An alliance of Jacobs and Tetra Tech

MEMO

Prepared for:	South Florida Water Management District
Prepared by:	J-Tech, an Alliance between Jacobs Engineering and Tetra Tech, Inc.
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Subject:	C-43 West Basin Storage Reservoir Water Quality Component Deliverable 9.1.1.3: Final Inline Alum Technical Memorandum

1.0 Background/Introduction

The South Florida Water Management District (SFWMD) selected J-Tech for the implementation and delivery of the C-43 West Basin Storage Reservoir (WBSR) Water Quality Feasibility Study (WQFS), which reviewed existing pertinent studies/literature; evaluated applicable water quality treatment technologies suitable for use; and conducted a cost-benefit, alternatives, and trade-off analysis. The analysis identified cost-effective, available, technically feasible, conventional and innovative biological, chemical, and physical treatment technologies for water quality improvement for eventual pre-treatment, in-reservoir treatment, and/or post-treatment application to the C-43 WBSR.

The most cost-effective options that reduce nutrients, especially nitrogen, and improve the quality of water leaving the C-43 WBSR to the Caloosahatchee River and its downstream estuary, while maintaining the current C-43 WBSR construction design, schedule, and project purpose were selected. The water quality treatment alternatives reviewed, pertinent to the Caloosahatchee River Basin, were predominantly gathered from the Florida Department of Environmental Protection (DEP) Accepted Water Technologies Library (DEP, 2020), as well as from information obtained from the public and technology vendors.

The C-43 WQFS identified aluminum (alum or Al) treatment as the most cost-effective treatment technology for improving water quality for discharges from the C-43 WBSR. Two alum treatment configurations were identified: offline treatment of the reservoir outflow and inline treatment at the inflow to the WBSR. Inline injection of alum during reservoir filling is expected to be useful in suppressing potential nuisance algal growth within the reservoir while optimizing performance of the downstream Water Quality Component (WQC). A key advantage of the inline treatment system is its ability to be designed and constructed concurrently with construction of the C-43 WBSR.

The purpose of this technical memorandum (TM) is to characterize the potential benefits and constraints of inline alum treatment to confirm that the inline system is compatible with existing C-43 WBSR functions and features. This TM presents a literature summary on performance, sludge production, and environmental impacts of stormwater-fed lake and reservoir alum injection systems. The TM also provides a preliminary evaluation on dose determination of the inline alum treatment system, conceptual layout for the inline system at the C-43 WBSR site, reservoir material compatibilities with alum, life cycle costs, operation management, reservoir response, and environmental impacts expected from alum treatment.

2.0 Literature Summary

Since the 1970s, alum treatment has become established as a standard technique for managing lake and water quality (North American Lake Management Society, 2004). Alum has been used to prevent the release of phosphorus from lake sediment with treated lakes showing significant reductions in phosphorus loading for up to 21 years and algae growth control for up to 11 years (Pilgrim and Brezonik, 2005). While the literature focuses on alum removal of phosphorus, the selected case studies include data on total nitrogen (TN), consistent with the current recognition that phosphorus and nitrogen both contribute to regulation of algal bloom development and that a dual nutrient control philosophy is being increasingly adopted (e.g., Paerl et al., 2020; Wurtsbaugh et al. 2019). The literature on the approach and effectiveness of alum application for lake management is extensive (Cooke et al., 2005). This section includes a summary of selected case studies and research intended to provide insight on the efficacy, safety, and future settling/floc formation due to alum injection into stormwater-fed lakes and reservoirs. The papers were selected to summarize long-term case studies in Florida (Bottcher et al., 2009; Harper and Herr, 1999; Hoge et al., 2007; Hoge et al., 2021), Minnesota (Pilgrim and Brezonik, 2005), Michigan (Steinman et al., 2018), and globally (Huser et al., 2016a; Huser et al. 2016b). Additionally, a conference call was held with experienced staff of the St. Johns River Water Management District (SJRWMD), where alum application has been an ongoing wetland restoration and nutrient control practice for the past 20 years.

2.1 Alum Treatment of Stormwater: The First Ten Years (Harper and Herr, 1999)

Harper and Herr (1999) studied the efficacy of alum treatment in stormwater including jar testing and full-scale application to three lakes in Florida (Lake Ella, Lake Dot, and Lake Osceola). Phosphorus reduction, alum quantities applied, floc settling characteristics, and toxicity observations were summarized. The primary mechanism of phosphorus removal is the direct formation of aluminum phosphate. Removal of suspended solids, algae, phosphorus, heavy metals, and bacteria occurs by enmeshment and adsorption on aluminum hydroxide precipitate.

One case study included was Lake Ella in Tallahassee, Florida. The lake was characterized as a shallow hypereutrophic lake with an approximate size of 13.3 acres. Lake Ella received untreated stormwater runoff from approximately 163 acres of highly impervious urban watershed. The alum treatment system is designed to treat approximately 95% of the hydraulic inputs.

A second case study included 5.9-acre Lake Dot in Orlando, Florida. This hypereutrophic lake received stormwater from a contributing watershed area of approximately 305 acres. The alum treatment system is designed to treat approximately 96% of the hydraulic inputs to the lake.

The third case study included Lake Osceola in Winter Park, Florida. This lake is characterized as eutrophic with an approximate area of 55.4 acres. Lake Osceola received urban stormwater from an approximate 153-acre urban watershed. The alum treatment system is designed to treat approximately 9% of the hydraulic inputs to the lake.

Bottcher et al. (1999) also included data on 29-acre Lake Lucerne in Orlando, Florida, which received untreated stormwater from a 267-acre watershed. The lake was retrofitted with an alum stormwater treatment system in June 1993.

2.1.1 Performance

Water quality testing was performed at lakes Ella, Dot, and Osceola. Each received a flow-proportioned dose of alum between 5–10 milligrams per liter (mg/L) aluminum using a variable speed chemical metering pump. Water quality monitoring showed improvements in dissolved oxygen (DO), TN, total phosphorus (TP), biological oxygen demand (BOD), chlorophyll *a*, Secchi disk depth, and Florida Trophic State Index (TSI) value. Table 1 provides a comparison of the pre- and post-alum treatment water quality for each of the lakes. Concentrations of TN, TP, and chlorophyll a, a measure of algal biomass, decreased significantly. A drop in pH was noted in two lakes with the introduction of alum treatment. The consistency of pH in Lake Dot is attributed to injection of alum and sodium aluminate to control pH levels within the lake.

Table 1. Lake Water Quality Response to Alum Injection

Parameter	Units	Lake Ella (Tallahassee, FL)		Lake Dot (Orlando, FL)		Lake Osceola (Winter Park, FL)	
		Before	*After*	*Before*	*After*	*Before*	*After*
# of Samples	-	15	11	5	15	12	46
pH	s.u.	7.41	6.43	7.27	7.17	8.22	7.63
DO (1 minute)	mg/L	3.5	7.4	6.6	8.8	8.8	8.8
TN	µg/L	1876	417	1545	696	892	856
TP	µg/L	232	26	351	24	37	26
BOD	mg/L	41	3.0	16.8	2.7	4.4	3.4
Chlorophyll *a*	mg/m^3	180	5.1	55.8	6.3	24.8	21.7
Secchi Disk Depth	m	0.5	> 2.2	<0.8	2.5	1.1	1.2
Dissolved Aluminum	µg/L	-	44	-	65	18	51
Florida TSI Value[a]	-	98	47	86	42	61	56
Lake Area	acres	13.3		5.9		55.4	
Watershed Area	acres	57		305		153	
Percent of Annual Hydraulic Inputs Treated	%	95		96		9	

Source: Harper and Herr, 1999.
[a] TSI Value of 0-59 = Oligotrophic through Mid-Eutrophic; 60-69 = Mid-Eutrophic through Eutrophic; 70-100 = Hypereutrophic

For Lake Lucerne, TP concentrations decreased from approximately 100 microgram grams per liter (µg/L) pre-injection to equilibrium concentrations of approximately 20–40 µg/L (Harper and Herr, 1999). Water column TN data were not available in the summary, but alum application decreased sediment TN by 41% from 9.978 mg/L to 5.846 mg/L and TP by 64% from 531 µg/L to 189 µg/L.

2.1.2 Sludge Production

Harper and Herr (1999) noted that sludge production is based on the injection concentration of alum to treat the stormwater runoff and the amount of time elapsed since the alum was injected. Within the first 6–8 days of treatment, the alum floc rapidly consolidated to an approximate volume of 20% of the initial floc volume. The floc continued to consolidate over a settling period with the maximum consolidation occurring after approximately 30 days.

Based on hundreds of laboratory tests, the sludge production was found to produce a volume of approximately 0.16–0.28% of the treated runoff flow. At a concentration of 5 mg/L as aluminum, the sludge production was approximately 0.16% of the treated flow with 1.6 cubic meters (m^3) sludge produced for every 1,000 m^3 treated, and 214 cubic feet (ft^3) sludge produced per 1 million gallons (MG) treated. On the high end of aluminum treatment with 10 mg/L as aluminum, the volume increased slightly with 0.28% of the treated flow as sludge volume with 2.8 m^3 per 1,000 m^3 treated stormwater flow and 374 ft^2 per 1 MG treated.

The jar tests were based on a 30-day consolidation period. Harper and Herr (1999) studied the floc accumulation rates in lakes Ella, Lucerne, and Osceola with each lake receiving alum treatment for at least five years. The observations of floc accumulation compared well to predicted rates. For Lake Ella, floc was predicted to accumulate at 1 centimeter per year (cm/yr). However, the observed accumulation rate from sediment core samples showed an accumulation rate of approximately 0.33 cm/yr. Lake Lucerne and Lake Osceola were predicted to accumulate 3.33 cm/yr and 0.5 cm/yr, respectively. Both lakes showed no measurable accumulation after more than five years of treatment. This response was attributed to additional floc consolidation and incorporation of the alum floc into the existing lake sediments (Harper and Herr, 1999).

2.1.3 Toxicity Assessment

Harper and Herr (1999) determined that floc formation is complete, with all Al^{+3} ions virtually removed from the water column, within 45–60 seconds of the initial dosing of alum. This information, along with careful selection of the injection point prevented toxicity within the lakes.

Studies of the lake sediment show reductions of loosely-bound and iron-bound associations, as well as an increase in aluminum phosphorus associations within the sediment suggesting a substantially more stable phosphorus in comparison to pre-treatment sediments. This more stable phosphorus ensures the phosphorus and the aluminum will not be leaked back into the water column once consolidated in the sediment. The stability of the compounds as well as the speed of floc formation immediately after introduction of alum into the stormwater prevented impact to the benthic community within the lakes.

A benthic survey was conducted by Harper and Herr (1999) in Lake Ella from 1985–1990 with surveys conducted immediately prior to lake drawdown, following dredging after the lake had refilled, and after 2.5 years of alum system operation. Benthic fauna recolonized the lake in response to improved water quality and reduced toxicity within the sediments from the stable lake sediment post alum treatment (Table 2).

Table 2. Benthic Survey Results within Lake Ella 1985 – 1990

Date	Lake Conditions	Average # of Organisms/m^2 (Limnodrilus sp.)
November 1985	Immediately prior to lake drawdown	0
January 1987	Following dredging, after lake had refilled for 3-4 months	0
May 1990	After 2.5 years of alum system operation	41

Source: Harper and Herr, 1999

2.2 Treatment of Lake Inflows with Alum for Phosphorus Removal (Pilgrim and Brezonik, 2005)

Pilgrim and Brezonik (2005) studied the effect of phosphorus removal on two separate lakes, which receive water using different techniques to examine the concentration of aluminum needed for treatment and the treatment potential. The two treatment facilities are located on Tanner Lake in Oakdale, Minnesota and Fish Lake in Eagan, Minnesota. Tanner Lake is a 70-acre lake with a highly residential watershed of more than 1,600 acres. Fish Lake is a 30-acre lake with a highly residential watershed of over 3,000 acres. The treatment facility at Tanner Lake includes two alum holding tanks, chemical feed pumps, a mixing chamber, and a hydrofoil impeller for mixing. Alum is dosed based on the changes in inflow water alkalinity and temperatures based on inflow rate and season. The treatment facility for Fish Lake uses pumps in a wet well and chemical feed pumps activated by water flowing into the wet well reaching a set stage. Water enters the wet well from the Hurley Wetland.

2.2.1 Performance

Performance data presented by Pilgrim and Brezonik (2005) indicated that alum injection reduced TP in the water column, stabilized phosphorus in the sediment, and controlled algal growth in lakes. Tanner Lake showed 52–84% TP removal. Table 3 presents the influent, effluent, and percent removal from 1998–2002.

Table 3. Tanners Lake Water Quality Improvements with Alum Additions

Parameter/Year	1998 (n=23)	1999 (n=21)	2000 (n=22)	2001 (n=16)	2002 (n=13)
Inflow TP (µg/L)	181	251	253	497	212
Outflow TP (µg/L)	66	97	87	82	100
% Removal	64	61	66	84	52

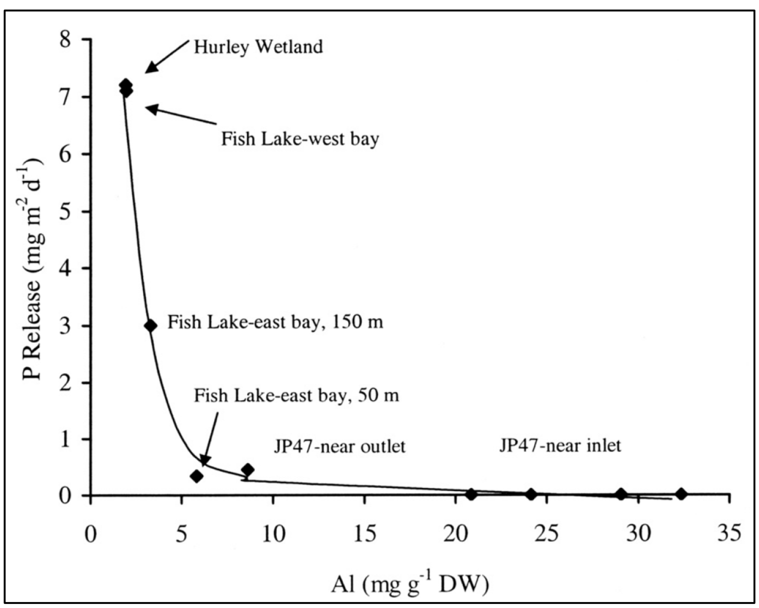
Source: Pilgrim and Brezonik, 2005.

Phosphorus reductions in Fish Lake showed a more nuanced response. The initial alum dose was set to be 1 mg/L, based upon an initial pilot study, but because of concern for potential effects of alum on benthic invertebrates and other aquatic organisms, only low doses were considered. The 1 mg/L dose was used for the first year, yielding a 41% reduction to an in-lake concentration of 88 µg/L. The following year, the dose was increased to 8 mg/L for a 64% reduction to 54 µg/L. The results from the Fish Lake example showed that the increase from 1 mg/L of alum to 8 mg/L improved TP removal and substantially reduced phosphorus loading (Pilgrim and Brezonik, 2005).

2.2.2 Sediment Phosphorus Stability

Data collected from Tanner Lake and Fish Lake show an inverse correlation of the aluminum concentration in the sediment and the amount of phosphorus released into the water column. Pilgrim and Brezonik (2005) found that aluminum in the lake's sediments inhibited phosphorus release from sediment cores. Source: Pilgrim and Brezonik (2005)

Figure 1 shows the inverse correlation found in Fish Lake with distance from the alum injection point at the inlet.



Source: Pilgrim and Brezonik (2005)

Figure 1. Graph Showing Inverse Correlation of Aluminum Concentration and Phosphorus Release

Study of floc settling rates showed nearly complete settling within six hours of introduction. The production of floc and its settling rate is not affected by pH as settling rates were found to be consistent with pH ranging from 6.3–9.

2.2.3 Toxicity Assessment

Toxicity was not specifically evaluated in this paper. However, it does provide an example where alum application rates may be constrained due to public concerns over impacts to benthic macroinvertebrates and still achieve significant TP reduction. It is noteworthy that the alum dose of 1 mg/L is similar to the dose determined in Section 3.0 in this memorandum, and that the performance demonstrated at Fish Lake showed a similar range of pre- and post-alum concentrations expected for the C-43 WBSR.

2.3 Longevity and Effectiveness of Alum Addition to Reduce Sediment Phosphorus Release and Restore Lake Water Quality (Huser et al., 2016a)

Huser et al. (2016a) identified 114 lakes that were treated with aluminum salts to reduce the internal phosphorus loading and studied their pre- and post-treatment water quality while assessing factors that affect the longevity of phosphorus in the sediment. Analysis of the water quality pre- and post-treatment showed a clear decline in TP and chlorophyll *a* concentration with an increase in Secchi depth indicating improvements in water quality. Factors affecting treatment potential included alum dose, watershed to lake area ratio, and lake morphology.

The alum dosing was shown to improve the stability of the phosphorus in the lake sediments. Higher dosing of alum, with dosing of 15 grams per square meter (g/m^2), showed improvements in stability of TP with water quality improvement (Huser et al., 2016a). This is founded on sediment-based methods of dosing rather than the water column concentration suggested for the treatment of influent phosphorus conditions.

The watershed to lake area ratio determines the mean residence time within the lake. The relationship of TP stability in the sediment to watershed to lake area ratio shows an inverse relationship. As the watershed size decreases in comparison to the lake, the residence time of the water increases within the lake and provides longer residence times of phosphorus in the sediment (Huser et al., 2016a).

The lake morphology was also found to affect the stability of the phosphorus in the lake. Deeper lakes with stratification tend to have higher stability of phosphorus in the sediment (Huser et al., 2016a). A lack of mixing creates an alkaline buffer of the water directly above the sediment that prohibits the release of phosphorus from the sediment.

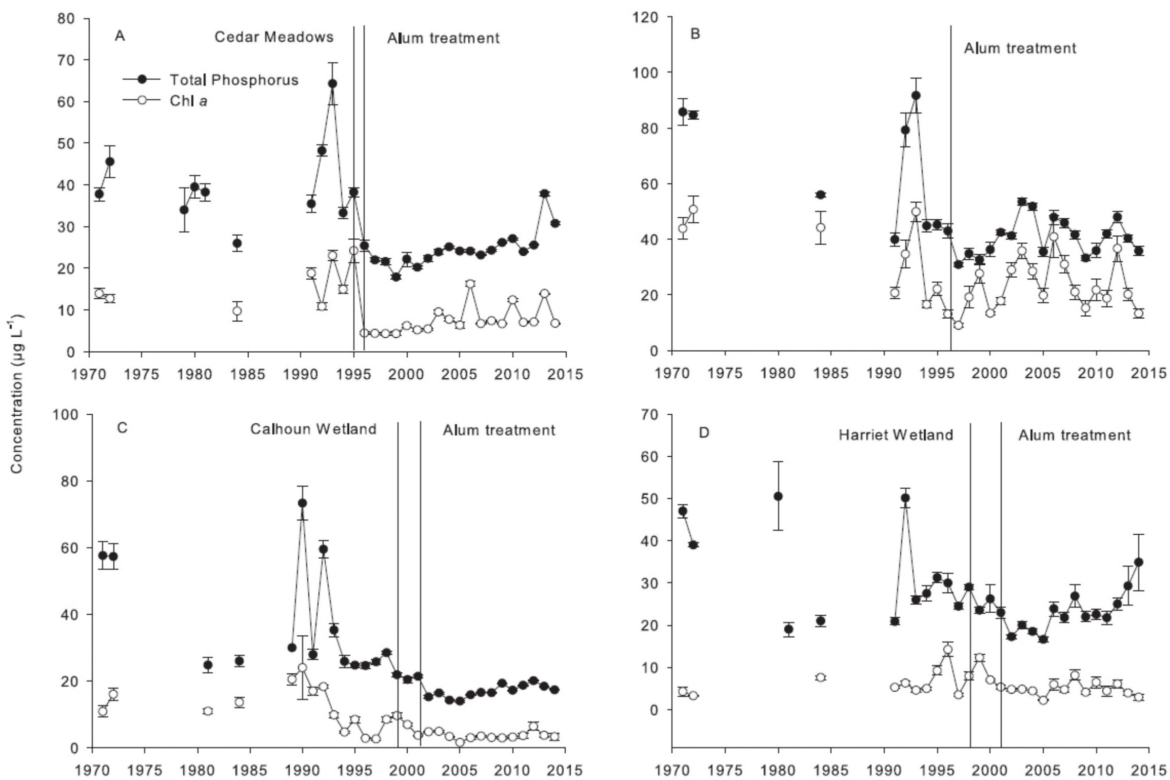
2.4 In-lake Measures for Phosphorus Control: The Most Feasible and Cost-effective Solution for Long-term Management of Water Quality in Urban Lakes (Huser et al., 2016b)

Huser et al. (2016b) studied the feasibility, effectiveness, and cost of long-term management of TP reduction in the Minneapolis Chain of Lakes, including Lake Harriet, Lake Calhoun, Cedar Lake, and Lake of the Isles. Each of the lakes received alum treatment, as well as varying external pre-treatment, with a goal of improving water clarity. Phosphorus was determined to be the main factor limiting productivity in each of the lakes with each of the lakes receiving a single alum treatment.

All lakes showed immediate improvements following alum treatment. However, this did not persist, given the lack of external phosphorus load reductions and the single alum dose (Huser et al., 2016b). All lakes showed a return to pre-treatment water quality levels of phosphorus concentrations and Secchi disk depth within five years. Phosphorus levels are shown in Figure 2 (Huser et al., 2016b).

Huser et al. (2016b) suggested that the main reason the lake met management goals within the first two years is likely due to limited reduction of external phosphorus loads and exhaustion of the phosphorus binding capacity. The alum dosing was likely under-dosed with little understanding of dose needs at the time of the treatments and the lack of external nutrient reduction. Huser et al. (2016b) suggested multiple treatments reoccurring every few years based on water quality conditions to extend the improved water quality conditions in each lake. Additionally, Huser et al. (2016b) suggested studying the different forms of phosphorus present in lake waters to ensure the phosphorus with the highest bioavailability is targeted.

Without including a study of the floc formation/accumulation in the lake and toxicity, Huser et al. provided a brief discussion of cost effectiveness where it is expressed that in-lake alum treatment was approximately 50 times more effective, on average, than pre-lake in-catchment treatment systems (2016b). For example, the restoration project for the chain of lakes totaled approximately \$12 million whereas the in-lake alum treatments for all four lakes combined totaled approximately \$560,000.



. Historical epilimnetic TP and Chl *a* data (and standard errors) for Cedar (A), Isles (B), Calhound (C), and Harriet (D) from the early 1970s through 2014. Solid lines indicate when major external measures and alum treatment were applied.

Figure 2. TP and Chlorophyll *a* in Minneapolis Chain of Lakes Pre- and Post-treatments (Huser et al., 2016b)

2.5 Alum Efficacy 11 Years Following Treatment: Phosphorus and Macroinvertebrates (Steinman et al., 2018)

Steinman et al. (2018) studied the internal phosphorus loading and benthic macroinvertebrate communities at four sites in Spring Lake, Michigan comparing pre-treatment and three studies of post-treatment conditions. The four sites within the lake included two shallow zones and two deep zones within the lake with testing occurring in 2004 (pre-treatment), 2006 (eight months post-treatment), 2010 (five years post-treatment), and finally 2016 (11 years post-treatment).

Spring Lake is considered an “unimpounded, drowned river mouth system” located on the western side of Michigan feeding into the Grand River. Spring Lake is approximately 1,300 acres in size with a mean depth of approximately 20 feet and a maximum of 43 feet. The hydraulic residence time within the lake ranges from approximately 150 days to 330 days, depending on wet or dry periods.

2.5.1 Water Quality Assessment

Surface water TP concentrations in Spring Lake remained at low concentrations similar to those before treatment. However, elevated concentrations were noted in 2016 at sites 1 and 2. TP concentrations at the surface remained similar or lower than in 2006 and 2010, while near-bottom concentrations increased suggesting internal loading. Figure 3 shows the TP concentrations for 2004, 2006, 2010, and 2016. The lag of increased near-bottom concentrations until 2016 suggests the longevity of the single alum treatment lasting for just over 10 years before concentrations began to increase.

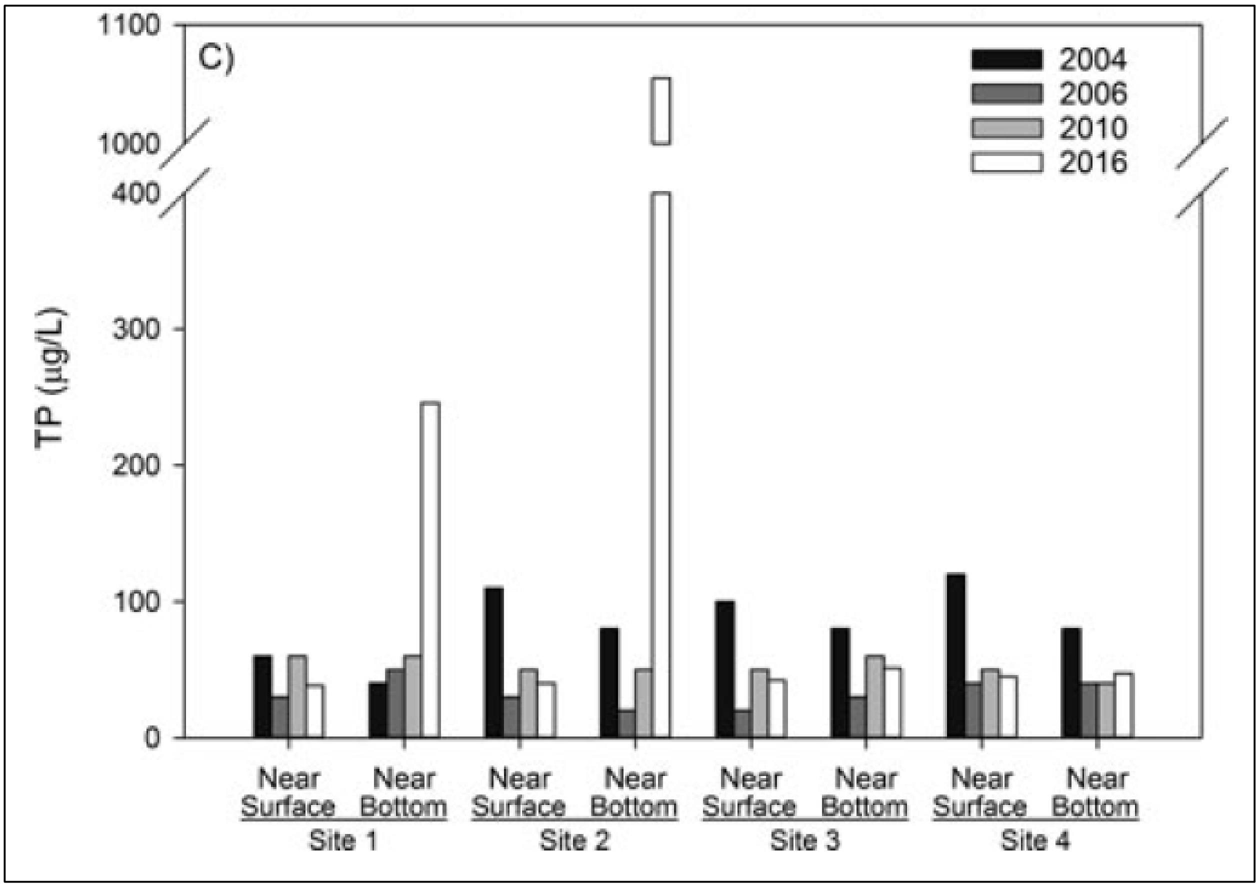


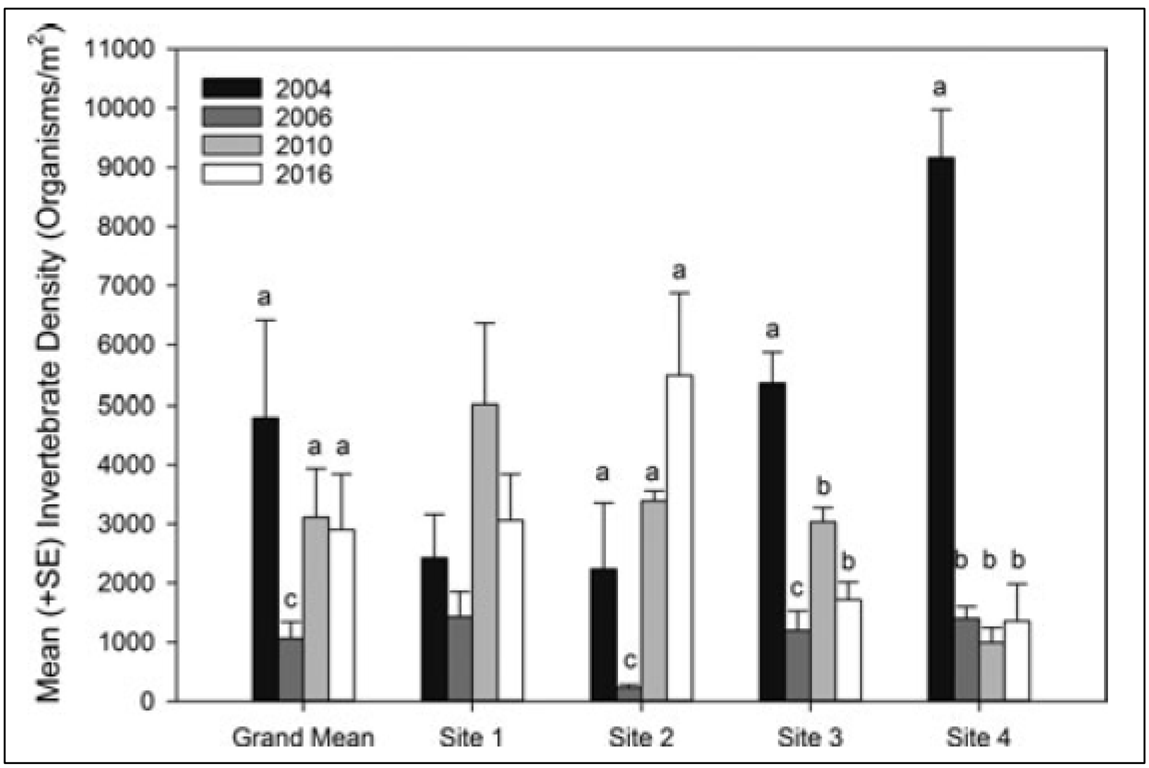
Figure 3. TP Concentrations for Spring Lake (Steinman et al., 2018)

The high concentrations of TP are correlated with low DO concentrations in the water column near the bottom of the lake at sites 1 and 2. The correlation suggests the redox-catalyzed release of phosphorus that would have been bound to iron oxides and oxyhydroxides. DO concentrations in the 2010 sampling were all greater than or equal to 3.9 mg/L at the near-bottom sites. In 2006, DO concentrations were below 0.5 mg/L yet the TP concentrations were less than 50 µg/L. The low TP concentrations in 2006 suggest the binding of phosphorus with alum was effective in 2006, with alum binding sites no longer available by 2016.

Results of the study imply the alum treatment efficacy being lost by year 11. Steinman et al. (2018) presents two possible reasons for this. The first reason is the highly variable bathymetry within the lake, which allowed the alum floc to migrate to the deeper waters within the lake decreasing the sediment cover percentage. The second reason is the saturation of the binding sites. With only a single dose, the alum has a finite number of binding sites which have been saturated with phosphorus and other possible nutrients prohibiting the uptake of new phosphorus being introduced from external loads. While alum treatments are effective at reducing the external load, single dose applications do little to reduce the external loading which competes with the internal loading phosphorus reducing the efficacy and longevity of the treatment.

2.5.2 Toxicity Assessment

Steinman et al. (2018) examined the macroinvertebrate colony population density before and after the alum treatment. A loss in population density may indicate the toxicity of the alum treatment. Results showed that all benthic invertebrate density declined within one year of alum treatment. The authors attributed this to the smothering of the alum floc as it rested on the lake floor. By 2016, the overall density of macroinvertebrates had recovered with significantly greater numbers than measured in 2006. Previous studies have shown that after an initial decline, recovery to pretreatment levels occurs within two years (Steinman et al., 2018). Two of the four sites at Spring Lake showed a recovery to pre-treatment levels while two sites showed results that had not fully recovered. Figure 4 shows the mean invertebrate density for pre- and post-treatment sites.



Note: Change in letter labels show significantly different results

Figure 4. Invertebrate Density Results for Spring Lake (Steinman et al., 2018)

2.6 Phosphorus Control Treatments in the Upper Ocklawaha River Basin (Hoge et al., 2021)

SJRWMD has applied multiple treatments of liquid aluminum sulfate in the Emeralda Marsh Conservation Area and Lake Harris Conservation Area (LHCA). The purpose was to reduce water column phosphorus concentrations in these areas. Alum was chosen because of its proven ability to trap and bind TP in a layer of flocculent material, which settles into the sediment.

The effectiveness was assessed from monthly samples, which were taken two months before and two months after the alum treatment. The TP treatment ranged from a 44% to 97% reduction. This was affected by the dosing concentration as well as the sediment biogeochemistry. The amount of buffer needed to maintain pH and alkalinity in the treatment areas was consistently less than the amount predicted by jar tests.

2.6.1 Performance Results for TP

The following performance results show the concentrations from testing two months pre-alum treatment and two months post-alum treatment. Table 4 presents the TP results with an overall average concentration reduction of 67% TP due to the alum treatment.

Table 4. SJRWMD Alum Injection TP Reduction Results

General Area	Description	TP Pre-alum (mg/L)	TP Post-alum (mg/L)	% Change	Dose Applied (mg/L Al)	Treatment Target
Lake Griffin Flow Way (LGFW)	Q Cell	0.205	0.087	-58	3.2	Sediment
	Z Cell	0.290	0.118	-59	10.3	Sediment
	T Cell	0.276	0.118	-57	6.6	Sediment
	Area 3, U pond	0.760	0.099	-87	-	-
Lowrie Brown (LB) (Area 4)	Single Treatment	0.228	0.063	-72	9.3	Water Column
Long Farm (LF)	1st treatment	4.580	0.365	-92	9.5	Water Column and Sediment
	2nd Treatment	1.244	0.504	-60	9.7	Water Column and Sediment
Eustis Muck Farm (EMF)	2nd Treatment	1.957	0.051	-97	20.7	Water Column
S.N. Knight North	1st Treatment	0.110	0.052	-53	12.6	Water Column
LHCA	1st Treatment	0.475	0.264	-44	26.9	Water Column
	2nd Treatment	0.284	0.108	-62	28.6	Water Column

Source: (Hoge et al. 2021)

Additional testing was conducted to research the long-term post-alum treatment effects on the TP concentrations. Table 5 presents the long-term phosphorus concentrations post-treatment. Post-alum treatment data include all water quality samples that were taken starting after the last day of treatment.

Table 5. SJRWMD Alum Injection TP Long-Term Reduction Results

Site	TP Pre-alum (mg/L)	TP Post-alum (mg/L)	% Change
LGFW-Q	0.215	0.257	20
LGFW-T	0.429	0.287	-33
LGFW-Z	0.447	0.199	-55
LB	0.323	0.082	-75

Site	TP Pre-alum (mg/L)	TP Post-alum (mg/L)	% Change
EMF	2.190	0.187	-91
LF-1	3.402	1.072	-68
LF-2	1.072	0.466	-56
LHCA-1	0.532	0.260	-51
LHCA-2	0.225	0.135	-42

Source: (Hoge et al. 2021)

2.6.2 Performance Results for TKN, TSS, and pH

Water quality sampling included multiple parameters including total Kjeldahl nitrogen (TKN), total suspended solids (TSS), and pH. As the major contributor of organic nitrogen, sampling focused on TKN concentrations pre- and post-alum treatments. Table 6 presents the TKN water quality testing results. The average treatment reduction for TKN in the systems was approximately 23%.

Table 6. SJRWMD Alum Injection TKN Reduction Results

General Area	Description	TKN Pre-alum (mg/L)	TKN Post-alum (mg/L)	% Change
Lake Griffin Flow Way	Q Cell	1.756	1.615	-8
	Z Cell	2.331	2.251	-3
	T Cell	2.121	2.023	-5
	Area 3, U pond	3.23	2.471	-23
Lowrie Brown (Area 4)	Single Treatment	3.096	2.176	-30
Long Farm	1st treatment	3.547	2.268	-36
	2nd Treatment	2.075	1.313	-37
Eustis Muck Farm	2nd Treatment	2.332	1.475	-37
S.N. Knight North	1st Treatment	1.324	1.018	-23
LHCA	1st Treatment	2.627	2.266	-14
	2nd Treatment	1.643	1.023	-38

Source: Hoge et al., 2021

Table 7 presents the results of pre- and post-alum treatment TSS concentrations. All concentrations were reduced with exception of the second treatment in the Long Farm pond where concentrations were low pre-alum treatment. Omitting the increase in Long Farm, the average TSS concentration reduction was approximately 33%.

Table 7. SJRWMD Alum Injection TSS Reduction Results

General Area	Description	TSS Pre-alum (mg/L)	TSS Post-alum (mg/L)	% Change
Lake Griffin Flow Way	LGFW, Q Cell	7.8	5.5	-29
	LGFW, Z Cell	12.0	11.5	-4
	LGFW, T Cell	5.0	3.5	-30
	Area 3, U pond	10.6	4.2	-60
Lowrie Brown (Area 4)	Single Treatment	52.8	7.6	-86
Long Farm	1st treatment	6.8	5.8	-15
	2nd Treatment	2.0	4.3	113
Eustis Muck Farm	2nd Treatment	12.5	5.3	-58
S.N. Knight North	1st Treatment	14.8	12.5	-15
LHCA	1st Treatment	65.9	44.8	-32
	2nd Treatment	38.8	23.3	-40

Source: Hoge et al., 2021

pH is unique as the goal is to have little effect on the pH with alum treatment. Changes in the water chemistry due to alum treatment can have an adverse effect on resuspension and release of other nutrients from the sediment. Ideal alum treatment have no change in pH values. Table 8 presents the results of pH pre- and post-alum treatment. The average change in pH over the system was approximately 4%. With the exception of Long Farm and Eustis Muck Farm, alkalinities ranged from 110 to 152 mg/L as calcium carbonate, which is greater than the guidance value of 75 mg/L suggested by Cooke et al. (2005) as concentrations capable of providing a natural buffering mechanism.

Table 8. SJRWMD Alum Injection pH Reduction Results

General Area	Description	pH Pre-alum (s.u.)	pH Post-alum (s.u.)	% Change
Lake Griffin Flow Way	LGFW, Q Cell	7.14	7.19	1
	LGFW, Z Cell	7.07	7.09	0
	LGFW, T Cell	6.87	7.12	4
	Area 3, U pond	6.73	6.57	-2
Lowrie Brown (Area 4)	Single Treatment	7.74	6.74	-13
Long Farm	1st treatment	6.35	6.73	6
	2nd Treatment	6.63	6.89	4
Eustis Muck Farm	2nd Treatment	7.75	7.31	-6
S.N. Knight North	1st Treatment	7.49	7.48	0
LHCA	1st Treatment	7.76	7.95	2
	2nd Treatment	8.08	7.60	-6

Source: (Hoge et al. 2021)

2.6.3 SJRWMD Recommendations for Future Alum Applications

Based on the SJRWMD experience, Hoge et al. (2021) provided recommendations for future alum applications. Recommendations focused on the understanding of the proper dosing for each individual system to ensure the highest treatment is being achieved.

- Jar tests are recommended before alum treatment to estimate the efficacy of the alum dosing estimation due to the complexity of lake water chemistry and its reaction with alum.
- Surface alum applications are not recommended in areas of dense vegetation.
- Dosing rates are vital to the efficacy of the application. Under-dosing can lead to the formation of microfloc, which leads to increased particulate phosphorus and residual aluminum in the water column.
- pH and alkalinity should be monitored to ensure alum dosing calculations are valid and at non-toxic levels.
- Measuring the particulate phosphorus and aluminum is the best way to determine if applications are underdosed creating microfloc.
- Flexible budgeting according to the volume of water treated is recommended.
- Improvement of water clarity due to treatment can increase algal blooms in shallow water bodies (less than two meters), so treatment should be performed when potential for resuspension is reduced.

The conference call held on March 1, 2021 confirmed these key findings. Other findings of interest include:

- SJRWMD considers alum treatment a useful restoration practice and would implement similar projects in the future as land and funding becomes available. Their applications are typically for shallow (4–6 feet) marsh basins.
- Only two incidents of toxicity occurred through the decades of implementation. One was a highly localized small-scale spill and another was an inadvertent excess application at a single site. No toxic response from routine application was ever observed.

- Microfloc can occur if doses are undersized, which reduces settling rates.
- Floc has been observed to persist as a bottom layer with low solids content.

2.7 Summary

All the projects summarized in this literature review demonstrated positive results of phosphorus reduction with alum treatment in lakes. However, these were single dose alum treatments. The single dose treatments were applied to reduce the internal cycling of phosphorus from the lake sediment. Studying the lake's water and sediment nutrient conditions helps to ensure the proper dose is applied and informs the longevity and efficacy of the dose. These treatments were shown to have lifespans ranging from 4 to 20 years. Long-term improvement may require additional alum doses.

Sludge production was shown to be minimal in lake alum treatment. Expected accumulation ranged from 1.6 m^3 to 2.8 m^3 sludge produced per 1,000 m^3. Lake sediment cores taken during treatment showed the levels were below the expected rates with two of the three lakes showing no accumulation of floc in the lake.

While the toxicity of alum treatment is important to consider, the results of the studies presented here show low toxicity probabilities with proper alum dosing. Harper and Herr (1999) and Steinman et al. (2018) showed that the macroinvertebrate species were able to not only recover but thrive within two years of an initial alum treatment. Additionally, it was shown by Harper and Herr (1999) that floc formation was complete within 45–60 seconds of application. By incorporating this with in-line alum treatment, floc formation can be achieved before introduction into the lake water column reducing the Al^{3+} toxicity.

3.0 Dose Determination

3.1 Basics of Alum Treatment

Alum ($Al_2(SO_4)_3{\cdot}14H_20$) is frequently used in both water and wastewater treatment systems for two primary reasons. First, it can act as a coagulant and settling aid. In this function, the alum can convert colloidal solids (i.e. non-settleable material) to a settleable particle and thus achieve removal of those particles and the associated nutrients (nitrogen and phosphorus). This mechanism is the primary reason alum addition can improve nitrogen removal. The second primary function of alum addition is the removal of soluble phosphorus. When added to water, alum quickly hydrolyzes to aluminum hydroxides ($Al(OH)_3$) or hydrous aluminum hydroxides (HAOs). The HAOs adsorb soluble orthophosphate ($PO4^{-3}$ or OP) and convert that soluble phosphorus to a particulate form that can settle out into a sludge blanket. The soluble reactive phosphorus (SRP) test is almost entirely made up of OP, and for the following discussion, the assumption is made that OP = SRP for the purposes of modeling.

The phosphorus adsorption can be categorized in two stages. First is the rapid adsorption phase, where the HAO flocs are very small. This stage happens within approximately the first minute of alum addition. This first stage does not, however, use the full adsorption capacity of the HAOs. Depending on the mixing intensity during this stage (higher is better), the HAOs can adsorb between 50% and 70% of the total adsorption capacity. The second stage is a longer-term adsorption that becomes slower and slower as time progresses. For practical purposes, most of this adsorption is completed within 30 minutes of alum addition. It is important to note that the HAO floc is still reactive after this 30-minute period (i.e. it can adsorb, or release OP should the exterior OP concentration changes). For example, when settled in the sludge blanket, OP releases from below the HAO floc could be adsorbed by the settled HAO flocs.

Models of this adsorption mechanism model have been developed and implemented in some wastewater simulation packages. Jacobs Engineering has implemented a system model of the C-43 WBSR inline treatment facility in the Sumo© Simulation platform by Dynamita (www.dynamita.com) version 19.3.

Based on the process outlined above, the primary design criterion is a rapid, high energy mix of the alum solution into the intake water stream. This will be accomplished at the C-43 WBSR pump station by recirculating a portion of the intake water within the intake channel through a mixing pump, or eductor, and adding the alum to that mixing stream.

3.2 Available Data for C-43 WBSR Water Quality

For purposes of modeling alum addition, there are two aspects that must be considered in the influent water quality. First are the total concentrations of the various components, such as TN, TP, and TSS. These values were provided from the S-78 water quality monitoring results and represent the likely quality of the influent water (J-Tech, 2021). The second aspect is the fractionation of those bulk components, i.e. how much of the TP is OP that can be adsorbed by the HAOs, and how much of the TN is ammonia, nitrate, colloidal, solids, or soluble.

The primary source of the water fractionation characterization was the S-78 sampling data, that provided nutrient fractionation data for both nitrogen and phosphorus. The median of these results are shown in Table 9.

Table 9. Nitrogen and Phosphorus Fractionation in S-78 Water Samples (J-Tech, 2021)

Component	Median	Units
Nitrogen		
Ammonia-N	0.052	mg N/L
Nitrate + Nitrite-N	0.087	mg N/L
Total Nitrogen	1.37	mg N/L
Organic Nitrogen-N	1.205	mg N/L
Organic N Dissolved	0.993	mg N/L
Organic N Particulate	0.2	mg N/L
Phosphorus		
Ortho Phosphate	0.050	mg P/L
Total Phosphorus	0.095	mg P/L
Organic Phosphorus	0.047	mg P/L
Organic P Dissolved	0.012	mg P/L
Organic P Particulate	0.035	mg P/L
Total Suspended Solids	4.0	mg/L

The above data were used to develop a portion of the needed input fractions for the simulation. Additional data required included the colloidal fractions. This fraction was estimated from jar testing (SFWMD, 2020) that was performed as part of this project. The change in total organic carbon (TOC) was documented at various alum dosages from the jar testing. Since alum addition cannot change the soluble levels of TOC, the only mechanism that alum can impact is the coagulation of colloidal organic carbon (OC). Thus, the change in TOC at the highest alum dosages (assuming full coagulation) can be used to infer the colloidal fraction in the influent water. Table 10 shows the results of these three tests and the resulting estimated fraction of colloidal organic carbon of the measured dissolved organic carbon (DOC).

Table 10. Organic Carbon Response to Alum Application in C-43 Jar Tests (SFWMD, 2020)

TOC	Test 1	Test 2	Test 3
Starting TOC	24.0	21.0	22.0
Starting DOC	23.0	20.0	21.0
Ending TOC	10.0	10.0	10.7
Colloidal OC	13.0	10.0	10.3
Colloidal OC/DOC	57%	50%	49%

The Sumo model calculates the mass balance based on chemical oxygen demand (COD). The COD data were not provided in any of the reports. J-Tech's experience in this area indicates that an assumption of COD = TOC/0.34 is reasonable for most organic material. Using this fractionation, the Sumo influent fractionation presented in Table 11 was used in the modeling effort.

Table 11. Sumo Model Influent Water Quality Characterization

Name	Percentage (%)
Fraction of Volatile Suspended Solids (VSS)/TSS	75
Fraction of filtered COD (SCCOD, 1.5 µm, incl. colloids) in total COD	95.5
Fraction of flocculated filtered (SCOD, wo colloids) COD in total COD	52
Fraction of Volatile Fatty Acids (VFA) in filtered COD (SCCOD, 1.5 µm, incl. colloids)	0
Fraction of soluble unbiodegradable organics (SU) in filtered COD (SCCOD, 1.5 µm, incl. colloids)	54
Fraction of particulate unbiodegradable organics (XU) in total COD	2
Fraction of heterotrophs (OHO) in total COD	1
Fraction of endogenous products (XE) of OHOs	1
Fraction of colloidal unbiodegradable organics (CU) in colloidal COD	83
Fraction of NHx in TKN	3.7
Fraction of PO4 in TP	51.3
Fraction of H2S in total sulfur (TS)	0
Fraction of N in readily biodegradable substrate (SB)	4
Fraction of N in particulate unbiodegradable substrate (XU)	1
Fraction of P in readily biodegradable substrate (SB)	1
Fraction of P in particulate unbiodegradable substrate (XU)	0.1

Note: Refer to Attachment 1 for Sumo documentation detailing fractionation parameters.

3.3 Model Selection and Setup

As described in Section 3.1, the C-43 WBSR inline treatment facility was set up in Sumo 19.3. The biokinetic model used for this work is the Sumo 2S model modified for alum addition. The process flow diagram used in the model is shown in Figure 5.

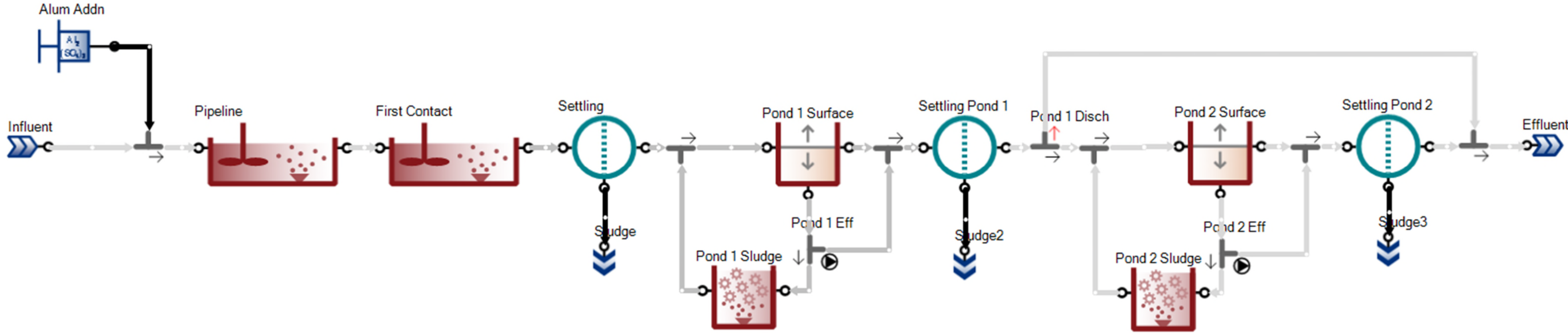


Figure 5. Sumo 19.3 Process Flow Diagram of C-43 WBSR Inline Alum System

The C-43 WBSR model was built to estimate the reservoir effluent under variable feed and storage conditions. One limitation of the model is that it does not model algae directly, so the TSS values settling and in the effluent are based on experience with typical reservoir numbers. The principal components of the model are as follows:

1. Alum addition is flow-paced to the influent flow rate at a target molar dosage of metal (moles of metal/mole of OP in the influent).
2. The pumps and pipe between the intake and reservoir Cell are modeled as a single complete mix reactor with an equivalent volume to the discharge pump piping.
3. First Contact: This is the portion of the reservoir area where the dosed alum has not yet settled out and is still reacting with the OP.
4. Settling: This is a unit that settles solids, mostly HAOs and adsorbed OP, and removes it from the model. It is assumed this removal is like solids settling into the sludge blanket and being removed from the system.
5. The two reservoir sections are modeled as variable volume systems. The sludge layer is modeled as a biofilm type system with a biofilm area equivalent to the Cell 1 area, complete with diffusion to and from the sludge blanket. Settling in this zone is modeled as an enhanced attachment rate to the biofilm area. The Cell 1 surface unit is getting oxygen from surface oxygen transfer.
6. After the Cell 1 model, a settling step, like the previous one is added to further remove solids from the model/sequester solids in the sludge blanket.
7. The C-43 WBSR can discharge from Cell 1 or Cell 2. Therefore, a diverter was put in place to allow diverting Cell 1 effluent to the plant effluent.
8. The Cell 2 model is identical to the Cell 1 model in structure and function. Effluent TSS from the Cell 2 settler is forced to reflect typical reservoir effluent TSS values of between 3 and 4 mg/L.

Preliminary modeling targeted an effluent quality of 0.08 mg/L TP in the cell effluent. This preliminary modeling was conducted with a spreadsheet model that approximates the HAO phosphorus adsorption reactions. This preliminary model indicated that an alum dosage of 0.6 mg/L alum would achieve the target effluent (at an influent TP of 0.15 mg/L TP).

The Sumo model was then set up at a steady state feed rate of 750 cubic feet per second (cfs) (full pump capacity assuming 12 hours per day of operation) with an alum molar dosage of 9 moles alum/mole OP. This resulted in an alum dosage of 0.6 mg/L alum or 3.4 gallons per minute (gpm) of bulk alum solution.

3.4 Results

3.4.1 Nutrient Reductions

The model nutrient profile across the system is shown in Figure 6 for TN and Figure 7 for TP. Effluent quality is summarized in Table 12. Attachments 2-A, 2-B, and 2-C provide the three-year dynamic simulation Sumo outputs for flow, total volume, and effluent phosphorous, respectively.

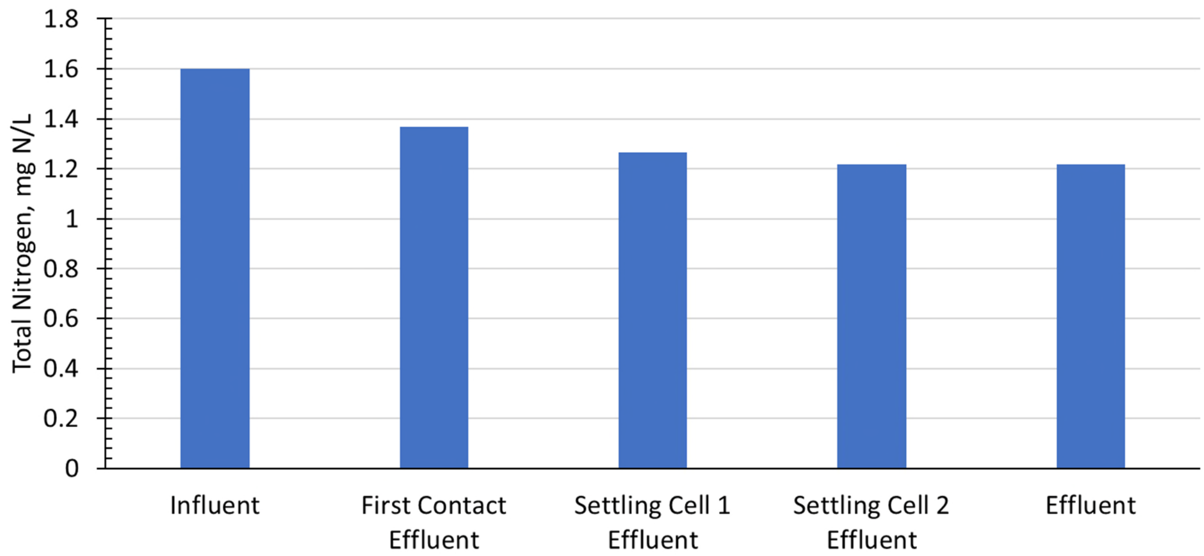


Figure 6. **C-43 WBSR Model Results TN Profile**

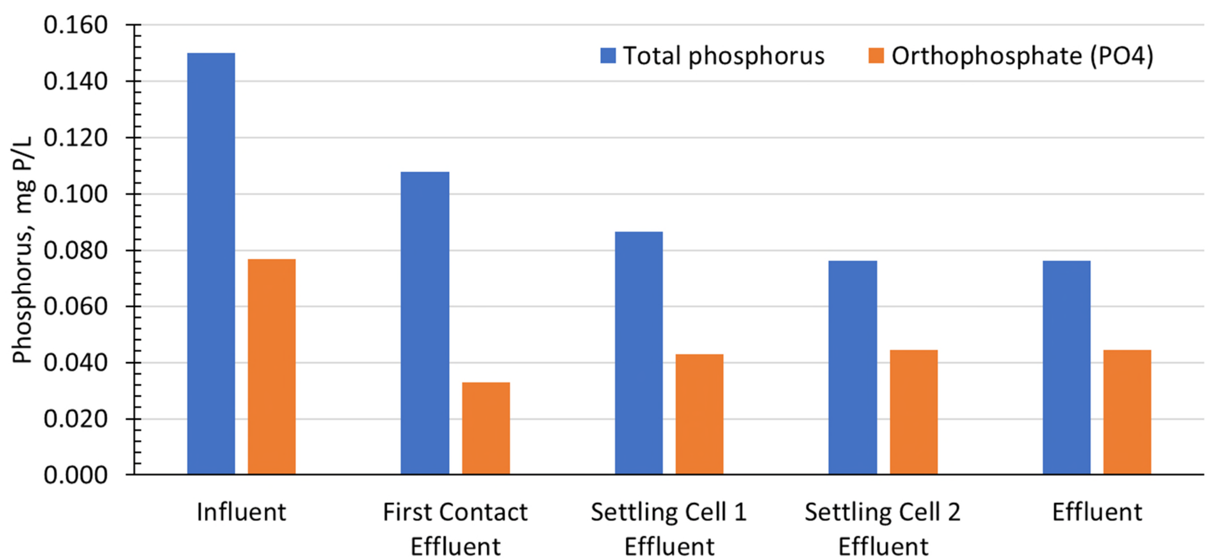


Figure 7. **C-43 WBSR Model Results TP Profile**

The results indicate that the OP levels drop very rapidly in the immediate area around the pump station discharge (First Contact Effluent), but that the OP increases a bit in the larger cell areas. However, this increase is offset by a decrease in TP related to solids settling in the cells. Achieving an effluent TP of less than 0.08 mg/L TP does appear to be achievable with only a small alum dosage (0.6 mg/L alum). Subsequent modeling indicated that an effluent TP of 0.1 mg/L TP could be achieved with an even smaller dose of 0.1 mg/L alum. A possible negative result is the OP increase in the cells. This indicates there is a possibility that longer holding periods might further increase the OP levels. Should this occur, it may be necessary to increase the alum dosage levels to counteract this increase. Preliminary dynamic modeling over a longer period (i.e. a year or more) suggests that this may not be a concern but additional modeling would better quantify this risk.

The TN reductions shown in Figure 6 for the model are a result of a combination of nitrate, ammonia, and colloidal nitrogen removal in the system.

Table 12. C-43 Model Influent and Effluent Results

Component	Influent	Effluent	Units
Flow rate	484	484	million gallons per day (MGD)
Total COD	71	43	mg/L
TOC		11.80	g C.m^3
TSS	3.59	3.60	mg/L
VSS/TSS ratio	0.75	0.92	g VSS.g TSS-1
Total BOD (5 days)	4.07	2.33	mg/L
pH	7.50	8.53	s.u.
Alkalinity	150	147	mg/L
TN	1.60	1.22	mg/L
Total ammonia (NHx)	0.056	0.001	mg/L
Nitrite (NO_2)	0.000	0.000	mg/L
Nitrate (NO_3)	0.100	0.000	mg/L
TP	0.150	0.076	mg/L
PO_4	0.077	0.044	mg/L

3.4.2 Aluminum Concentration

The aluminum profile through the system is estimated in Table 13. Note that this result can be affected by many aspects of the simulation that have significant levels of uncertainty. The full-scale experience in this area likely provides a higher degree of certainty around the results. The predicted values are well below the calculated U.S. Environmental Protection Agency (USEPA) toxicity criterion of 0.87 mg/L (see Section 8.2.1 below).

Table 13. C-43 Model Aluminum Results

Parameter	Influent	First Contact Effluent	Settling Cell 1 Effluent	Settling Cell 2 Effluent	Effluent	Unit
Total Aluminum	0.000	0.302	0.151	0.075	0.075	mg/L

3.4.3 Floc Production and Accumulation

The model is only capable of predicting the amount of solids that settle into the sludge blanket. The actual accumulation will be dependent on the amount of degradation that occurs in that zone. The daily mass rates shown in Table 14 are the settling rates assuming peak flows 12 hours per day.

Table 14. C-43 Model Sludge Settling Rate Results at Peak Inflow Rates

Parameter	First Contact Sludge	Cell 1 Sludge	Cell 2 Sludge	Unit
TSS mass flow	30	15	7.3	tons/day
VSS mass flow	27	13	6.7	tons/day

The sludge production over a three-year period was modeled using a representative time-varying input of flow and concentration to the model. Table 15 summarizes the annual and three-year sum of solids produced in reservoir cell. Results indicate that Cell 1 will accumulate solids at a rate approximately twice that of Cell 2.

Table 15. C-43 Predicted Solids Accumulation for a Three-year Period

Year	Sum of TSS Mass Flow (First Contact Sludge Pipe)	Sum of VSS Mass Flow (First Contact Sludge Pipe)	Sum of TSS Mass Flow (Cell 1 Sludge Pipe)	Sum of VSS Mass Flow (Cell 1 Sludge Pipe)	Sum of TSS Mass Flow (Cell 2 Sludge Pipe)	Sum of VSS Mass Flow (Cell 2 Sludge Pipe)
2000	2,189,035	1,789,549	4,753,333	4,445,492	2,925,587	2,709,329
2001	2,341,775	1,721,856	2,981,669	2,796,465	598,950	560,600
2002	2,443,646	1,850,592	4,632,304	4,360,921	1,949,042	1,827,249
Total	**6,974,456**	**5,361,997**	**12,367,306**	**11,602,878**	**5,473,579**	**5,097,178**

Sludge is anticipated to be relatively uniform within the reservoir, with a deepening tendency near the pipe inlet to the reservoir. Concentrations of suspended solids in the water column adjacent to the inlet pipes are expected to be on the order of less than 10 mg/L. Based upon a typical solids content of 4% for settled alum solids, this deposition equates to an annual accretion rate of 0.33 cm/yr in the C-43 WBSR Cell 1. This estimate is identical to observed accumulation rates noted in other Florida lakes receiving full-scale alum dosing by Harper and Herr (1999). Similarly, this sedimentation rate is consistent in general with Florida lakes. Brenner et al. (1999) estimated accretion rates ranging from 0.46 cm/yr to 0.79 cm/yr in Orange Lake. Brenner et al. (2001) found an average accretion rate of 0.33 cm/yr (range 0.24–0.40 cm/yr) at ten sites within Blue Cypress Lake marsh. Accretion rates are estimated to be approximately half of this value in Cell 2. Given this calculation, the estimated depth of accumulation after 50 years would be slightly over six inches.

With time, it is reasonable to anticipate that an organic layer will develop on the reservoir bottom. Florida lakes and marshes have been measured to accumulate approximately 70 cm (2 feet) over the past century (Brenner et al., 2001). Productive Florida lakes typically include an unconsolidated organic muck layer at the sediment-water interface. Typical depths of this layer can be 1–4 inches or more. The unconsolidated layer is comprised primarily of fresh organic material, such as dead algal cells, and may be easily resuspended by wind action or boating activities, which disturb the bottom. As the sediment depth increases, the organic layer becomes more consolidated with a consistency like pudding. These deeper layers typically do not resuspend into the water column except during vigorous mixing action within the lake. Observations of sediment cores from lakes receiving alum applications indicate that the alum becomes incorporated into the surface layer and into the sediment (Harper and Herr, 1999). Harper (2020) indicates that alum addition is the cost-effective alternative to managing flocculent sediment. Florida lakes that have received alum addition (e.g., Lake Conine) show evidence of a decline in accumulated algal pigments in lake sediments and a reduction in trophic state (Riedinger-Whitmore et al., 2005).

With the presumed cycle of annual drawdown, some consolidation of floc sediment bottom may be expected. Cooke et al. (2005) noted that experience in eutrophic Florida lakes indicated a 40–50% volume reduction of muck-type sediments. With time, the crystalline structure of newly formed alum floc combined into larger structures and the hydroxide content increases. Stability of floc particles increases as well as trapped particles and ions within the crystalline structure, which remain stable under a wide range of pH and redox conditions (Harper and Herr, 2009). This process has been described as requiring 30–90 days, which is consistent with the typical expected duration of storage. Microfloc may still be present, however, based upon observations by SJRWMD. In that circumstance, the offline polishing systems assessed during the WQFS could be expected to provide a final level of polishing before discharge to the river.

4.0 Conceptual Design Inline Alum Application System

To apply alum to the C-43 WBSR, the conceptual plan is to blend bulk liquid alum into each pump intake channel with a high-speed submersible mixer. Alum will be metered by a control valve and flow meter system at each channel to the high-speed mixer. Alum pumping will not be needed since the base of the alum storage system is above elevation 20 feet, the maximum water surface is 8 feet, and the submersible mixer acts as an eductor and draws its own vacuum. This will provide enough head for a control valve to regulate the flow of alum to the mixer. The mixer will only be in operation while that channel is pumping through control interlocks, and there will be a separate automated valve (from the control valve) that will close the alum feed line when the associated pump is not in service. Alum will be supplied from a tank farm located as described in Section **Error! Reference source not found.**. The tank farm will include multiple double walled fiber reinforced plastic (FRP) tanks for alum storage, and a fill station with spill control for offloading tanker trucks of alum.

4.1 Process Description and Control

Two scenarios were evaluated for the inline alum system. The base case assumes an alum gravity-feed system and the alternate option consists of an alum pumped system. This section presents the process description and control for both scenarios.

4.1.1 Process Description

Base Case: Bulk liquid alum will be delivered to the site via tanker truck, offloaded using a new fill station, and stored in double walled FRP tanks in a new tank farm. Liquid alum will flow by gravity to the S-470 Pump Station to aid in phosphorus removal in the reservoir. Each channel vertical mixed flow pump will have dedicated flow control valves and flow meters to control the dosage. The liquid alum will be added to a high-speed mixer located in the channel on the intake side of the channel vertical mixed flow pump. The tank farm will include a fill station with offloading pump, containment, and a safety shower/eyewash station. The alum feed pumps will be located in the tank farm to minimize suction piping. A sunshade (open-sided pre-engineered metal building [PEMB]) will be provided over the tank farm to protect the tanks, pumps, and associated equipment.

Alternative Adder: Feed pumps will transfer liquid alum to the S-470 Pump Station to aid in phosphorus removal in the reservoir. Flexibility will be provided to add the alum to a high-speed mixer located in the channel on the intake side or to an injection quill on the discharge side of the channel vertical mixed flow pump. Each channel vertical mixed flow pump will have dedicated duty/standby alum feed pumps.

Three options are under consideration for injection of alum into the system flow path. Table 16 summarizes key considerations for each option. For the purpose of this conceptual design, the WaterChamp™ system is proposed, which allows for most efficient mixing, least alum use, and can be maintained without entering the inlet channel. Two other conceptual approaches – an injection quill and a dilution pump – are provided as alternatives, which do not require maintenance in the inlet channel. However, there are considerations of greater alum use and pump operation that will require further evaluation in the final design.

Table 16. Alum Injection System Alternatives and Considerations

Type	Considerations
Vacuum Induction System (WaterChamp™)	•Most efficient mixing •Least alum use •Attached to guiderail •Remove for maintenance with davit hoist through hatch •No in-channel maintenance

Type	Considerations
Injection Quill	•Up to 50% more alum use •Pipe corrosion risks increased at injection point •Higher pressure operation •Requires alum pumps and associated maintenance
Pump and Dilution	•Mixing pump priming and maintenance •Higher flows needed to achieve optimum dilution

4.1.2 Process Control

Base Case: Each channel vertical mixed flow pump will have dedicated flow control valves and flow meters to control the alum dosage. The high-speed mixers will be interlocked to the associated channel vertical mixed flow pump. The alum dose will be set remotely by the operator. The flow set point and associated flow control valve setting will adjust based on the target alum dosage. When one of the constant speed channel vertical mixed flow pumps turn on, the paired high-speed mixer will also turn on and will remain on until alum feed is stopped or the paired channel vertical mixed flow pump turns off.

Alternative Adder: Each channel vertical mixed flow pump will have dedicated duty/standby alum feed pumps. The alum feed pumps and high-speed mixer (when in use) will be interlocked to the associated channel vertical mixed flow pump. The dosing location and speed of the alum feed pumps will be set remotely by the operator. The alum feed pump speed will be selected based on the target alum dosage. When the operator selects the dosing location, actuated valves will adjust. When one of the constant speed channel vertical mixed flow pumps turn on, the paired duty alum feed pump and high-speed mixer (when that dosing location is selected) will also turn on and will remain on until alum feed is stopped or the paired channel vertical mixed flow pump turns off.

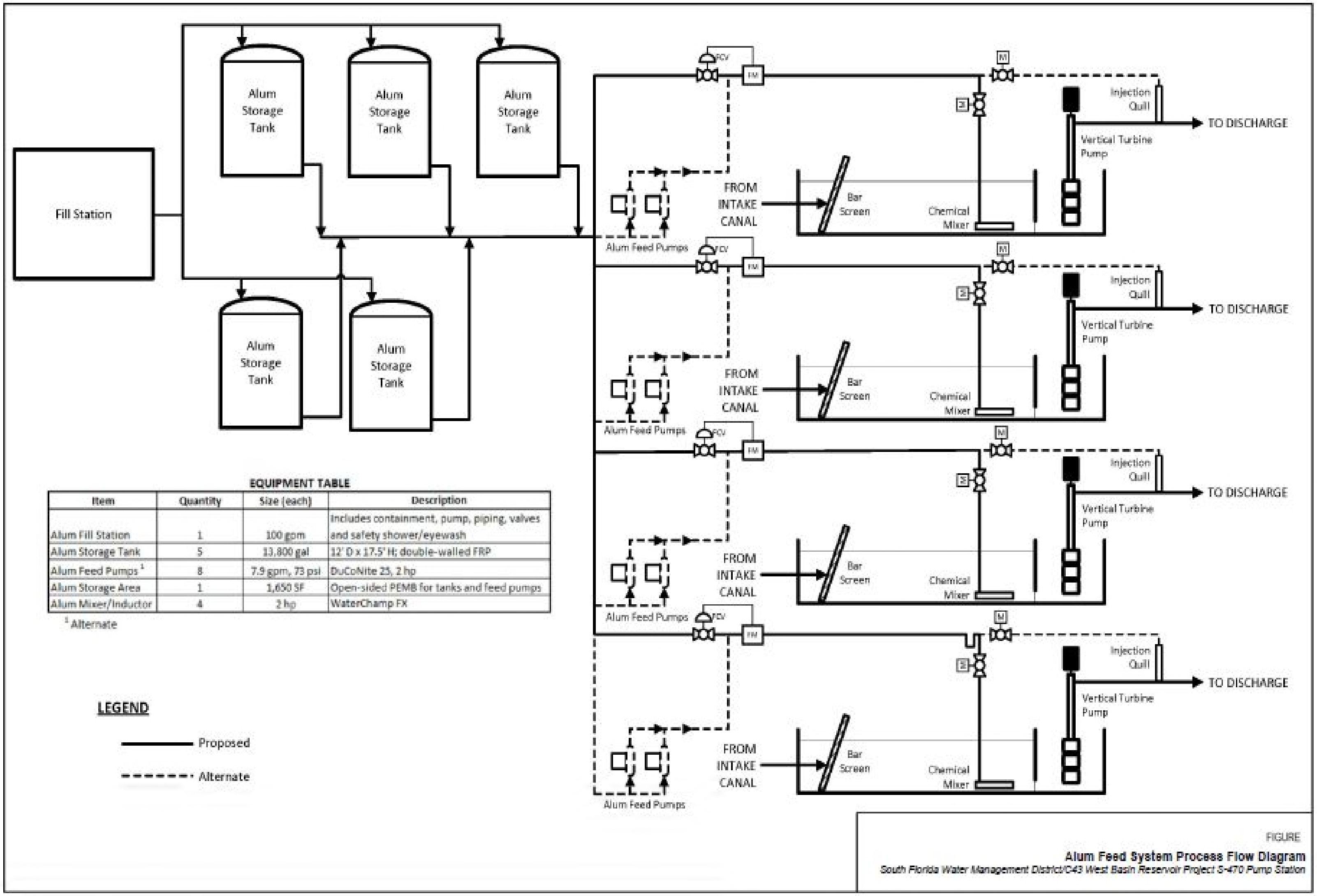
4.2 Conceptual Infrastructure Site Plan

The process design criteria and recommended process features are summarized in Table 17. A process flow diagram is included in Figure 8. Available footprint, capacity requirements, site topography, and site access points were evaluated to determine the conceptual layout of the inline alum system. Figure 9 and Figure 10 present the conceptual layout of the inline alum system and proposed location of the tank farm, a main component of the system. The semi-circle allocated space provides the available footprint required for the tank farm with a capacity of 70,000 gallons approximately for 14 days of alum storage.

Table 17. Conceptual Design Criteria, C-43 Inline Alum Treatment System

Component	Value	Units
Influent		
Peak Total Pumping Capacity	1,500	cfs
Daily Pumping Duration	12	hours/day
# of Pumps	4 constant speed vertical mixed flow	
Design TP	0.15	mg/L
Design TN	1.37	mg/L
Alum Dosage		
Target Effluent TP	<= 0.080	mg/L
Average	0.6	mg/L
Peak	2.0	mg/L
Bulk Alum		
Strength	49	wt% as $Al_2(SO_4)_3 \cdot 14H_2O$
Density	11.10	lbs/gallon

Component	Value	Units
Alum Usage		
Minimum Flow Criteria	One vertical mixed flow pump in service (375 cfs) at 50% of average dosage	
Minimum Total Alum Flow	0.85	gpm
Average Flow Criteria	Four vertical mixed flow pumps in service (1,500 cfs) at average dosage	
Average Total Alum Flow	6.8	gpm
Daily Average Total Alum Flow	4,916	gallons per day
Average Flow Criteria	Four vertical mixed flow pumps in service (1,500 CFS) at peak dosage	
Average Total Alum Flow	22.8	gpm
Alum Flow Range per Channel		
Minimum	0.85	gpm
Average	1.71	gpm
Peak	5.69	gpm
Bulk Alum Storage		
On-Site Storage Capacity	14	Days at average dosage and peak flows
	68,824	gallons
Delivery Truck Size	11,600	gallons
Bulk Tank Sizing	Receive one tanker load at 10% full	
Minimum Bulk Tank Size	12,760	gallons
Estimated Number of Bulk Tanks	5	
Bulk Tank Liquid Volume	13,800	gallons each
Estimated Bulk Tank Diameter	12	feet
Estimated Bulk Tank Height	16.5	feet
Tank Type	Vertical double walled FRP	
Alum Dosing System		
Number	4	
Control Approach	Gravity Fed flow meter and control valve with interlocked (with channel Vertical mixed flow pump) automated shutoff valve	
Alum Mixer	WaterChamp™ type submerged chemical mixer (https://www.evoqua.com/en/evoqua/products--services/disinfection-systems/disinfection-dosing-equipment/water-champ--fx-chemical-induction-system/)	



EQUIPMENT TABLE

Item	Quantity	Size (each)	Description
Alum Fill Station	1	100 gpm	Includes containment, pump, piping, valves and safety shower/eyewash
Alum Storage Tank	5	13,800 gal	12' D x 17.5' H; double-walled FRP
Alum Feed Pumps [1]	8	7.9 gpm, 73 psi	DuCoNite 25, 2 hp
Alum Storage Area	1	1,650 SF	Open-sided PEMB for tanks and feed pumps
Alum Mixer/Inductor	4	2 hp	WaterChamp FX

[1] Alternate

Figure 8. Process Flow Diagram

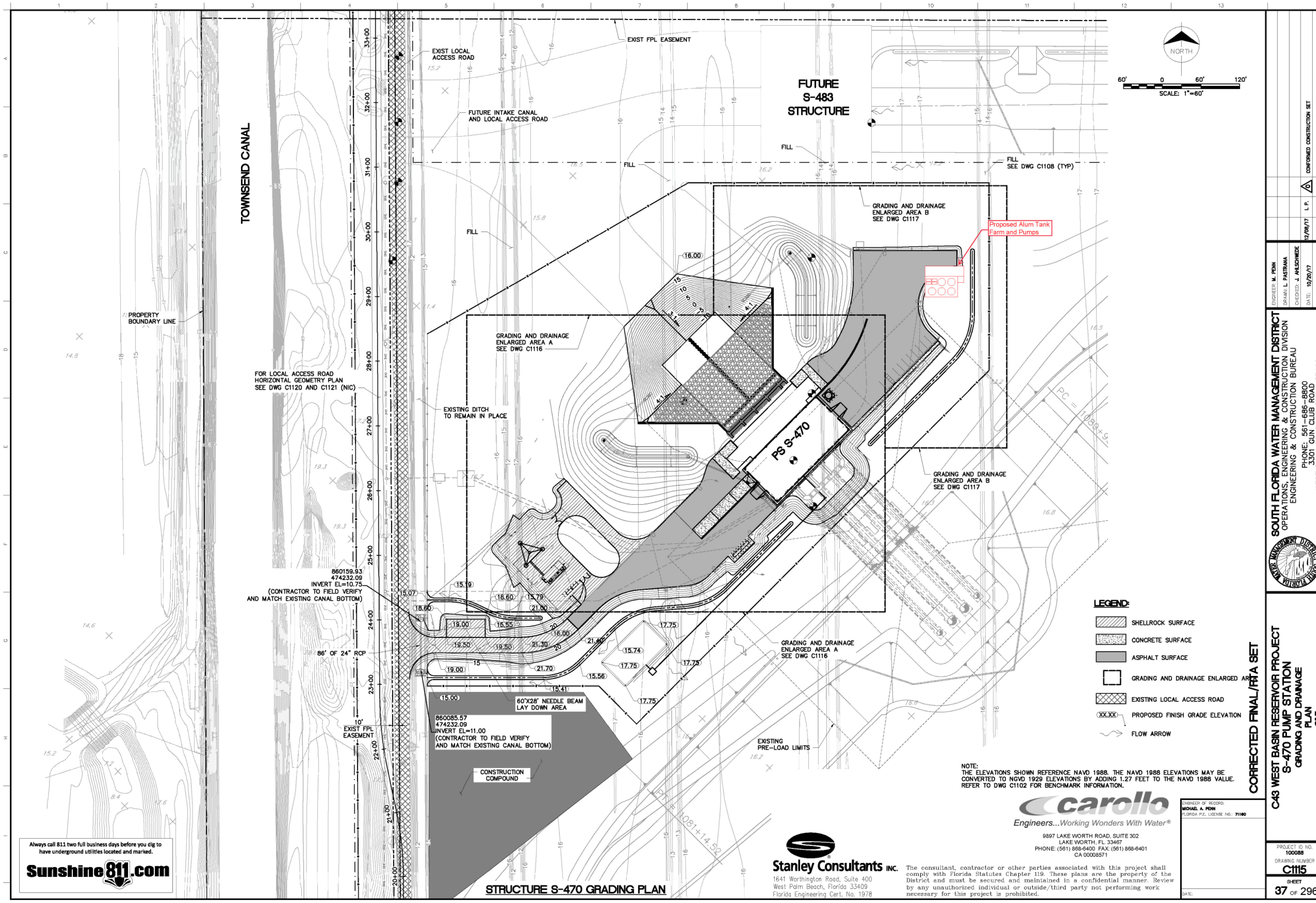


Figure 9. C-43 WBSR Inline Alum System Conceptual Site Plan

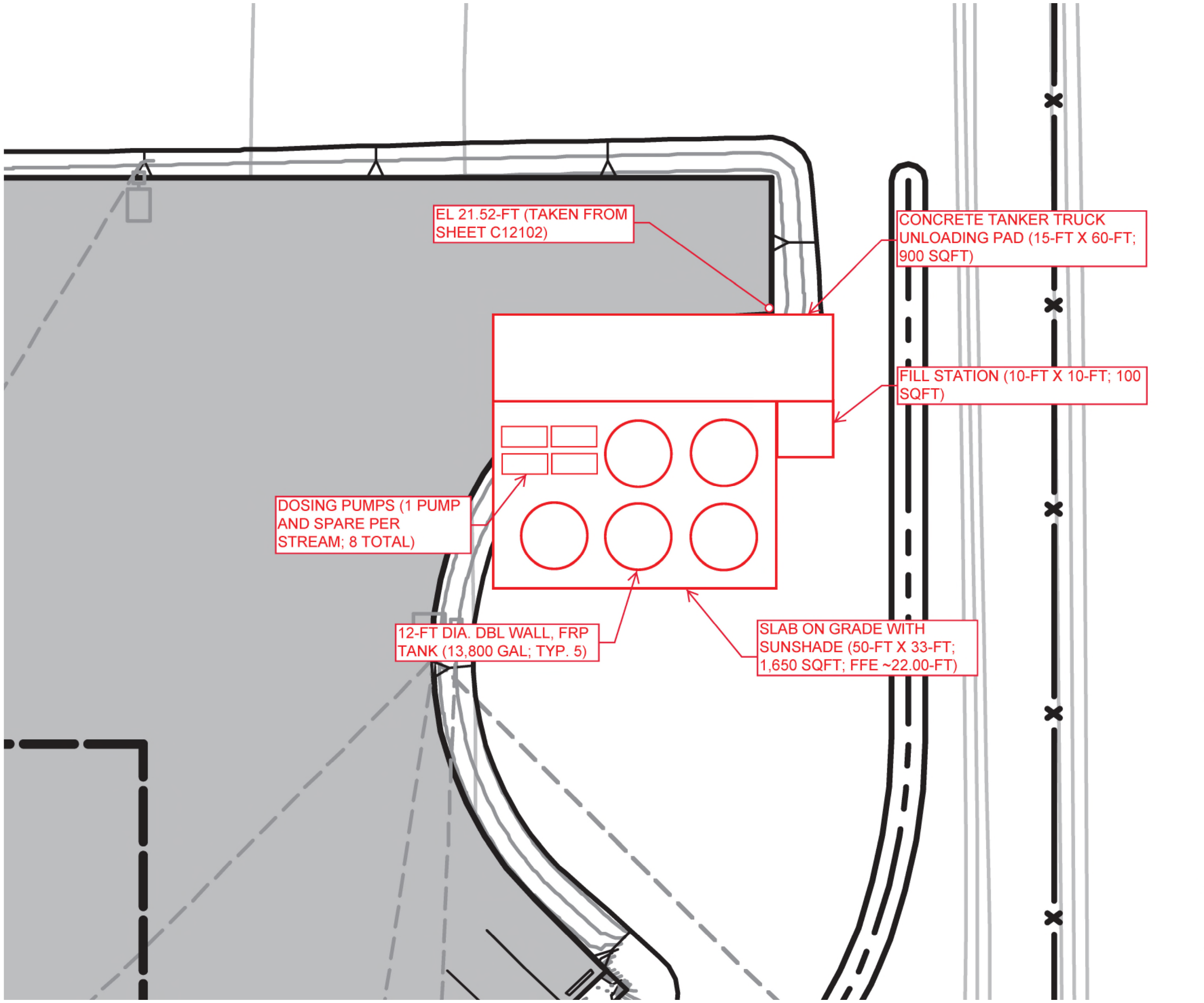


Figure 10. C-43 Inline Alum System Conceptual Layout Plan

4.3 Siting Considerations

Site characteristics and the current status of construction of the C-43 WBSR pump station were evaluated to determine potential implications of the addition of the inline alum system. Table 18 summarizes the potential implications and considerations taken or that will be taken at the detailed design phase.

Table 18. C-43 Alum Addition System Siting Considerations

Siting Implications	Considerations/Resolutions
Location of piping, pumps, infrastructure of the inline alum system, footprint requirements	Space was allocated and reserved for inline alum infrastructure. Space has been reserved for duct bank at the pump station.
Space and location for dosing pumps	Wall space was identified at operations gallery floor slab by intake base (space in between grading on northwest of pump station) where alum dosing pumps could be mounted on the wall. Pumps could also be placed nearby the tank farm (elevations work for gravity flow and there is available space).
Alum storage onsite	Alum storage tanks will need double containment and a fill station with spill control for offloading tanker trucks of alum.
Topography	Elevations of the site were evaluated to determine feasibility of gravity flow. While the system may work by gravity flow, a more detailed evaluation will be needed at design phase to confirm location/size of valve for gravity flow.
Alum tanker trucks – access/entrance roads	Will need to determine access routes for alum delivery at detailed design phase. A possible delivery route for alum could be to deliver alum from the northwest side of plant and leave from the northeast side of the site (by south of dam).

5.0 Alum Characteristics and Materials Compatibility

Handling and contact characteristics of alum were reviewed to confirm that alum could be applied to the C-43 WBSR inflow without unintended consequences to the reservoir infrastructure. This section provides a brief overview of pertinent characteristics.

5.1 Alum

Alum ($Al2(SO4)3 \cdot 14H20$) is normally supplied in acidic bulk solutions at approximately 40% weight as the hydrate. It is frequently used in both water and wastewater treatment for the purposes of both coagulation and phosphorus adsorption (moving OP from soluble to particulate phase). Since the bulk alum solution is acidic, care must be taken to provide appropriate materials of construction of those components in direct contact with the alum solution, including the dosage point. Once alum is mixed into water, it quickly hydrolyzes into aluminum hydroxide ($Al(OH)3$), which is generally considered to be low to non-corrosive. The dosage point itself should be designed for the potential of bulk alum being in contact with the material, if mixing fails for some unexpected reason. Once mixed into solution, the bulk water corrosivity normally controls materials of construction with some consideration for the lower pH created by the addition of the acidic alum solution.

5.2 Materials

Materials were evaluated with the assumption that the alum is fully mixed at a maximum concentration of 20 mg/L. As previously described, the alum quickly hydrolyzes into aluminum hydroxide and the bulk water corrosivity is the fundamental driver for corrosion, not necessarily the alum. The water quality parameters used to perform a full corrosivity analysis were not available at the time of the analysis; therefore, the shift in pH was used as the primary guide for increase in corrosivity after the alum is added. The alum addition is expected to shift the pH from about 7.50 to 7.36 before entering the reservoir Cell 1.

- **Concrete**: Concrete performs well in water at near neutral pH. The pH is not fully indicative of the corrosivity to concrete but would be more of a concern the pH dropped below 6.5. Sulfates are known to attack concrete but an increase in sulfate from the anticipated alum concentrations will have negligible impact to the corrosivity of the water.
- **Carbon Steel**: Carbon steel components are typically protected with an epoxy coating. Epoxy will not be affected with small shifts in pH. Epoxy is also resistant to aluminum sulfate and aluminum hydroxide at high concentrations.
- **Stainless Steel**: Stainless steel is resistant to both aluminum sulfate and aluminum hydroxide at high concentrations. The corrosivity impact of alum addition for stainless steel is expected to be negligible.
- **Clay-bentonite**: Clay materials are typically nonreactive to various water quality parameters and clays are also not evaluated from a corrosivity standpoint. However, chemical additions such as alum can cause changes in the swelling. Swelling of clay is typically not influenced in a pH range of about 5 to 9.
- **Rip rap:** The rip rap is anticipated to be limestone and granite. Lowering the pH can dissolve minerals such as limestone but the overall shift in pH is expected to have a negligible impact.

Until a full corrosivity analysis based on bulk water quality can be performed, further corrosion mitigation measures should not be necessary since the impact of the alum addition is not anticipated to be significant.

Following a review of the Draft Inline Alum Treatment Conceptual Design, SFWMD's Technical Review Board requested the following information needs, with respect to materials compatibility, as part of the final design:

- Evaluate the use of stainless steel pipes instead of the epoxy coated pipes during design for corrosion issues and material lifespan.
- Further evaluate potential pH changes and any impacts on the soil cement during design. If there are impacts, concrete crystalline waterproofing (CCW) will be added to the soil cement.

6.0 Operation and Maintenance

The proposed inline alum system is expected to have minimal operational requirements. This section provides an overview of operational management needs and a list of typical operational activities.

6.1 Overview of Operational Management

The alum storage system will consist of a number of double contained FRP tanks. The area around the tanks will require general cleaning as appropriate. The tanks will be supplied with level monitors/alarms as well as leak detectors. These will need periodic maintenance. The fill system will consist of a tanker connection valves to direct the bulk alum to the appropriate tank. Operations will need to choose which tank to be filled based on level in that tank, and its ability to receive a full tanker load. Care will need to be taken to not overfill tanks. Each tank discharge (to the dosing point) will have a basket strainer that will need occasional cleaning. This is needed to protect the downstream valves from plugging.

The alum dosage system will consist of a flow meter and control valve system at each pump inlet channel. The valve actuator and flow meter will need occasional maintenance, in addition to recommended flow meter calibration. The actual alum mixer in each inlet channel is a submerged high-speed mixer. As in any submerged piece of equipment, the mixer will require regular maintenance as recommended by the equipment supplier.

From a process perspective, the alum addition system will be used to control the reservoir phosphorus levels. Given the large size of the system, the impacts of changing alum dosage will only be immediately visible in the near vicinity of the pump station outlets at the reservoir cell. Regular TP and OP sampling should be conducted on the raw water and the water at three places within the reservoir system, near the pump station outlet, Cell 1 outlet, and Cell 2 outlet to determine if dosages can be raised or lowered, depending on the quality goals of the system. A field test kit can be used for this monitoring. It is expected that this monitoring would be needed more often initially (i.e. weekly), but as operations staff gain experience, this monitoring might be reduced to monthly.

6.2 Typical Operational Activities

Typical operational activities anticipated from the alum treatment system include the following:

- Coordination and supervision of chemical deliveries.
- Tank farm maintenance and cleaning (monthly).
- Flow meter and control valve maintenance (monthly).
- WaterChamp™ maintenance, per manufacturer recommendation (twice per year).
- Dosage monitoring: weekly during the first months, then monthly while in operation.
- Flow checks: all flows are approximately equal between lanes while in service.

7.0 Life Cycle Cost

Capital costs were estimated by pricing materials required for storage, dosing and related items and applying standard markups. Operational costs were derived and updated from the WQFS. Total Net Present Value was calculated over a 50-year period.

7.1 Capital Cost

A high-level budgetary capital cost estimate was prepared for the addition of the inline alum treatment system and is provided in Table 19. The rough order of magnitude capital cost was estimated between $3.55 million and $6.33 million.

Table 19. C-43 WBSR Inline Alum Treatment System

Item	Unit Design Criteria	Quantity	Basis	Unit Cost	Estimated Cost
Alum Storage Tank	13,800 gal double wall FRP	5	Prior experience	$39,000	$195,000
Alum Storage Area Fill Station	Fill Station, piping, pump valves, safety shower and eyewash	1	Prior experience	$125,000	$125,000
Alum Mixer/Inductor	WaterChamp	4	Prior experience	$50,000	$200,000
Alum Feed Pumps	DuCoNite 25:7.9 gpm @73 psi: 2 hp	8	Prior experience	$20,000	$160,000
Total Equipment Cost (TEC)					**$680,000**
Freight and Taxes		6%	of TEC		$40,800
Spare Parts		2%	of TEC		$13,600
Purchased Equipment Cost - Delivered (PEC-D)					**$734,400**
CONSTRUCTION - DIRECT					
Equipment Installation		35%	of TEC		$238,000
Process Piping		40%	of TEC		$272,000
Concrete Reinforced Containment Area		LS	Prior experience	$20,000	$20,000
Instrumentation and Controls		LS	Prior experience	$250,000	$250,000.00
Electrical		LS	Prior experience	$110,000	$110,000.00
Civil		15%	of TEC		$102,000
Concrete		5%	of TEC		$34,000
Structural Steel		0%	of TEC		$-
Architectural		0%	of TEC		$-
Heat Tracing for Pipe, Tanks, Valves		LS	Allowance	$-	$-
Alum Storage Area Sunshade Enhanced Wind Loads		2,100 ft^2	Prior experience	$450	$945,000
Service Facilities		0%	of TEC		$-
Total Direct Cost (TDC)					**$1,971,000**
Indirects					
Contractor's Field Indirects		5%	of TDC		$98,550
Contractor's OH & Supervision (Onsite)		12.5%	of TDC		$246,375
Contractor's Offsite Management		3.75%	of TDC		$73,913
Bonds, Insurance		2%	of TDC		$44,348
Mobilization & Demobilization		12.5%	of TDC		$246,375
Permitting and Legal Fees		1%	of TDC		$19,710
Safety, Security		0.5%	of TDC		$9,855
Subtotal (Indirects TDIC)					**$739,125**
Total Direct Cost + Indirect Cost					$2,710,125
Contractor's Profit		15%	of TDC + TDIC		$406,519
Total Direct Cost + Indirect Cost, Including Profit	**Total Probable Construction Cost (TPCC)**				**$3,116,644**
EPCM Costs					
Engineering Costs		16%			$498,663

C-43 West Basin Storage Reservoir Water Quality Component
Inline Alum Treatment

Item	Unit Design Criteria	Quantity	Basis	Unit Cost	Estimated Cost
Construction Management		8%			$249,332
Procurement		1%			$31,166
Project Controls, Scheduling, Accounting, Inspection and Testing		1%			$31,166
Startup Expenses, O&M, Commissioning		1%			$31,166
Environmental, Validation		1%			$31,166
Client Engineering Costs		0%			$-
Total Estimated Capital Cost (without contingency)					$3,989,304
Contingency		25%			$997,326
Escalation		2%			$79,786
Total Estimated Capital Cost (a)					$5,066,416
				Minus 30%	**$3,546,491.26**
				Plus 25%	**$6,333,020.10**

7.2 Operation and Maintenance Costs

Annual operation and maintenance (O&M) costs are estimated between $400,000 and $700,000, which include the cost and delivery of alum, operational maintenance, mechanical replacement, and general site upkeep and reporting, as presented in Table 20. Total alum usage per year is estimated to be 92.22 tons for a total cost ranging between $54,597 (average flow and dose and current pricing) and $327,580 (peak flow and dose and historic high pricing). Labor was estimated to include two full-time equivalents using SFWMD's O&M Estimating Tool for an annual total of $281,000.

Table 20. O&M Estimate for the Inline Alum Treatment System

Parameter	Low Range	High Range
Hp	8.00	8.00
KW	5.97	5.97
Hours per Year Running	1,825.00	1,825.00
Total Days per Year Running	76.04	76.04
Power Cost ($/kWh)	0.08	0.08
Annual Power Cost ($)	**852.81**	**852.81**
Average Influent Flow Rate (cfs)	750.00	750.00
Average Flow Rate (mgd)	484.70	484.70
Average Alum Dose (mg/l)	0.60	0.60
Average Daily Alum Usage (lb/day)	2,425.46	2,425.46
Annual Dry tons of Alum per Year	92.22	92.22
Cost ($/dry ton)	592.04	592.04
Average Annual Alum Cost	**54,596.72**	**327,580.35**
Equipment Cost ($)	490,505.00	490,505.00
Equipment Maintenance and Repair Annual Multipliers	0.03	0.03
Maintenance and Repair Annual Cost	15,549.01	15,549.01
Total Annual O&M Cost	**70,998.55**	**343,982.17**
Other Cost %	0.20	0.20
Subtotal Annual O&M Cost	**85,198.25**	**412,778.60**
Contingency	0.20	0.20
Labor		
Field Operations	80,000.00	80,000.00
Hydro Data Operations	26,000.00	26,000.00
Water Quality Data Acquisition and Management	175,000.00	175,000.00
Final Total Annual O&M Labor and Contracts	**281,000.00**	**281,000.00**
Total O&M	**400,000.00**	**700,000.00**
Number of Years, n	50.00	50.00
Annual Discount Rate	0.04	0.04
Annual Inflation	0.03	0.03

7.3 Long-term Net Present Value

Assuming a 4% discount rate, the long-term Net Present Value of the proposed inline system is estimated between $30 million and $46 million for a 50-year life cycle, with theoretical replacements of entire hardware at years 15, 30, and 35 (Table 21).

Table 21. Net Present Value for a 50-year Life Cycle Cost Estimate

Year	Low Range Cost ($)	High Range Cost ($)
0	4,500,000	6,000,000
1	412,000	721,000
2	424,360	742,630
3	437,091	764,909
4	450,204	787,856
5	463,710	811,492
6	477,621	835,837
7	491,950	860,912
8	506,708	886,739
9	521,909	913,341
10	537,567	940,741
11	553,694	968,964
12	570,304	998,033
13	587,413	1,027,974
14	605,036	1,058,813
15	7,010,853	9,347,804
16	641,883	1,123,295
17	661,139	1,156,993
18	680,973	1,191,703
19	701,402	1,227,454
20	722,444	1,264,278
21	744,118	1,302,206
22	766,441	1,341,272
23	789,435	1,381,511
24	813,118	1,422,956
25	837,511	1,465,645
26	862,637	1,509,614
27	888,516	1,554,902
28	915,171	1,601,549
29	942,626	1,649,596
30	10,922,681	14,563,575
31	1,000,032	1,750,056
32	1,030,033	1,802,558
33	1,060,934	1,856,635
34	1,092,762	1,912,334
35	1,125,545	1,969,704
36	1,159,311	2,028,795
37	1,194,091	2,089,659
38	1,229,913	2,152,348
39	1,266,811	2,216,919
40	1,304,815	2,283,426
41	1,343,960	2,351,929
42	1,384,278	2,422,487
43	1,425,807	2,495,162
44	1,468,581	2,570,017
45	17,017,181	22,689,575

Year	Low Range Cost ($)	High Range Cost ($)
46	1,558,017	2,726,531
47	1,604,758	2,808,327
48	1,652,901	2,892,576
49	1,702,488	2,979,354
50	1,753,562	3,068,734
NPV	**30,000,000**	**46,000,000**

8.0 Reservoir Response

8.1 Potential for Algal Blooms and the Benefit of Alum Treatment

Cyanobacteria blooms could occur in the C-43 WBSR given the range of TP concentrations in source waters. Inflow TP values range between 80 to 160 µg/L and TN values range from 1.1 to 1.5 mg/L. The trophic classification for the C-43 WBSR would therefore be hypereutrophic by either or both nutrient ranges (Lakewatch, 2000).

The risk of cyanobacteria blooms is not entirely determined by TP concentration. Phosphorus will be the limiting dissolved nutrient to phytoplankton growth in the C-43 WBSR. Without reference to temperature, light attenuation, or other limnologic factors, per Carlson (1977) in the range of expected chlorophyl *a* concentrations produced would be approximately 50 to 136 µg/L (Equation 1). The potential for high primary productivity within the C-43 WBSR is thus obvious. The potential for cyanobacteria blooms, such as observed in source waters, requires consideration of more than phosphorus.

Equation 1. $\boldsymbol{ln(Chl) = 1.449\, ln(TP) - 2.442}$

Light will limit primary productivity in the C-43 WBSR. The mean light attenuation coefficient (k) measured in the C-43 WBSR Test Cell Project ranged from 1.02 to 4.5 m^{-1} across sampling stations. Per Equation 2, there is a reduction of light intensity at two meters of 87% for k = 1.02 m^{-1} and 99.99% for k = 4.5 m^{-1}. Thus, the photic zone is likely to be in the upper two to three meters.

Equation 2. $\boldsymbol{I_z = I_0 e^{-kz}}$

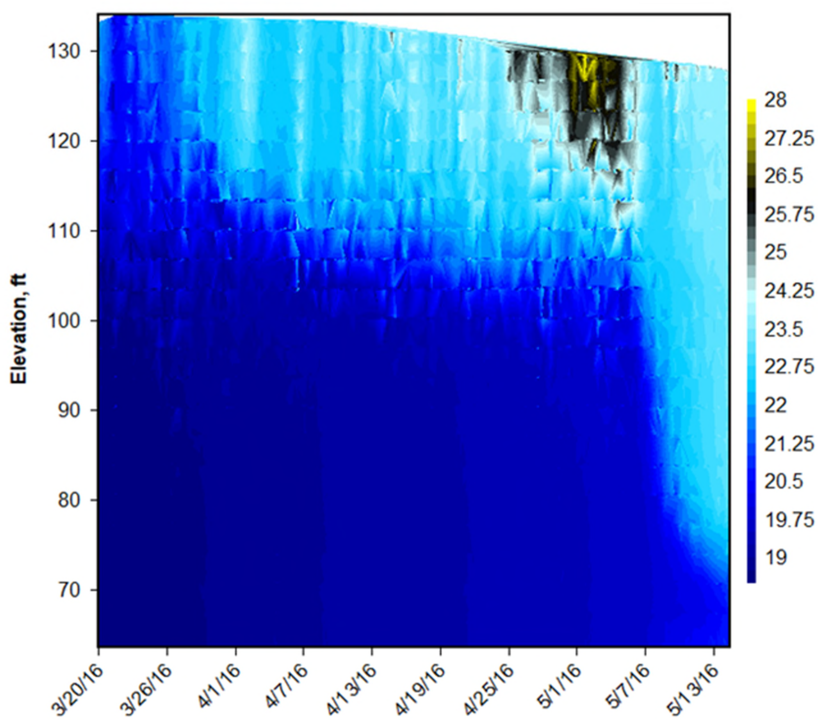
> where I_z is light intensity at depth z (m), I_0 is light intensity at the water surface, and k is the light attenuation coefficient

Shallow photic zones favor cyanobacteria growth, such as observed in Lake Okeechobee (Havens et al., 2003; Havens et al., 1998). There are two potential hydrodynamic considerations in the reservoir that merit attention in addition to the observed propensity of source waters to cyanobacteria blooms.

The reservoir will be polymictic because of the large (3.0 miles) fetch (USACE, 2007) and shallow depth (15 to 25 feet). The Osgood Index (ratio of mean depth to square root of surface area) for the reservoir is 0.12, indicating relatively frequent mixing and infrequent stratification (Cooke et al., 2005). Even regular turnover, however, does not necessarily prevent cyanobacteria blooms. There is a critical depth and critical turbulence for any basin which tends to suppress cyanobacteria by disruption of buoyancy regulation (Huisman et al., 1999; Huisman et al., 2004). A critical depth estimate for the reservoir would entail hydrodynamic modeling and detailed calculation of light attenuation. Nevertheless, it is reasonable to assume that the critical depth is greater than the actual depth of the reservoir even at full stage elevation. Natural or mechanically induced mixing cannot be claimed at this time as a potential control for cyanobacteria blooms without supporting models.

Although thermal stratification may not be necessary for blooms to occur (Huisman et al., 1999), onset of thermal stratification can be rapid and decisively stimulate blooms. Data from C.W. Bill Young Reservoir (Lithia, Florida) demonstrates this dynamic. Vertical profiler data[1] reveal that onset of intensified thermal stratification can occur within a week and initiate a cyanobacteria bloom (Figure 11, Figure 12, and Figure 13). Note that a "super-epilimnion" formed over a well-established epilimnion. C.W. Bill Young water is tea colored with a Secchi disk depth of one to two meters in the period depicted herein. Thus, photic zone depth is likely no more than three to six meters. A destratification aeration system was turned on when it became clear that a cyanobacteria bloom was established. Destruction of the bloom by mixing cyanobacteria out of the light followed. Reservoir average depth was approximately 15 meters at the time. Empirically established by bloom destruction, C.W. Bill Young Reservoir depth at the time of bloom initiation was greater than the critical depth.

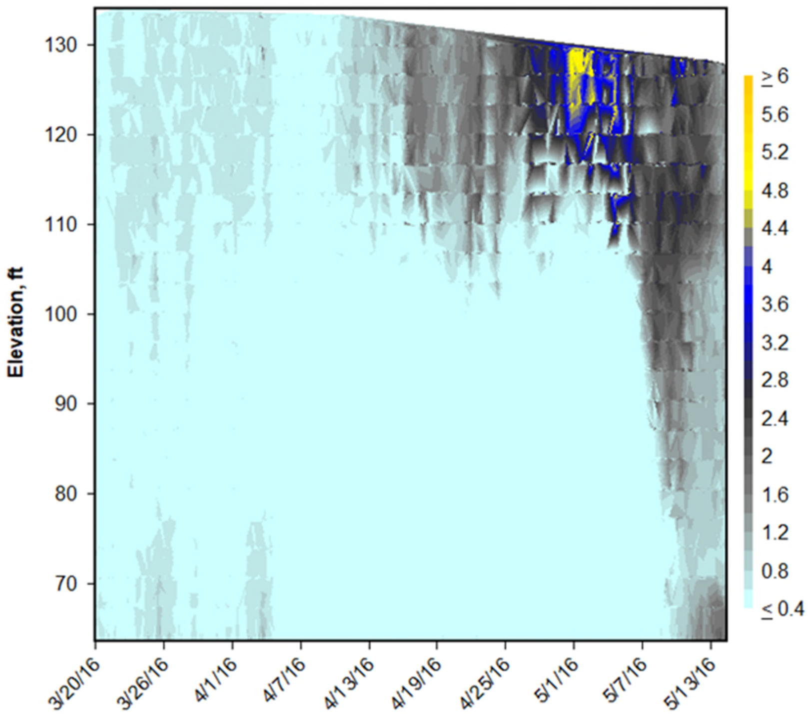
The key observation from C.W. Bill Young from the perspective of C-43 WBSR algal management is that intense thermal stratification and subsequent cyanobacteria bloom occurred in the upper 15 feet of a well-mixed (isothermal) water column. Similar hydrodynamic conditions would likely set up in the C-43 WBSR. If so, hydrodynamic control of cyanobacteria blooms is a concept of limited application to C-43 WBSR. In-basin nutrient control is therefore the correct strategy to control cyanobacteria blooms.



Note: Thermal stratification was disrupted by high winds on May 2 and then by destratification aeration on May 6. Temperature units °C.

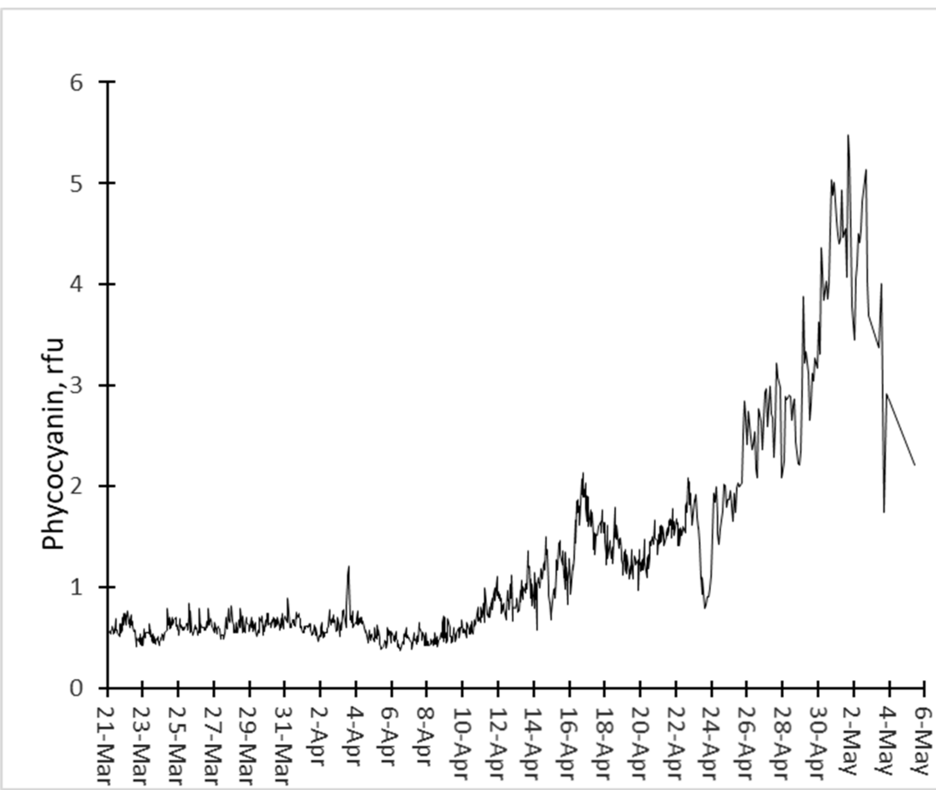
Figure 11. Formation of a Super-epilimnion in C.W. Bill Young Reservoir, Lithia Florida

[1] EXO2, 1 meter intervals every two hours.



Note: Phycocyanin units as rfu.

Figure 12. Formation of an Incipient Super-epilimnion Cyanobacteria Bloom in C.W. Bill Young Reservoir



Note disruption caused by high winds May 2 and aeration initiation May 6.

Figure 13. Cyanobacteria Growth at 1 m Depth During Period in Figure 11 and Figure 12

8.2 Nutrient Management of Algae with Alum

The objective of the inline alum treatment system is to position SFWMD to manage algae growth in the C-43 WBSR. The emphasis on nutrient management must concentrate on phosphorus for both fundamental and practical reasons. Fundamentally, whatever the biological availability of nitrogen may be, there are non-heterocyst cyanobacteria that will fix nitrogen to the extent possible with available of phosphorus and light. Practically, there will be some removal of nitrogen through the flocculation intended for phosphorus removal.

8.2.1 Estimating Aluminum Toxicity for Low Doses

Phosphorus can be effectively managed in the basin with ultra-low dosing methods. Geochemical augmentation is a method of alum addition that employs soluble doses (non-flocculating) that maintain total aluminum concentrations below the criterion continuous concentration (CCC), otherwise known at the chronic toxicity threshold (USEPA, 2018).

The USEPA CCC is set by a most sensitive receptor model for which alum toxicity depends on pH, dissolved organic carbon (DOC), and hardness. The model is available online. Taking pH to be 7.5, DOC to be 10 mg/L, and hardness to be 45 mg/L as $CaCO_3$, the CCC in the C-43 WBSR would be 870 µg/L. The CCC is calculated from the full chronic value (FCV), which is calculated from the four most sensitive receptor organisms per methods described by USEPA (2018). If the genus *Salmo* (salmon) and *Salvelinius* (brook trout), neither of which can live in regional waters, were removed from consideration the next four most sensitive genera would give FCV of 3,056 µg/L and CCC of 3,100 µg/L (Table 24). It may not be necessary to modify the CCC to meet local conditions, but it is useful for consideration of the margin of ecological safety of geochemical augmentation.

Table 22. Toxicity Model Results

Normalization Chemistry	
pH:	7.5
Total Hardness:	50
DOC:	10

All concentrations reported are µg/L total Aluminum

FAV	6283
CMC	3100
CCC	870

Note: Snip from summary sheet of USEPA model. FAV is final aquatic value (acute toxicity) and CMC is criterion maximum concentration.

Table 23. Receptor Organism Ranking Model ResultsTable 23

Chronic Ranked GMCV

Rank		GMCV	Genus	
13		86,064	Aeolosoma	Invert
12	>	28,492	Rana	Amphib - Other Data
11		21,393	Chironomus	Invert
10		14,848	Brachionus	Invert
9		13,085	Lymnaea	Mollusk
8		6,418	Pimephales	Fish
7		5,820	Hyalella	Invert
6		4,957	Ceriodaphnia	Invert
5		4,305	Lampsilis	Mollusk
4		4,134	Daphnia	Invert
3		3,579	Danio	Fish
2		1,702	Salvelinus	Fish
1		1,158	Salmo	Fish

Note: Snip from model of Table 22. GMCV is genus mean chronic value.

Table 24. Recalculated CCC with *Salmo* and *Salvelinus* Removed from Receptor Species

N	Rank	Genus	GMCV	ln(GMCV)	$\ln(GMCV)^2$	P=R/(N+1)	sqrt(P)
11	4	*Hyallela*	5,820	8.67	75.15	0.333	0.577
	3	*Lampsilis*	4,305	8.37	70.02	0.250	0.500
	2	*Daphnia*	4,134	8.33	69.34	0.167	0.408
	1	*Danio*	3,579	8.18	66.96	0.083	0.289
			Sum:	33.55	281.5	0.833	1.77
S^2 =	2.70	**S = Slope**					
L =	7.657	**L = X-axis intercept**					
A =	8.025	**A = LnFCV**					
		P = cumulative probability					
FCV =	**3056**	µg/L total aluminum					
CCC	**3100**	total aluminum rounded to two significant figures					

For a TP value of 160 µg/L (a conservative estimate of the expected inflow TP), the CCC has an Al:P mass ratio of 5.4:1, which is a molar ratio of 6.2:1.

8.2.2 A Recent Reservoir Example

Recent jar testing for Clayton County Water Authority (CCWA) in Georgia provides insight into molar ratios and phosphorus removal. Results are presented for polyaluminum chloride tested on wetland effluent (DOC of 7.0 mg/L, pH of 7.1, hardness of 66 mg/L, and CCC of 690 µg/L). Results suggest that given low concentrations and substantial competition for alum from DOC, phosphorus removal is an exponential function of the molar ratio while at a 6:1 molar ratio total aluminum concentration is only 7% of the CCC (57 µg/L). Thus, reaction of alum with phosphate and DOC water are a strong buffer against exceedance of CCC in dosing. Alum does not accumulate, rather it depletes.

Jar test results demonstrate that Al:P molar ratios near 4:1 are likely to reduce TP by 50% (Figure 14). Removal of TP has strong functional ties to turbidity removal (Figure 15). Turbidity removal is a linear function of the Al:P molar dose (Figure 16). These results suggest that Al:TP ratios of 1:1 to 3:1 would be sufficient to substantially reduce TP of inflow without approaching the CCC threshold.

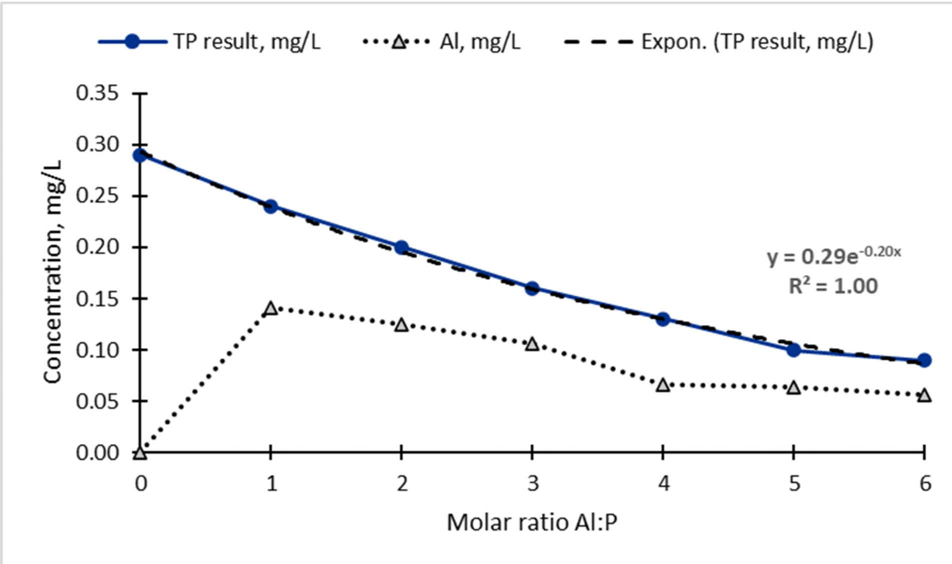


Figure 14. Jar Test Results

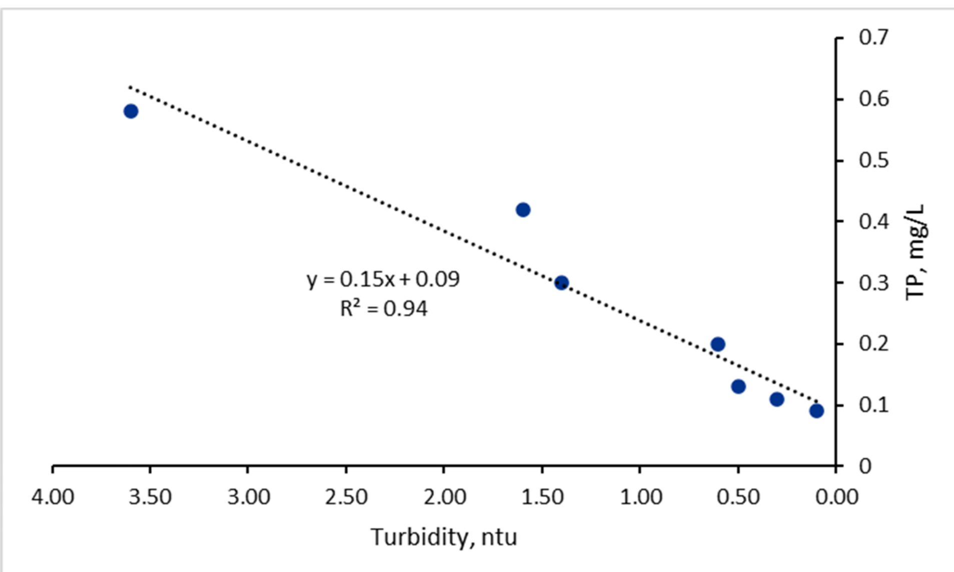


Figure 15. TP Removal as a Function of Turbidity Removal

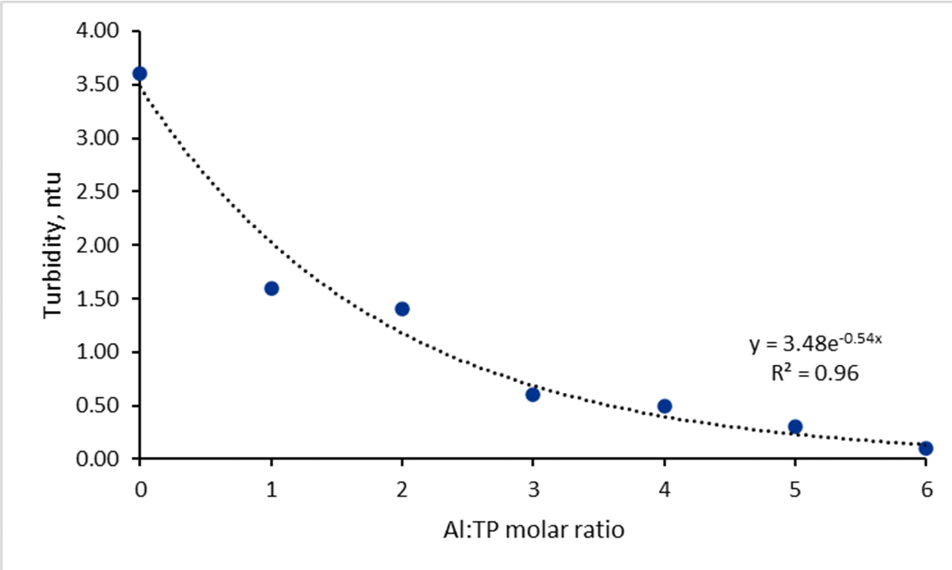


Figure 16. Turbidity Removal by Dose

Jar tests cannot capture cumulative effects of long-term dosing. CCWA commissioned the jar tests because it manages three drinking water reservoirs that receive tertiary effluent. A 267-acre treatment wetland conditions water before discharge into the first two reservoirs (Shamrock and Blalock) before water flows downstream to Hooper Reservoir. Shamrock and Blalock reservoirs are equipped with hypolimnetic oxygenation systems (installed 2019) that suppress internal nutrient loading and aluminum chlorohydrate (ACH) injection systems to scavenge inflow TP from the water column. Hooper Reservoir has a destratification aeration system (installed 2019) and an ACH dosing system. Dosing systems pump ACH into bubble plumes for dispersion. ACH dosing began in January 2020. Combined wastewater inflow into the reservoirs is approximately 16 MGD. Blalock Reservoir's deepest depth is approximately 27 feet (area 260 acres), Shamrock 24 feet (area 60 acres), and Hooper 8 feet (114 acres).

The cumulative effect of ACH injection is evident in the reservoirs as a downward drift in TP concentrations at rates from 0.5 to 1.4 µg/L/day (Figure 17, Figure 18, Figure 19). Total aluminum concentrations never rose above 110 µg/L, which is about 10% to 20% of the CCC depending on average reservoir pH on given day.

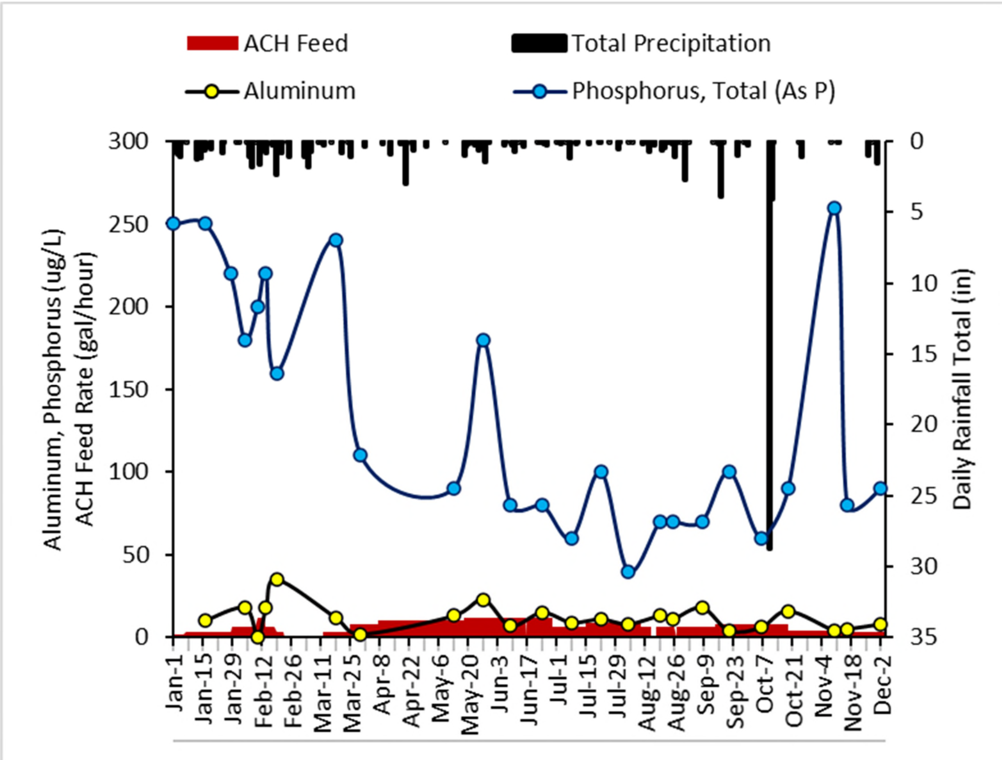


Figure 17. **Shamrock Reservoir TP, Al, ACH Feed Rate, and Precipitation**

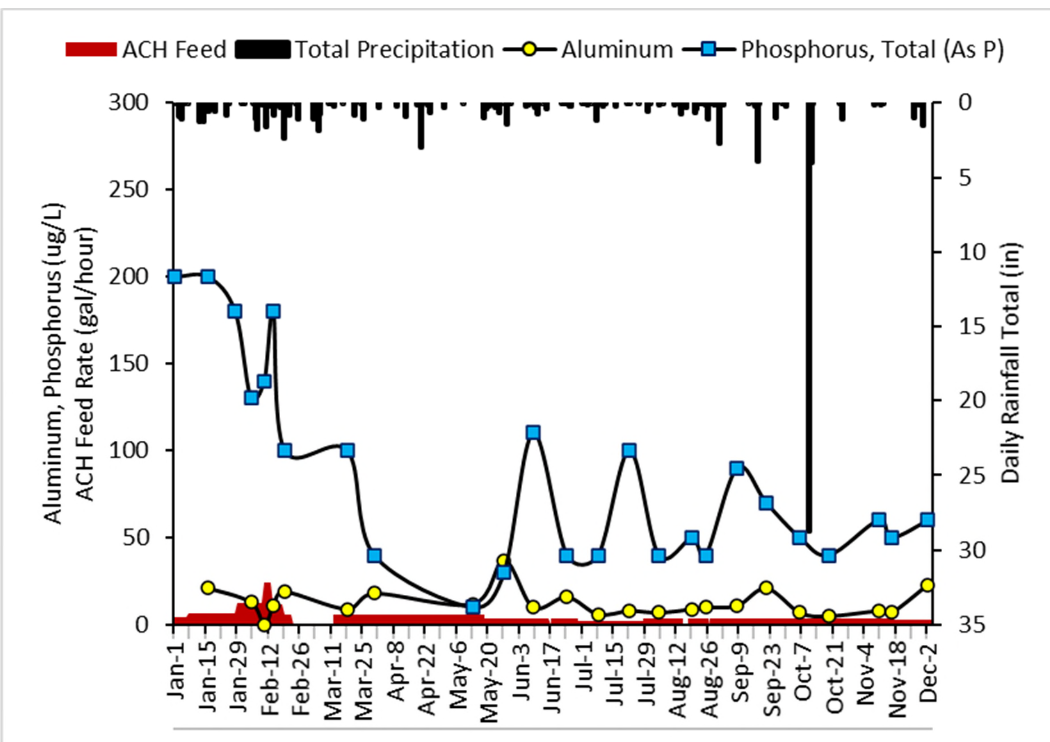


Figure 18. **Blalock Reservoir TP, Al, ACH Feed Rate and Precipitation**

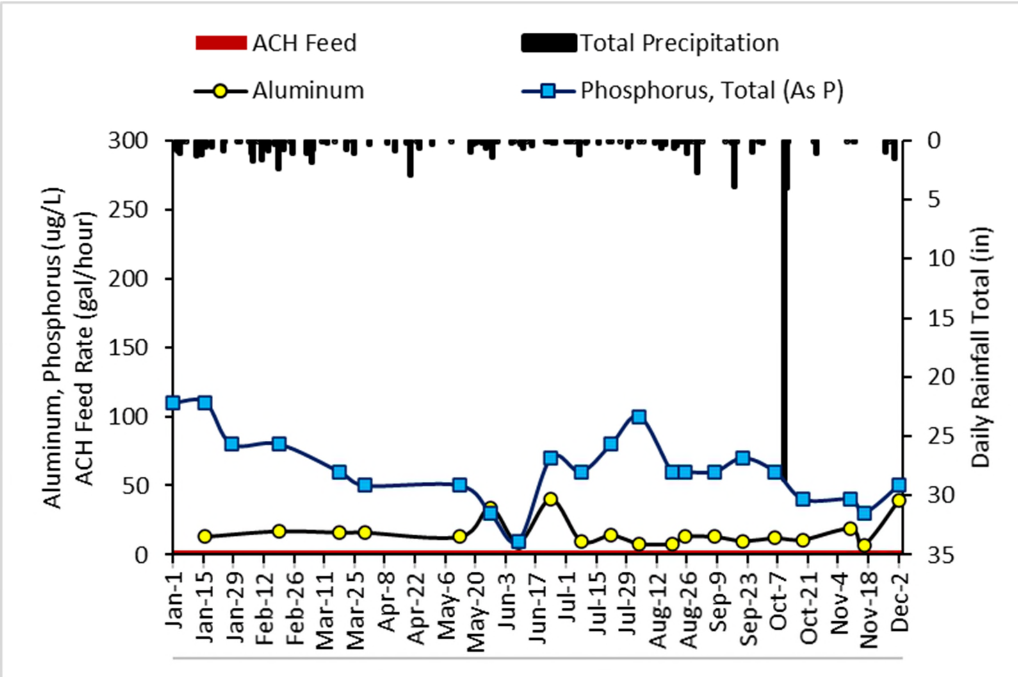


Figure 19. Hooper Reservoir TP, Al, ACH Feed Rate and Precipitation

Evidence from the CCWA reservoirs indicates that TP concentrations near 50 µg/L are attainable with geochemical augmentation dosing methods. This result has also been observed in stormwater ponds with continuous alum injection (Austin et al., 2017; Osgood, 2012). In a treatment wetland study observing TP removal rates by alum dose, there was no significant difference in TP removal rates between sub-flocculating doses (Austin et al., 2018). A significant increase in TP removal rates occurred at a flocculating dose. A dose-response study has not been done for geochemical augmentation in basins.

The C-43 WBSR does not have a specific TP management target. However, there will be a range of TP that both can be maintained with alum injection and will tend to suppress cyanobacteria blooms. The example of the CCWA reservoirs demonstrates that alum can lower the trophic state of a reservoir from hypereutrophic to low eutrophic/high mesotrophic while keeping total alum concentrations well below the USEPA CCC threshold.

Given this apparently large safety margin, there probably is a wide range of candidate dosing rates. The preponderance of evidence is that a 1:1 to 4:1 Al:P molar ratio dosing rate is a reasonable range for management of TP sufficient to lower the trophic state of the reservoir.

8.2.3 Ecological Safety of Alum

The 2018 USEPA Aquatic Life Ambient Water Quality for Aluminum establishes a reliable standard for assessing the ecological safety of alum addition to freshwater. These criteria supersede prior criteria (USEPA, 1988) that did not consider the effects of water chemistry on aluminum toxicity. In comparison to current criteria, prior criteria were extraordinarily conservative, setting a freshwater chronic toxicity criterion of 87 µg/L total aluminum across a pH range of 6.5 to 9.0 regardless of DOC or hardness. In comparison, for pH of 7.0, DOC 10 mg/L, and hardness of 40 mg/L, the of current CCC is 660 µg/L. There were insufficient data available for the prior criterion to consider the effects of water chemistry even though it was recognized at the time that these effects could substantially attenuate aluminum toxicity.

It may be true that much concern over the potential toxicity of aluminum has its origins in outdated ambient water criteria. Nevertheless, it does not necessarily follow that current criteria alone obviate concern. Other lines of evidence merit attention.

Pettersson et al. (1988) observe that aluminum uptake in *Anabaena cylindrica*, a cyanobacterium, induces phosphorus starvation. Aluminum binds to adenosine triphosphate (ATP) by competing with Mg^{2+}. The Al^{3+}-ATP complex is not available for cellular metabolism. In general, cyanobacteria have a significantly higher metal demand than eukaryotic phytoplankton, which extends to aluminum uptake. Marine cyanobacteria growth has been observed to be stimulated by aluminum enrichment (Liu et al., 2018) and inhibited by it (Liu et al., 2020). Geochemical augmentation of a small Kansas lake caused cyanobacteria populations to crash with only moderate effect on primary productivity (Austin et al., 2017). For cyanobacteria, the picture of aluminum toxicity is mixed. There may be a beneficial effect of alum geoaugmentation if it suppresses cyanobacteria growth, but there is insufficient evidence to assert this as a management strategy.

Traditional alum application to lakes and reservoirs entails barge application and creation of sweep floc in the wake of the barge path. Although the alum application rate to the C-43 WBSR is substantially less, a brief summary of ecological safety of traditional methods is informative. In a broad overview, Cooke at el. (2005) conclude that the body of evidence falls decisively in favor of ecological safety. The aluminum hydroxide floc stabilizes within two to four months, which removes intermediate to long-term concerns of alum resuspension (Egemose et al., 2009). There are impacts, however, to traditional alum application that merit attention.

Macroinvertebrate density in floc-covered sediments has been shown to significantly decline in the year following whole-lake alum application (Steinman and Ogdahl, 2008). Sediment cores following whole lake treatment have surficial sediment Al:P molar ratios greater than 100:1 (Dugopolski et al., 2008). It is possible that the alum concentration within the pore volume of these sediments exceeds the CCC. Alum treatment of lake inflows uses a settling basin that discharges water rich in dissolved aluminum to lake waters. In a study of adverse ecological effects of this method, Pilgrim and Brezonik (2005) found no adverse effects in the lake, but nearly complete elimination of macroinvertebrates in the settling pond. The lake received maximum total alum concentrations of 458 µg/L, which are well below a likely CCC in a moderately hard, eutrophic lake. In this study, the Al settling rate in the lake was observed to be 57 meters per year.

The overall picture is reasonably clear from the literature: a fresh layer for aluminum hydroxide floc is poor macroinvertebrate habitat, but Al concentrations meeting the CCC have no adverse effect on lake ecology. Consequently, potential ecological impacts to C-43 WBSR ecology are dose-dependent. A flocculating dose may have an adverse impact to sediment invertebrates within a small zone at the inlet at higher alum doses. Otherwise, adverse ecological impacts are not expected.

A site-specific issue of concern involves bioaccumulation of aluminum in apple snails (Sharfstein and Pierce, in preparation). In a wetland receiving water with a total aluminum content of 240 µg/L, apple snails accumulated average soft tissue loads of 812 milligrams per kilogram, which potentially may expose the snail kite to excessive aluminum. Snails were unaffected. Although higher alum concentrations may occur in parts of C-43 WBSR, the habitat structure of the reservoir is very different from the wetland. The lack of emergent vegetation leaves only the reservoir perimeter as a potentially suitable place for apple snails to lay eggs. Consequently, poor breeding habitat will constrain apple snail populations. Additionally, snail kite predation behavior will restrict capture of apple snails to the reservoir perimeter to depths of approximately six inches, offering limited opportunity to consume aluminum-enriched snails. Prevention of aluminum exposure to the snail kite may entail keeping the C-43 WBSR at a depth that will prevent the short-term establishment of emergent vegetation and mud flats, assuming that aluminum exposure is found to be a significant concern.

Dose-dependency of adverse ecological impacts offers a high degree of operational control. Because a flocculating dose of alum is not required to manage TP in the C-43 WBSR, dosing protocol would be constrained by two factors: (1) CCC, or (2) discovery of site-specific impacts at a given dosing rate. Consequently, the ecological risk is low and manageable.

8.3 Other Limnological Considerations

Internal nutrient loading is a key driver of cyanobacteria harmful algal blooms (Cyano-HAB) through anoxic sediment conditions and resuspension of sediments, which are both potential drivers of Cyano-HAB in the C-43 WBSR. Both phosphorus and nitrogen can be limiting to Cyano-HAB (Paerl et al., 2020). Geochemical augmentation with alum potentially can mitigate these drivers.

Shallow depths do not necessarily prevent anoxia in lake sediments. A large, shallow lake with a large fetch, such as Lake Okeechobee, may experience intermittent thermal stratification, but not long enough to induce anoxia at the sediment surface (Rodusky et al., 2005). On the other end, stormwater ponds which are typically less than three meters deep may thermally stratify long enough to become anoxic and release phosphorus from sediments (Palmer-Felgate et al., 2011; Taguchi et al., 2020). Physical limnology factors such as fetch and degree of wind-sheltering are important. Sediment oxygen demand (SOD) is a master forcing function of a tendency toward anoxia within the larger hydrodynamic context. Minimizing SOD is therefore desirable.

SOD is a function of algal loading of sediments, which is function of nutrient enrichment. An empirical functional relationship of SOD as a function of chlorophyll *a* concentration in the spring (just prior to periods of potential thermal stratification) is provided by Walker (1985) in an empirical equation for natural lakes (Equation 3).

Equation 3. $SOD\ (mg/m^2) = Chl\text{-}a^{0.45}$

Note that Equation 3 is not dimensionally consistent. Jacobs Engineering (unpublished data) has found that Walker equation predictions are fairly close to operational hypolimnetic oxygen demand in reservoirs with hypolimnetic (pure) oxygen systems. Equation 3 is probably best viewed as a semi-quantitative transfer function between spring primary productivity and SOD. Lowering spring chlorophyll *a* clearly reduces the potential for a strong SOD that would drive anoxia during transient summer thermal stratification events. Thus, alum sequestration of phosphate has the potential to suppress oxygen depletion rates.

Depletion of DO was observed in the C-43 WBSR Test Cell Project. In a geochemical augmentation project for a small Kansas lake with a maximum depth of eight feet, the post-dosing DO dynamic was elimination of anoxia near the sediment surface (Austin et al., 2017). Note that the lake was destratified and subject to sustained Cyano-HABs which were eliminated by alum geochemical augmentation. If phosphorus is the primary driver of primary productivity in the C-43 WBSR, then permanent sequestration of inflow PO_4-P will curtail the tendency for an internal loading dynamic to occur. The effect of alum geochemical augmentation on sediment resuspension has not been studied. Presumably, alum-bound phosphorus will not be bioavailable in suspended sediment particles.

The effect of alum geochemical augmentation on nitrogen dynamics requires more research to characterize sufficiently to inform operations. In an investigation of alum nanoparticle addition to activated sludge, inhibition of denitrification substantially reduced TN removal efficiency (Chen et al., 2012). This mechanism, if widespread, may not be relevant to the C-43 WBSR. Of greater interest is dissolved organic nitrogen (DON). Alum has been demonstrated to preferentially bind DON compounds with molecular weights greater than 10 kiloDaltons (Dwyer et al., 2009). Substantial removal of color accompanies DON removal because alum binds preferentially with large DOC compounds, which include color. Bacterial respiration transforms bioavailable DON (BDON) to recalcitrant DON (RDON) which does not stimulate primary productivity (Bronk et al., 2007). There are tens of thousands of DON compounds present in C-43 WBSR source waters. The shift from BDON to RDON involves a small percentage of those compounds (Osborne et al., 2013).

If the turbidity reductions observed in jar tests (Figure 16) include DON-rich DOC, then the induced sedimentation of DOC would tend to remove BDON from the water column. Weathering of DON in sediments would likely transform BDON to RDON. This mechanism of DON inactivation, however, is merely plausible based on known mechanisms. Research is required to support or reject this hypothesis. If nitrogen limitation is an important driver of Cyan-HAB formation C-43 WBSR, then this this hypothesis merits scientific attention.

8.4 Conclusions and Recommendations

Dosing of alum at an Al:P ratio of 1:1 to 4:1 will remove a large fraction of inflow TP and turbidity without reaching the chronic toxicity threshold for aluminum set by USEPA. It is likely that significant DON removal will be tied to turbidity attenuation. Flow proportioning of alum dosing will allow operational investigation of the optimal Al:P ratio. Currently, there is not sufficient information to favor any one of the common formulations of alum over the other (alum, polyaluminum chloride, or aluminum chlorohydrate) for use in the C-43 WBSR.

Geochemical augmentation could be characterized as plume dispersion with reaction. Hydrodynamic models could be constructed with a conservative tracer (virtual or real) and calibrated to the C-43 WBSR to provide a physical representation of inflow dynamics. A combination of jar tests, sediment sampling, sediment traps, water quality samples, and continuous sensors would provide data to adapt the model to depletion rates for aluminum, phosphorus, and DON. Devising and executing an appropriate monitoring program is strongly encouraged.

As algae management is the focus within the C-43 WBSR, characterization of phytoplankton and zooplankton samples of river and reservoir water is essential. Additionally, phycocyanin and chlorophyll *a* data are important.

9.0 General Conclusions

The proposed inline alum treatment system is intended to provide SFWMD with direct management control over the potential for algal blooms within the C-43 WBSR. This approach was introduced in the C-43 WQFS (J-Tech, 2020) as a cost-effective method of reservoir water quality management. The WQFS recommended further evaluation as an operational control over algal management in the reservoir. Follow up correspondence, team experience, and literature review determined that alum treatment poses no adverse ecological effect and warrants continued evaluation as a WQC technology. Cooke et al. (2005) concluded that the body of evidence falls decisively in favor of ecological safety for alum application. To reduce phosphorus levels, SJRWMD has applied alum to re-flooded fields, injected liquid alum into water, and spread residual alum on fields. In all consultations and risk assessments, the U.S. Fish and Wildlife Service has determined that the use of alum is not likely to adversely affect protected species (H. Rauschenberger, pers. commun, January 14, 2021). Reports issued by SJRWMD over 20 years ago provide guidance on ecologically safe alum concentrations (Gensemer and Playle, 1998) now superseded by the U.S. Environmental Protection Agency aluminum toxicity criterion (2018), and provide summaries of literature and lake application case histories (Water & Air Research, 1999).

Given the size of the application in terms of flow rate, area, and use of chemicals, this TM was prepared to address technical and management aspects of the proposed approach. Based upon the summary of information provided, the following conclusions are offered:

1. The practice of alum treatment for water quality improvement has been implemented nationwide since the 1970s, and in Florida since the 1980s. Case studies document significant reduction in TN, TP, and TSS. Significant reductions in pH were not observed. No toxic responses of aquatic biota were reported. Some temporary impacts to benthic macroinvertebrate community composition were noted in several case studies but this was assigned to changes in macroinvertebrate substrate suitability. Subsequent monitoring indicated a return to typical community structure.

2. Dose determination performed for this project using dynamic modeling indicated that a relatively low dose (0.6 mg/L alum) would be sufficient to achieve a reservoir concentration of 0.08 mg/L TP and 1.23 mg/L TN. A lower dose of 0.1 mg/L alum was expected to yield a TP concentration of 0.1 mg/L, representing a possible savings in alum cost and a reduction in sludge production.
3. Sludge production would be significant but would be widely dispersed across the two reservoir cells, with an estimated annual accumulation rate of approximately 0.33 cm/yr in Cell 1 and approximately half that in Cell 2.
4. The need to control the potential for microfloc was identified as an operational and management focus. The production of microfloc results from doses that are less than what may be indicated from conventional jar testing results and may require additional time for settling. Offline treatment systems, such as those investigated during the WQFS (e.g., constructed wetlands), would benefit the project by polishing suspended microfloc in the reservoir discharge.
5. Conceptual plan review identified an area on the north side of the S-470 Pump Station that was suitably sized for a tank farm to store enough alum for a two-week period. Alum would be dispensed into the inlet forebays of the four pumps through gravity flow from five 13,800-gallon storage tanks. During reservoir construction, conduits were installed to reserve space for alum conveyance through pump station walls.
6. The conceptual capital cost for the inline alum system was estimated between \$3.55 million and \$6.33 million. Consistent with the conceptual level of design, these estimates are Class 5 with an accuracy range of –30%/+50% and are subject to change.
7. Conceptual annual O&M costs were estimated between \$400,000 and \$700,000, and include the cost and delivery of alum, operational maintenance, mechanical replacement, and site upkeep and reporting.
8. Characteristics of alum composition and effects on materials were reviewed for impacts to the reservoir and pump station. No adverse effects were identified for the proposed alum concentration.
9. Operational requirements were reviewed. There would be a need for daily, weekly, and monthly operational activities of alum storage and dosing system maintenance.
10. Available recent experience with other reservoir alum applications was reviewed and results indicate that the potential for cyanobacteria blooms does exist in the C-43 WBSR; therefore, some degree of control is warranted, such as through alum treatment. Comparable performance with other current reservoir alum applications was reviewed and found to be effective.
11. The ecological safety of the alum application was reviewed in light of current aluminum concentration criteria, and all proposed concentrations are significantly below USEPA standards. No adverse effects are expected at the proposed doses. Hydraulic modeling of the reservoir is recommended to confirm solids accumulation and location. Monitoring is recommended to track phytoplankton response, nutrient concentrations, and aluminum concentrations.

9.1 Area of Focused Study

During the review of the Draft Inline Alum Treatment Conceptual Design, SFWMD's Technical Review Board issued the following comments and information needs to take forward into the final design phase:

- Evaluate the use of stainless steel pipes instead of the epoxy coated pipes for corrosion issues and material lifespan.
- Evaluate the residuals deposition in more detail.
- Further evaluate potential pH changes and any impacts on the soil cement. If there are impacts, CCW can be added to the soil cement.
- Coordinate with DEP on the additional regulatory requirements for the inline alum system.
- Develop an O&M plan to establish seasonal alum dosing concentrations.

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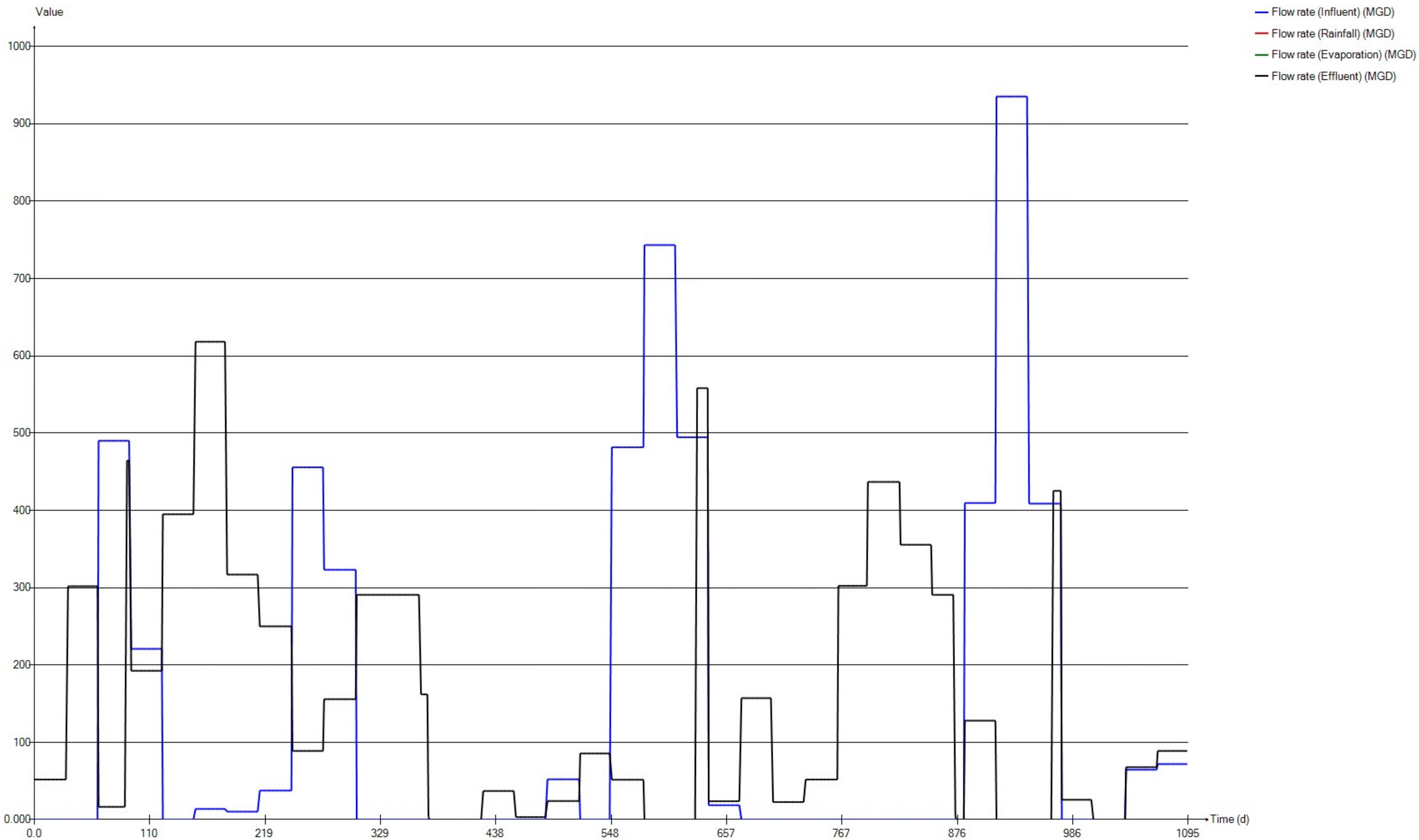
Attachment 1. Sumo Fractionation Parameters

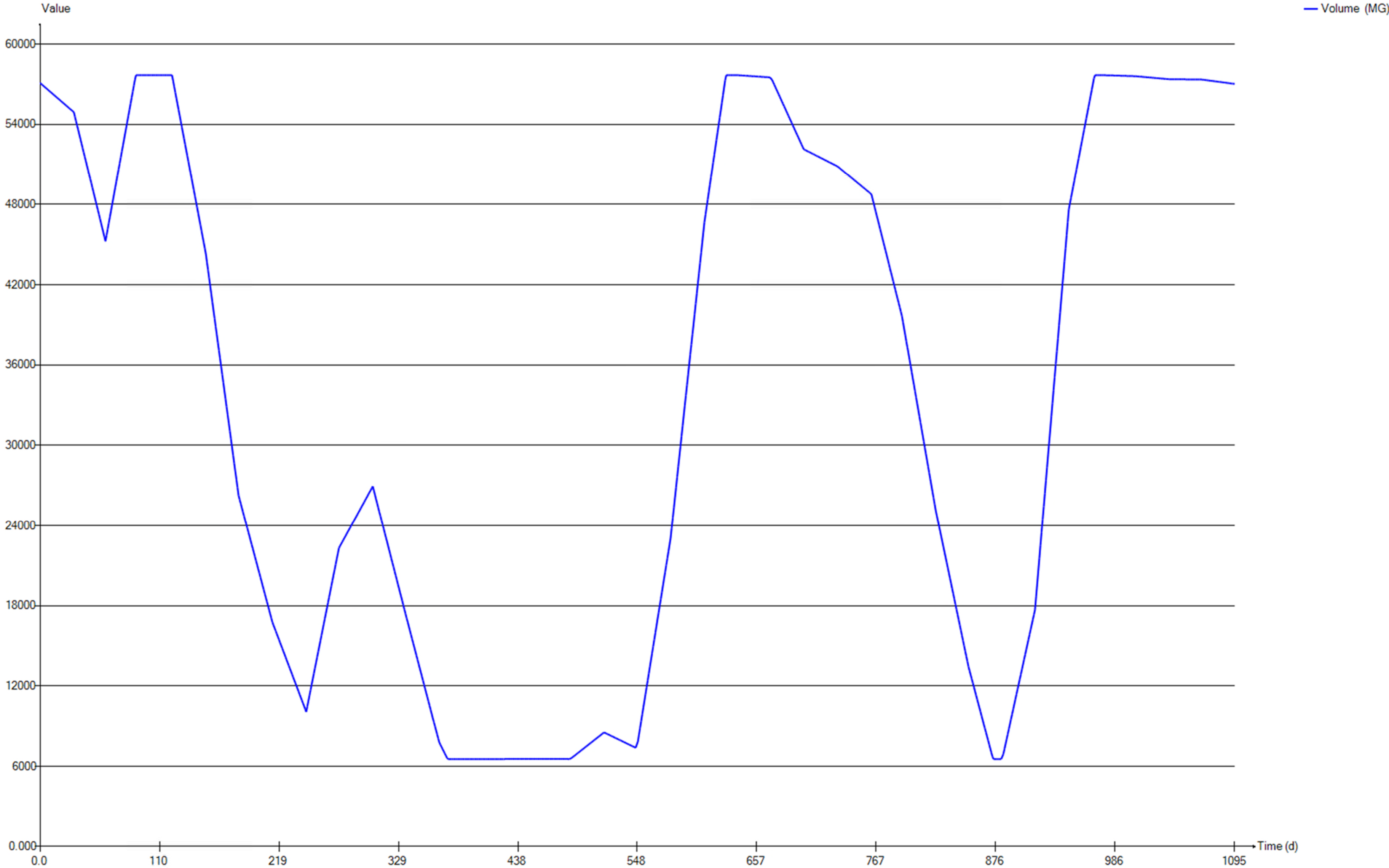
	Composition	Codelocation(Integrated)		
Symbol	Name	Expression	Unit	Decimals
SC_{COD}	Filtered chemical oxygen demand	$fr_{SCCOD,TCOD}*T_{COD}$	$g\ COD.m^{-3}$	1
C_{COD}	Colloidal chemical oxygen demand	$SC_{COD}-S_{COD}$	$g\ COD.m^{-3}$	1
S_{COD}	Filtered flocculated chemical oxygen demand	$fr_{SCOD,TCOD}*T_{COD}$	$g\ COD.m^{-3}$	1
X_{INORG}	Inorganics in influent and biomass	$X_{VSS}/fr_{VSS,TSS}-(X_{VSS}+i_{TSS,PP}*X_{PP}+X_{Me,TSS}+X_{precip})$	$g\ TSS.m^{-3}$	1
S_{VFA}	Volatile fatty acids (VFA)	$fr_{VFA,SCCOD}*SC_{COD}$	$g\ COD.m^{-3}$	1
S_U	Soluble unbiodegradable organics	$fr_{SU,SCCOD}*SC_{COD}$	$g\ COD.m^{-3}$	1
S_B	Readily biodegradable substrate (non-VFA)	$S_{COD} - S_U - S_{VFA}$	$g\ COD.m^{-3}$	1
X_{OHO}	Ordinary heterotrophic organisms (OHO)	$fr_{XOHO,TCOD}*T_{COD}$	$g\ COD.m^{-3}$	1
X_E	Endogenous decay products	$fr_{XE,XOHO}*X_{OHO}$	$g\ COD.m^{-3}$	1
C_U	Colloidal unbiodegradable organics	$fr_{CU,CCOD}*C_{COD}$	$g\ COD.m^{-3}$	1
C_B	Colloidal biodegradable substrate	$C_{COD}-C_U$	$g\ COD.m^{-3}$	1
X_U	Particulate unbiodegradable organics	$fr_{XU,TCOD} * T_{COD}$	$g\ COD.m^{-3}$	1
X_B	Slowly biodegradable substrate	$T_{COD} - (SC_{COD} + X_U+X_E+X_{E,ana}+X_{BIO}+X_{PHA}+X_{GLY})$	$g\ COD.m^{-3}$	1
S_{NHx}	Total ammonia (NH_x)	$fr_{SNHx,TKN}*T_{KN}$	$g\ N.m^{-3}$	1
S_{PO4}	Orthophosphate (PO_4)	$fr_{SPO4,TP}*T_P$	$g\ P.m^{-3}$	1
$X_{N,BIO}$	Particulate biodegradable organic N in biomass	$i_{N,BIO}*X_{BIO}+i_{N,XE}*(X_E+X_{E,ana})$	$g\ N.m^{-3}$	1
$S_{N,B}$	Soluble biodegradable organic N (from S_B)	$fr_{N,SB}*S_B$	$g\ N.m^{-3}$	1
$X_{N,B}$	Particulate biodegradable organic N (from X_B)	$T_{KN}-(S_{NHx}+X_{N,BIO}+S_{N,B}+i_{N,SU}*S_U+i_{N,CU}*C_U+i_{N,CB}*C_B+X_{N,U})$	$g\ N.m^{-3}$	1
$X_{N,U}$	Particulate unbiodegradable organic N	$fr_{N,XU}*X_U$	$g\ N.m^{-3}$	1
$X_{P,BIO}$	Particulate biodegradable organic P in biomass	$i_{P,BIO}*(X_{BIO}+X_E+X_{E,ana})$	$g\ P.m^{-3}$	1
$S_{P,B}$	Soluble biodegradable organic P (from S_B)	$fr_{P,SB}*S_B$	$g\ P.m^{-3}$	1
$X_{P,B}$	Particulate biodegradable organic P (from X_B)	$T_P-(S_{PO4}+X_{PP}+X_{P,BIO}+S_{P,B}+i_{P,SU}*S_U+i_{P,CU}*C_U+i_{P,CB}*C_B+X_{P,U}+X_{HFO,P})$	$g\ P.m^{-3}$	1
$X_{P,U}$	Particulate unbiodegradable organic P	$fr_{P,XU}*X_U$	$g\ P.m^{-3}$	1
$X_{HFO,H}$	Active hydrous ferric oxide, high surface (HFO,H)	$G/(K_G+G)*S_{Fe3}$	$g\ Fe.m^{-3}$	1
$X_{HFO,L}$	Active hydrous ferric oxide, low surface (HFO,L)	$K_G/(K_G+G)*S_{Fe3}$	$g\ Fe.m^{-3}$	1

Attachment 1. Screen View from Sumo Documentation detailing Fractionation Parameters

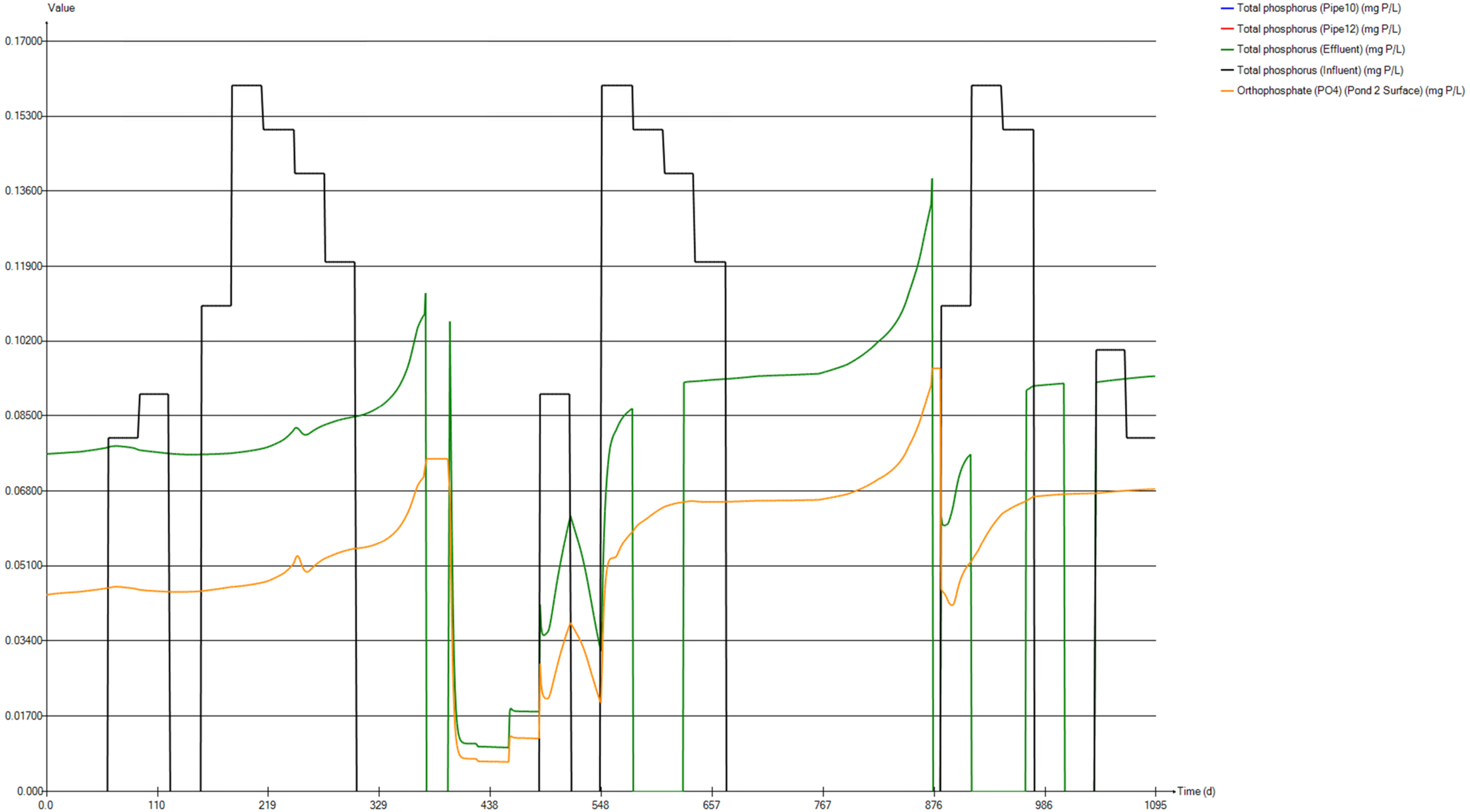
Attachment 2. Three-year Dynamic Simulation SUMO Model Outputs



Attachment 2-A. Three-year Dynamic Simulation SUMO Output – Flows



Attachment 2-B. Three-year Dynamic Simulation SUMO Output – Total Volume



Attachment 2-C. Three-year Dynamic Simulation SUMO Output – Effluent Phosphorus