281	
51	10	3/01 - 15:00	3/01 - 10:00	5	Composite	3	Effluent	0.17	0.11	0.09	0.08	0.06	0.01	0.03	0.08	0.05			1.0	0.111	
52	10	3/02 - 08:00	3/01 - 15:30	16.5	Composite	2	Influent (filter basin)	0.26	0.12	0.11	0.06	0.14	0.05	0.06	0.15	0.09			10.0	0.279	
53	10	3/02 - 08:00	3/01 - 15:30	16.5	Composite	3	Effluent	0.16	0.10	0.09	0.08	0.06	0.01	0.02	0.07	0.05			1.5	0.132	
56	11	3/02 - 11:10			Grab	1	Influent (pre-chemical)	0.27	0.17	0.13	0.10	0.10	0.03	0.07	0.14	0.07					

		Sample Collection Data						Data by Field Analysis (AASI Field Laboratory)											Data by LAB Analysis (Cascade Analytical)		
WQ ID No.	Trial No.	Collection Time	Composite Start Time	Composite Duration (hrs)	Sample Type	Site ID	Sample Collection Site	Total P	Soluble Total P	Reactive P	Soluble Reactive P	Insoluble Total P	Insoluble Reactive P	Soluble Non-reactive P	Non-reactive P	Insoluble Non-reactive P	Turbidity (ntu)	pH	TSS (mg/L)	Total P (mg/L P)	Total Fe (mg/L)
57	11	3/02 - 11:10			Grab	3	Effluent	0.13	0.10	0.05	0.07	0.03		0.03	0.08	0.05					
58	11	3/02 - 11:10			Grab	4	Blank	0.01		0.01											
54	11	3/02 - 13:30	3/02 - 10:30	3	Composite	2	Influent (filter basin)	0.35	0.16	0.15	0.05	0.19	0.10	0.11	0.20	0.09			20.0	0.276	
55	11	3/02 - 13:30	3/02 - 10:30	3	Composite	3	Effluent	0.21	0.18	0.06	0.05	0.03	0.01	0.13	0.15	0.02			4.7	0.137	
59	12	3/03 - 06:30	3/02 - 16:00	14.5	Composite	2	Influent (filter basin)	0.33	0.11	0.11	0.04	0.22	0.07	0.07	0.22	0.15			18.0	0.248	
60	12	3/03 - 06:30	3/02 - 16:00	14.5	Composite	3	Effluent	0.16	0.10	0.06	0.04	0.06	0.02	0.06	0.10	0.04			2.0	0.107	0.925
61	12	3/03 - 11:00			Grab	1	Influent (pre-chemical)	0.29	0.20	0.11	0.09	0.09	0.02	0.11	0.18	0.07					
62	12	3/03 - 11:00			Grab	3	Effluent	0.17	0.10	0.05	0.06	0.07		0.04	0.12	0.08					
63	12	3/03 - 11:00			Grab	4	Blank	0.02		0.01											
64	12	3/03 - 16:00	3/03 - 11:00	5	Composite	2	Influent (filter basin)	0.26	0.09	0.12	0.08	0.17	0.04	0.01	0.14	0.13			16.0	0.236	
65	12	3/03 - 16:00	3/03 - 11:00	5	Composite	3	Effluent	0.16	0.09	0.08	0.07	0.07	0.01	0.02	0.08	0.06			2.7	0.100	1.160
66	12	3/04 - 06:00	3/03 - 17:00	13	Composite	2	Influent (filter basin)	0.31	0.13	0.14	0.11	0.18	0.03	0.02	0.17	0.15			10.0	0.289	
67	12	3/04 - 06:00	3/03 - 17:00	13	Composite	3	Effluent	0.19	0.13	0.16	0.14	0.06	0.02		0.03	0.04			<1.0	0.165	0.585
70	12	3/04 - 10:00			Grab	1	Influent (pre-chemical)	0.28	0.19	0.16	0.18	0.09		0.01	0.12	0.11					
71	12	3/04 - 10:00			Grab	3	Effluent	0.16	0.13	0.14	0.08	0.03	0.06	0.05	0.02						
72	12	3/04 - 10:00			Grab	4	Blank	0.03		0.01											
68	12	3/04 - 16:00	3/04 - 10:00	6	Composite	2	Influent (filter basin)	0.30	0.10	0.09	0.04	0.20	0.05	0.06	0.21	0.15			20.0	0.265	
69	12	3/04 - 16:00	3/04 - 10:00	6	Composite	3	Effluent	0.16	0.09	0.05	0.03	0.07	0.02	0.06	0.11	0.05			3.0	0.104	1.100
73	12	3/05 - 06:30	3/04 - 18:30	12	Composite	2	Influent (filter basin)	0.34	0.10	0.11	0.05	0.24	0.06	0.05	0.23	0.18			24.0	0.299	
74	12	3/05 - 06:30	3/04 - 18:30	12	Composite	3	Effluent	0.14	0.10	0.05	0.05	0.04	0.00	0.05	0.09	0.04			3.0	0.099	1.040
75	13	3/05 - 10:00			Grab	1	Influent (pre-chemical)	0.34	0.21	0.11	0.11	0.13	0.00	0.10	0.23	0.13					
76	13	3/05 - 10:00			Grab	3	Effluent	0.15	0.10	0.06	0.03	0.05	0.03	0.07	0.09	0.02					
77	13	3/05 - 10:00			Grab	4	Blank	0.03		0.01											
80	13	3/05 - 13:00			Grab	1	Influent (pre-chemical)	0.32	0.22	0.13	0.11	0.10	0.02	0.11	0.19	0.08					
81	13	3/05 - 13:00			Grab	3	Effluent	0.17	0.13	0.06	0.05	0.04	0.01	0.08	0.11	0.03					
78	13	3/05 - 14:00	3/05 - 10:00	4	Composite	2	Influent (filter basin)	0.32	0.11	0.16	0.05	0.21	0.11	0.06	0.16	0.10	8.17	7.20	35.0	0.258	
79	13	3/05 - 14:00	3/05 - 10:00	4	Composite	3	Effluent	0.13	0.10	0.09	0.05	0.03	0.04	0.05	0.04		1.87	7.20	3.0	0.090	1.280
82	13	3/06 - 07:00	3/05 - 14:30	16.5	Composite	2	Influent (filter basin)	0.29	0.13	0.12	0.07	0.16	0.05	0.06	0.17	0.11	8.32	6.70	32.5	0.276	
83	13	3/06 - 07:00	3/05 - 14:30	16.5	Composite	3	Effluent	0.14	0.11	0.08	0.11	0.03		0.00	0.06	0.06	1.37	7.20	<1.0	0.077	0.900
84	13	3/06 - 08:55			Grab	1	Influent (pre-chemical)	0.40	0.26	0.18	0.17	0.14	0.01	0.09	0.22	0.13	4.17	7.40			
85	13	3/06 - 08:55			Grab	3	Effluent	0.16	0.11	0.12	0.12	0.05	0.00		0.04	0.05	1.19	7.20			
86	13	3/06 - 08:55			Grab	4	Blank	0.03		0.01											
89	13	3/06 - 13:15			Grab	1	Influent (pre-chemical)	0.29	0.20	0.14	0.10	0.09	0.04	0.10	0.15	0.05	3.54	7.40			
87	13	3/06 - 13:15	3/06 - 08:15	5	Composite	2	Influent (filter basin)	0.28	0.10	0.11	0.07	0.18	0.04	0.03	0.17	0.14	8.21	7.20	40.0	0.249	
88	13	3/06 - 13:15	3/06 - 08:15	5	Composite	3	Effluent	0.16	0.09	0.07	0.09	0.07		0.00	0.09	0.09	1.66	7.30	1.0	0.088	1.270
90	13	3/06 - 13:15			Grab	3	Effluent	0.12	0.09	0.09	0.06	0.03	0.03	0.03	0.03	0.00	1.30	7.20			
91	14	3/07 - 06:30	3/06 - 17:00	13.5	Composite	2	Influent (filter basin)	0.27	0.09	0.11	0.08	0.18	0.03	0.01	0.16	0.15	8.28	7.30	32.0	0.244	
92	14	3/07 - 06:30	3/06 - 17:00	13.5	Composite	3	Effluent	0.11	0.04	0.07	0.04	0.07	0.03	0.00	0.04	0.04	1.30	7.50	3.0	0.067	1.300
93	14	3/07 - 06:50			Grab	1	Influent (pre-chemical)	0.34	0.21	0.13	0.12	0.13	0.01	0.09	0.21	0.12	2.97	7.30			
94	14	3/07 - 06:50			Grab	3	Effluent	0.11	0.08	0.06	0.04	0.03	0.02	0.04	0.05	0.01	1.25	7.30			
95	14	3/07 - 06:50			Grab	4	Blank	0.02		0.01											
96	14	3/07 - 16:00	3/07 - 07:00	9	Composite	2	Influent (filter basin)	0.27	0.11	0.12	0.07	0.16	0.05	0.04	0.15	0.11	9.10	7.40	36.7	0.222	
97	14	3/07 - 16:00	3/07 - 07:00	9	Composite	3	Effluent	0.14	0.11	0.09	0.07	0.03	0.02	0.04	0.05	0.01	1.85	7.40	2.7	0.077	1.600
98	14	3/07 - 16:15			Grab	1	Influent (pre-chemical)	0.29	0.18	0.13	0.12	0.11	0.01	0.06	0.16	0.10	3.70	7.40			
99	14	3/07 - 16:15			Grab	3	Effluent	0.12	0.09	0.12	0.07	0.03	0.05	0.02	0.00		1.04	7.40			
100	16	3/08 - 06:30	3/07 - 22:00	8.5	Composite	2	Influent (filter basin)	0.30	0.07	0.13	0.05	0.23	0.08	0.02	0.17	0.15	7.43	7.50	30.0	0.268	0.248
101	16	3/08 - 06:30	3/07 - 22:00	8.5	Composite	3	Effluent	0.11	0.06	0.05	0.07	0.05			0.06	0.07	1.21	7.50	4.0	0.067	0.0555
102	16	3/08 - 17:00	3/08 - 07:00	10	Composite	2	Influent (filter basin)	0.26	0.10	0.13	0.04	0.16	0.09	0.06	0.13	0.07	5.95	7.50	30.0	0.248	0.1100
103	16	3/08 - 17:00	3/08 - 07:00	10	Composite	3	Effluent	0.11	0.10	0.05	0.04	0.01	0.01	0.06	0.06	0.00	1.28	7.50	2.3	0.065	0.0398
104	16	3/08 - 17:15			Grab	1	Influent (pre-chemical)	0.31	0.18	0.14	0.11	0.13	0.03	0.07	0.17	0.10	2.56	7.50			
105	16	3/08 - 17:15			Grab	3	Effluent	0.10	0.08	0.06	0.06	0.02	0.00	0.02	0.04	0.02	1.13	7.50			
106	16	3/08 - 17:15			Grab	4	Blank	0.02		0.01											
107	16	3/09 - 07:00	3/08 - 19:30	11.5	Composite	2	Influent (filter basin)	0.17	0.09	0.06	0.07	0.08		0.02	0.11	0.09	5.96	7.64	30.0	0.507	0.093
108	16	3/09 - 07:00	3/08 - 19:30	11.5	Composite	3	Effluent	0.13	0.09	0.05	0.05	0.04	0.00	0.04	0.08	0.04	1.15	7.60	5.3	0.119	

APPENDIX E

WERF PHOSPHORUS STUDY ABSTRACTS

WERF PROJECT NUTR1R06m

THE BIOAVAILABLE PHOSPHORUS (BAP) FRACTION IN EFFLUENT FROM ADVANCED SECONDARY AND TERTIARY TREATMENT

by:

Bo Li
University of Washington

Michael T. Brett
University of Washington

2014

Disclaimer Page

The Water Environment Research Foundation, a not-for-profit organization, funds and manages water quality research for its subscribers through a diverse public-private partnership between municipal utilities, corporations, academia, industry, and the federal government. WERF subscribers include municipal and regional water and water resource recovery facilities, industrial corporations, environmental engineering firms, and others that share a commitment to cost-effective water quality solutions. WERF is dedicated to advancing science and technology addressing water quality issues as they impact water resources, the atmosphere, the lands, and quality of life.

For more information, contact:
Water Environment Research Foundation
635 Slaters Lane, Suite G-110
Alexandria, VA 22314-1177
Tel: (571) 384-2100
Fax: (703) 299-0742
www.werf.org
werf@werf.org

This report was co-published by the following organization.

IWA Publishing
Alliance House, 12 Caxton Street
London SW1H 0QS, United Kingdom
Tel: +44 (0) 20 7654 5500
Fax: +44 (0) 20 7654 5555
www.iwapublishing.com
publications@iwap.co.uk

Library of Congress Catalog Card Number: XXXXXXXXXX
Printed in the United States of America
IWAP ISBN: XXXXXXX

This report was prepared by the organization(s) named below as an account of work sponsored by the Water Environment Research Foundation (WERF). Neither WERF, members of WERF, the organization(s) named below, nor any person acting on their behalf: (a) makes any warranty, express or implied, with respect to the use of any information, apparatus, method, or process disclosed in this report or that such use may not infringe on privately owned rights; or (b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

Organizations that helped prepare this report XXXXX

INCLUDE ONLY IF EPA FUNDED:

The research on which this report is based was developed, in part, by the United States Environmental Protection Agency (EPA) through Cooperative Agreement No. ________ with the Water Environment Research Foundation (WERF). However, the views expressed in this document are not necessarily those of the EPA and EPA does not endorse any products or commercial services mentioned in this publication. This report is a publication of WERF, not EPA. Funds awarded under the Cooperative Agreement cited above were not used for editorial services, reproduction, printing, or distribution.

This document was reviewed by a panel of independent experts selected by WERF. Mention of trade names or commercial products or services does not constitute endorsement or recommendations for use. Similarly, omission of products or trade names indicates nothing concerning WERF's or EPA's positions regarding product effectiveness or applicability.

ACKNOWLEDGMENTS

The project team would like to thank JB Neethling and H. David Stensel for their guidance throughout the project and the WWTP staff at North Durham Water Reclamation Facility, South Durham Water Reclamation Facility, Hayden Wastewater Research Facility, Coeur d'Alene Advanced Wastewater Treatment Plant, Metropolitan Syracuse Wastewater Treatment Plant, Ruidoso Village Regional Wastewater Treatment Plant, Broad Run Water Reclamation Facility, Rock Creek Wastewater Treatment Plant, Durham Advanced Wastewater Treatment Facility, Blue Plains Advanced Wastewater Treatment Plant, City of Las Vegas Water Pollution Control Facility, Iowa Hill Wastewater Treatment Plant, Farmers Korner Wastewater Treatment plant and Snoqualmie Wastewater Reclamation Facility for their kind support with sampling and sample transport.

Research Team

Principal Investigator:
Michael T. Brett, Ph.D
University of Washington, Seattle

Project Team:
Bo Li, Ph.D candidate
University of Washington, Seattle

Technical Review Commitee

Krishna Pagilla, Ph.D., P.E.
Illinois Institute of Technology

H. David Stensel, Ph.D., P.E.
University of Washington, Seattle

Thomas C. Stiles
Kansas Department of Health and Environment

G. David Waltrip
Hampton Roads Sanitation District

Kenneth N. Wood, P.E.
DuPont Engineering

James Wheeler, P.E.
U.S. Environmental Protection Agency

Heng Zhang, Ph.D., P.E.
Metropolitan Water Reclamation District of Greater Chicago

Water Environment Research Foundation Staff

Director of Research:	Daniel M. Woltering, Ph.D.
Program Director/Manager:	Amit Pramanik, Ph.D., BCEEM

ABSTRACT AND BENEFITS

Abstract:

Due to the widespread severity of eutrophication in surface waters, there is a strong impetus to require ultra-low effluent phosphorus (P) concentrations (*i.e.*, <100 µg L^{-1}) in many municipal wastewater treatment plant discharges. Chemical addition, with filtration or membrane separation, is commonly used to meet these low targets and therefore most of the effluent P from tertiary P removal facility is in the soluble phase. This study examined the bioavailability of phosphorus (BAP) in the effluents of advanced phosphorus removal treatment systems using algal bioassay experiments. Effluent BAP was determined for 17 full-scale wastewater treatment plants representing a wide range of phosphorus removal technologies, including enhanced biological phosphorus removal and chemical coagulant addition in secondary and tertiary treatment processes. The phosphorus in the effluent samples was operationally characterized as particulate or dissolved, and reactive or nonreactive P using filtration and chemical characterization. A standard bioassay was used to determine the BAP of both total and soluble fractions. The operational fractions were then statistically compared to the BAP concentrations. The nutrient removal technologies tested included alum and ferric based chemical P removal, enhanced biological P removal (EBPR), single and two-stage tertiary treatment, and membrane separation processes.

The results of this study suggest that the effluent total reactive phosphorus (TRP) concentration has, of the operational characterizations we assessed, the strongest statistical association with the total effluent BAP concentration ($r^2 = 0.81$) with an average total BAP to TRP ratio of 0.61 ± 0.24. The results of this work should encourage water quality modelers and total maximum daily load (TMDL) permit writers to consider the importance of BAP when assessing the likely ecological impacts of municipal nutrient removal facility effluent discharges. These results also indicate that the bioavailability and P species composition varies with the nutrient removal process and that in most cases a large portion (>50%) of the effluent P was recalcitrant to algal growth. Comparisons between different technologies indicate higher chemical doses, which also achieved lower effluent P concentrations, decreased the fraction of the phosphorus that was bioavailable (BAP%). We also characterized the bioavailability of a variety of well-defined P containing compounds. These results clearly showed the operationally defined P classification scheme from classic chemical methods is problematic. Algal phosphorus uptake experiments also suggest that P species with high bioavailability, including some organic P species, are unlikely to persist in natural surface waters because their uptake kinetics are very rapid. Finally these results further suggest recalcitrant P compounds, such as humic-metal-P complexes, phytic acid and/or apatite may be the dominant components of the recalcitrant dissolved P pool in effluents identified in this and other studies.

Benefits:

- Provides a more scientific method for setting wastewater treatment plant (WWTP) discharge permit limitations for effluent P based on actual algae bioavailability.
- Provides a simple, quick method to estimate bioavailable phosphorus in treated effluents.

- Provides a basis to avoid unnecessarily high chemical use and reduce operation costs, sludge production and greenhouse gas footprint for wastewater treatment.
- Shows the classic SRP chemical characterization is a poor predictor of the bioavailability of P containing compounds.
- Proposes a rational classification scheme to more clearly describe P containing compounds based on their bioavailability.

Keywords: Bioavailable phosphorus, advanced wastewater treatment, phosphorus removal, recalcitrant P.

WERF

Water Environment Research Foundation
Collaboration. Innovation. Results.

Nutrients

FINAL REPORT

Mineralization Kinetics of Soluble Phosphorus and Soluble Organic Nitrogen in Advanced Nutrient Removal Effluents

Co-published by

IWA PUBLISHING

NUTR1R06p

MINERALIZATION KINETICS OF SOLUBLE PHOSPHORUS AND SOLUBLE ORGANIC NITROGEN IN ADVANCED NUTRIENT REMOVAL EFFLUENTS

by:

Bo Li
Lu Fan
Michael T. Brett
University of Washington

2015

WERF

The Water Environment Research Foundation, a not-for-profit organization, funds and manages water quality research for its subscribers through a diverse public-private partnership between municipal utilities, corporations, academia, industry, and the federal government. WERF subscribers include municipal and regional water and water resource recovery facilities, industrial corporations, environmental engineering firms, and others that share a commitment to cost-effective water quality solutions. WERF is dedicated to advancing science and technology addressing water quality issues as they impact water resources, the atmosphere, the lands, and quality of life.

For more information, contact:
Water Environment Research Foundation
635 Slaters Lane, Suite G-110
Alexandria, VA 22314-1177
Tel: (571) 384-2100
Fax: (703) 299-0742
www.werf.org
werf@werf.org

This report was co-published by the following organization.

IWA Publishing
Alliance House, 12 Caxton Street
London SW1H 0QS, United Kingdom
Tel: +44 (0) 20 7654 5500
Fax: +44 (0) 20 7654 5555
www.iwapublishing.com
publications@iwap.co.uk

Library of Congress Catalog Card Number: 2014945544
Printed in the United States of America
IWAP ISBN: 978-1-78040-730-2

This report was prepared by the organization(s) named below as an account of work sponsored by the Water Environment Research Foundation (WERF). Neither WERF, members of WERF, the organization(s) named below, nor any person acting on their behalf: (a) makes any warranty, express or implied, with respect to the use of any information, apparatus, method, or process disclosed in this report or that such use may not infringe on privately owned rights; or (b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

University of Washington.

The research on which this report is based was developed, in part, by the United States Environmental Protection Agency (EPA) through Cooperative Agreement No. EM-83406901-0 with the Water Environment Research Foundation (WERF). However, the views expressed in this document are not necessarily those of the EPA and EPA does not endorse any products or commercial services mentioned in this publication. This report is a publication of WERF, not EPA. Funds awarded under the Cooperative Agreement cited above were not used for editorial services, reproduction, printing, or distribution.

This document was reviewed by a panel of independent experts selected by WERF. Mention of trade names or commercial products or services does not constitute endorsement or recommendations for use. Similarly, omission of products or trade names indicates nothing concerning WERF's or EPA's positions regarding product effectiveness or applicability.

About WERF

The Water Environment Research Foundation, formed in 1989, is America's leading independent scientific research organization dedicated to wastewater and stormwater issues. Throughout the last 25 years, we have developed a portfolio of more than $130 million in water quality research.

WERF is a nonprofit organization that operates with funding from subscribers and the federal government. Our subscribers include wastewater treatment facilities, stormwater utilities, and regulatory agencies. Equipment companies, engineers, and environmental consultants also lend their support and expertise as subscribers. WERF takes a progressive approach to research, stressing collaboration among teams of subscribers, environmental professionals, scientists, and staff. All research is peer reviewed by leading experts.

For the most current updates on WERF research, sign up to receive Laterals, our bi-weekly electronic newsletter.

Learn more about the benefits of becoming a WERF subscriber by visiting www.werf.org.

ACKNOWLEDGMENTS

The project team would like to thank JB Neethling and H. David Stensel for their guidance throughout the project. Thanks also go to the staff at Spokane County Regional Water Reclamation Facility, City of Post Falls Water Reclamation Facility, Hayden Wastewater Research Facility, Coeur d'Alene Advanced Wastewater Treatment Plant, and Inland Empire Paper Company for their kind support with sampling and sample transport. Funding for the project was provided by WERF, and in Washington by Spokane County, City of Spokane, Liberty Lake Sewer and Water District, Kaiser Aluminum, and Inland Empire Paper Company, and in Idaho by City of Coeur d'Alene, City of Post Falls, and Hayden Area Regional Sewer Board.

Research Team

Principal Investigator:
Michael T. Brett, Ph.D.
University of Washington

Project Team:
Bo Li, Ph.D.
Lu Fan
University of Washington

Technical Reviewers

April Gu, Ph.D.
Northeastern University

Krishna Pagilla, Ph.D., P.E., BCEE
Illinois Institute of Technology

Phil Zahreddine, M.S. EnvEng.
U.S. Environmental Protection Agency

WERF Nutrient Removal Challenge Issue Area Team

Rajendra (Raj) P. Bhattarai, P.E., BCEE
Austin Water Utility, City of Austin, TX

Joseph A. Husband, P.E., BCEE
ARCADIS U.S., Inc.

David Jenkins, Ph.D.
University of California, Berkeley

Gary R. Johnson, P.E., BCEE
Independent Consultant

Terry L. Johnson, Ph.D., P.E., BCEE
Black & Veatch Corporation

Ted McKim, P.E., BCEE
Reedy Creek Energy Services

Sudhir Murthy, Ph.D., P.E.
DC Water

Tung Nguyen
Sydney Water Corporation

Clifford W. Randall, Ph.D., Dist.M.ASCE
Virginia Polytechnic Institute and State University

Matt Ries, P.E.
Water Environment Federation

Elizabeth Southerland, Ph.D.
Phil Zahreddine, MSEnvEng
U.S. Environmental Protection Agency

G. David Waltrip, P.E.
Hampton Roads Sanitation District

Kenneth N. Wood, P.E.
DuPont/OnBoard Services, Inc.

Heng Zhang, Ph.D., P.E.
Metropolitan Water Reclamation District of Greater Chicago

Water Environment Research Foundation Staff

Director of Research and Senior Program Director for this Project:
Amit Pramanik, Ph.D., BCEEM

ABSTRACT AND BENEFITS

Abstract:

Given the importance of the watershed protection plans, direct determination of phosphorus (P) mineralization kinetics in advanced wastewater treatment facility effluents is crucial for developing the most protective strategies for minimizing eutrophication in receiving surface waters. In this study, bioassays were used to determine the mineralization rate of dissolved P in effluents from a broad range of advanced nutrient removal technologies (MBR, traditional biological, tertiary membrane, Blue PRO^{TM}, etc.). Mineralization kinetics were described by a Gamma model and three first-order decay models. A traditional one-pool model correlated poorly with the experimental data (i.e., $r^2 = 0.73 \pm 0.09$), whereas two and three-pool models performed much better (i.e., $r^2 > 0.9$). These models provided strong evidence for the existence of recalcitrant P in the effluents from these facilities. The Gamma model showed the mineralization of organic P followed a reactive continuum and further suggested the partitioning of P loads with different bioavailability levels should be accounted for the future modeling practices. Although the Gamma model should be considered a theoretically correct model, the results also suggested simpler two and three-pool models could provide similar fits depending on the effluents.

Benefits:

- Provides wastewater discharger-specific dissolved phosphorus mineralization first-order rate kinetics that can be used in the Long Lake Washington TMDL model.
- Resolves outstanding issues on the bioassay protocol from the Phase I Spokane BAP study (i.e., possible effluent toxicity and nutrient co-limitation).
- Simultaneously determines the bioavailability of dissolved N and P in the effluents of BNR facilities.
- Fully characterizes the phosphorus composition in all samples processed for BAP experiments and the nitrogen composition for samples processed for BAN experiments.

Keywords: Bioavailable phosphorus, bioavailable nitrogen, advanced wastewater treatment, phosphorus removal, nitrogen removal, recalcitrant P, recalcitrant N, case studies.