CURRENT RESEARCH AND TRENDS IN ALUM TREATMENT OF STORMWATER RUNOFF

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ABSTRACT

Alum treatment of runoff has been used as a stormwater retrofit option for the past 20 years. This technology has evolved from the initial demonstration research projects to a viable retrofit option for urban areas. A considerable amount of data has now been collected on the water quality and ecological impacts of alum treatment systems. Alum treatment of stormwater consistently provides removal efficiencies of 85-95% for total phosphorus, >95% for total suspended solids (TSS), 35-70% for total nitrogen, 60-90% for metals, and 90->99% for total and fecal coliform bacteria.

Although only positive chemical and ecological impacts have been reported in waterbodies receiving alum floc, current state policies require collection and disposal of the generated floc, and this issue has received considerable attention in recent years. A variety of floc collection and disposal techniques have been evaluated, including settling ponds, in-lake floc traps, underground vaults, and CDS units. Current floc disposal techniques include disposal to sanitary sewer systems and drying ponds. Chemical characterization of floc suggests that the material can be used as fill or applied to soil surfaces to reduce release of phosphorus, metals, and organics under flooded conditions.

System reliability has been substantially enhanced in recent years, but commitment to long-term maintenance is a concern with many systems. However, in spite of the additional costs associated with floc disposal and maintenance, alum treatment continues to provide pollutant removal at a substantially lower unit cost ($/kg removed) than traditional treatment systems such as ponds.

INTRODUCTION

Aluminum is the most abundant metallic element in the lithosphere and the third most abundant element in the earth, comprising approximately 8% of the earth's crust (Hem, 1986). The soil represents the largest pool of aluminum at the earth's surface. The chemistry of aluminum in natural waters is quite complex. Aluminum has a high ionic charge and a small crystalline radius which combine to yield a level of reactivity which is unmatched by any other soluble metal.

Since at least Roman times, salts of aluminum have been added to drinking water and surface water to reduce turbidity and improve appearance. Aluminum compounds have been used extensively as flocculating agents in the treatment of wastewater for over 100 years. The most commonly used aluminum coagulant is aluminum sulfate,

$Al_2(SO_4)_3 \bullet nH_2O$, which is commonly referred to as alum. Liquid alum is manufactured by dissolving aluminum bauxite ore in sulfuric acid. Commercial-grade alum is a clear, viscous, light green to yellow solution which is 48.5% aluminum sulfate by weight and has a specific gravity of 1.34.

The addition of alum to water results in the production of chemical precipitates which remove pollutants by two primary mechanisms. Removal of suspended solids, algae, phosphorus, heavy metals and bacteria occurs primarily by enmeshment and adsorption onto aluminum hydroxide precipitate according to the following net reaction:

$$Al^{+3} + 6H_2O \rightarrow Al(OH)_{3(s)} + 3H_3O^{+}$$

This reaction occurs rapidly and is generally complete within 30-45 seconds. The aluminum hydroxide precipitate, $Al(OH)_3$, is a gelatinous floc which attracts and adsorbs colloidal particles onto the growing floc, thus clarifying the water.

Removal of additional dissolved phosphorus occurs as a result of direct formation of $AlPO_4$ by:

$$Al^{+3} + HnPO_4^{n-3} \rightarrow AlPO_{4(s)} + nH^{+}$$

The alum precipitate formed during coagulation of stormwater can be allowed to settle in receiving waterbodies or collected in small settling basins. Alum precipitates are exceptionally stable in sediments and do not re-dissolve due to changes in redox potential or pH under conditions normally found in surface waterbodies. Over time, the freshly precipitated floc ages into more stable complexes, eventually forming gibbsite. The solubility of dissolved aluminum in the treated water is regulated primarily by the ambient pH level. Minimum solubility for dissolved aluminum occurs in the pH range of 5.5-7.5. As long as the pH of the treated water is maintained within the range of 5.5-7.5, dissolved aluminum concentrations will be minimal. In many instances, the concentration of dissolved aluminum in the treated water will be less than the concentration in the raw untreated water due to adjustment of pH into the range of minimum solubility.

There are numerous advantages associated with the use of alum for coagulation of stormwater runoff. First, alum coagulation provides rapid, highly efficient removal of solids, phosphorus, and bacteria. Liquid alum is relatively inexpensive, resulting in low unit costs per mass of pollutant removed. Unlike iron compounds, alum does not deteriorate under long-term storage. Due to the quality of the raw materials used for manufacture of alum, liquid alum contains substantially less heavy metal contamination than other metal coagulants. Alum floc is chemically inert and is immune to dissolution from normal fluctuations in pH and redox potential in surface waterbodies. In contrast, iron floc is only inert under oxidized conditions and at relatively elevated pH levels.

In 1985, a lake restoration project was initiated at Lake Ella, a shallow 13.3 acre hypereutrophic lake in Tallahassee, Florida, which receives untreated stormwater runoff from approximately 163 acres of highly impervious urban watershed areas through 13 separate stormsewers. Initially, conventional stormwater treatment technologies, such as retention basins, exfiltration trenches and filter systems, were considered for reducing available stormwater loadings to Lake Ella in an effort to improve water quality within the lake. Since there was little available land surrounding Lake Ella that could be used for construction of traditional stormwater management facilities, and the cost of purchasing homes and businesses to acquire land for construction of these facilities was cost-prohibitive, alternate stormwater treatment methods were considered.

Chemical treatment of stormwater runoff was evaluated using various chemical coagulants, including aluminum sulfate, ferric salts and polymers. Aluminum sulfate (alum) consistently provided the highest removal efficiencies and produced the most stable floc. In view of successful jar test results on runoff samples collected from the Lake Ella watershed, the design of a prototype alum injection stormwater system was completed. Construction of the Lake Ella alum stormwater treatment system was completed in January 1987, resulting in a significant improvement in water quality.

Since the Lake Ella system, more than 50 additional alum stormwater treatment systems have either been constructed or are currently being evaluated, with most located within the State of Florida. Alum treatment of stormwater runoff has now been used as a viable stormwater treatment alternative in urban areas for over 20 years. Over that time, a large amount of information has been collected related to optimum system configuration, water chemistry, sediment accumulation and stability, construction and operation costs, comparisons with other stormwater management techniques, and floc collection and disposal (Livingston, Harper, and Herr, 1994; Harper and Herr, 1992; Harper, Herr, and Livingston, 1997, 1998a, and 1998b; Harper, 1990, 1991, 1992, 1999, and 2005).

SYSTEM CONFIGURATION

Once alum has been identified as an option for stormwater treatment, extensive laboratory testing must be performed to verify the feasibility of alum treatment and to establish process design parameters. The feasibility of alum treatment for a particular stormwater stream is typically evaluated in a series of laboratory jar tests conducted on representative runoff samples collected from the project watershed area. This laboratory testing is an essential part of the evaluation process necessary to determine design, maintenance, and operational parameters such as the optimum coagulant dose required to achieve the desired water quality goals, chemical pumping rates and pump sizes, the need for additional chemicals to buffer receiving water pH, post-treatment water quality characteristics, floc formation and settling characteristics, floc accumulation, annual chemical costs and storage requirements, ecological effects, and maintenance procedures. In addition to determining the optimum coagulant dose, jar tests can also be used to evaluate floc strength and stability, required mixing intensity and duration, and determine design criteria for floc collection systems.

In a typical alum stormwater treatment system, alum is injected into the stormwater flow on a flow-proportioned basis so that the same dose of alum is added to the stormwater flow regardless of the discharge rate. A variable speed chemical metering pump is typically used as the injection pump. The operation of the chemical injection pump is regulated by a flow meter device attached to the incoming stormwater line to be treated. Mixing of the alum and stormwater occurs as a result of turbulence in the stormsewer line. If sufficient turbulence is not available within the stormsewer line, artificial turbulence can be generated using aeration or physical stormsewer modifications.

Mechanical components for the alum stormwater treatment system, including chemical metering pumps, stormsewer flow meters, electronic controls, and an alum storage tank, are typically housed in a central facility which can be constructed as an above-ground or below-ground structure. Alum feed lines and electrical conduits are run from the central facility to each point of alum addition and flow measurement. Alum injection points can be located as far as 3000 ft or more from the central pumping facility. The capital costs of constructing an alum stormwater treatment system do not increase substantially with increasing size of the drainage basin which is treated. As a result, alum treatment has become increasingly popular in large regional treatment systems.

The largest alum stormwater treatment system is located along the Apopka-Beauclair Canal which extends between Lake Apopka and Lake Beauclair in Central Florida. This canal carries discharges from Lake Apopka, a 30,000-acre shallow hypereutrophic lake, into Lake Beauclair which forms the headwaters of the Harris Chain-of-Lakes. Inflow from the Apopka-Beauclair Canal into Lake Beauclair is thought to be the single largest source of phosphorus loadings to the Harris Chain-of-Lakes. The Apopka-Beauclair Canal Nutrient Reduction Facility (NuRF) is designed to provide alum treatment for the canal discharges prior to reaching Lake Beauclair. A schematic of the NuRF Facility is given on Figure 1. Discharge rates and water level elevations in the Apopka-Beauclair Canal are regulated by the Apopka-Beauclair Canal lock and dam. The NuRF Facility uses the difference in water level elevations between upstream and downstream portions of the canal to force the canal water into two parallel treatment basins. Liquid alum is added upstream of the point of inflow into the treatment basin, and the generated floc settles onto the bottom of the basins. These basins are designed to allow treatment of up to 300 cfs while still providing a minimum detention time of three hours for capture of the floc material. Treated discharges from the ponds enter a small canal which conveys the treated water downstream of the lock and dam structure where it ultimately reaches Lake Beauclair. Flow in excess of 300 cfs, which rarely occurs, will be allowed to bypass the treatment system.

Approximately 1-2 times each year, depending upon treated flow rates, floc removal will be necessary from the two settling ponds. This removal will be achieved using an automated dredging system constructed as part of these ponds. This system will automatically dredge the accumulated floc from the bottom of the pond and pump the dredge slurry to a large centrifuge located in the adjacent floc processing building. The centrifuge will decrease the water content of the sludge to approximately 40%, so that it can be hauled to the adjacent floc drying area. The floc drying area consists of an elevated area constructed on permeable soils where the floc will continue to dry naturally.

It is anticipated that the dry floc will be used either as landfill cover or by the St. Johns River Water Management District as a soil amendment for various Lake Apopka restoration projects. The alum floc still contains considerable uptake capacity for phosphorus and other species and can be used to reduce phosphorus release from flooded farm lands which are converted to water quality treatment areas. The NuRF Facility contains storage capabilities for approximately 124,000 gallons of alum to meet chemical demand under high flow conditions. At the maximum design treatment rate of 300 cfs, the facility will utilize approximately eight tanker loads (4500 gallons) of alum each day.

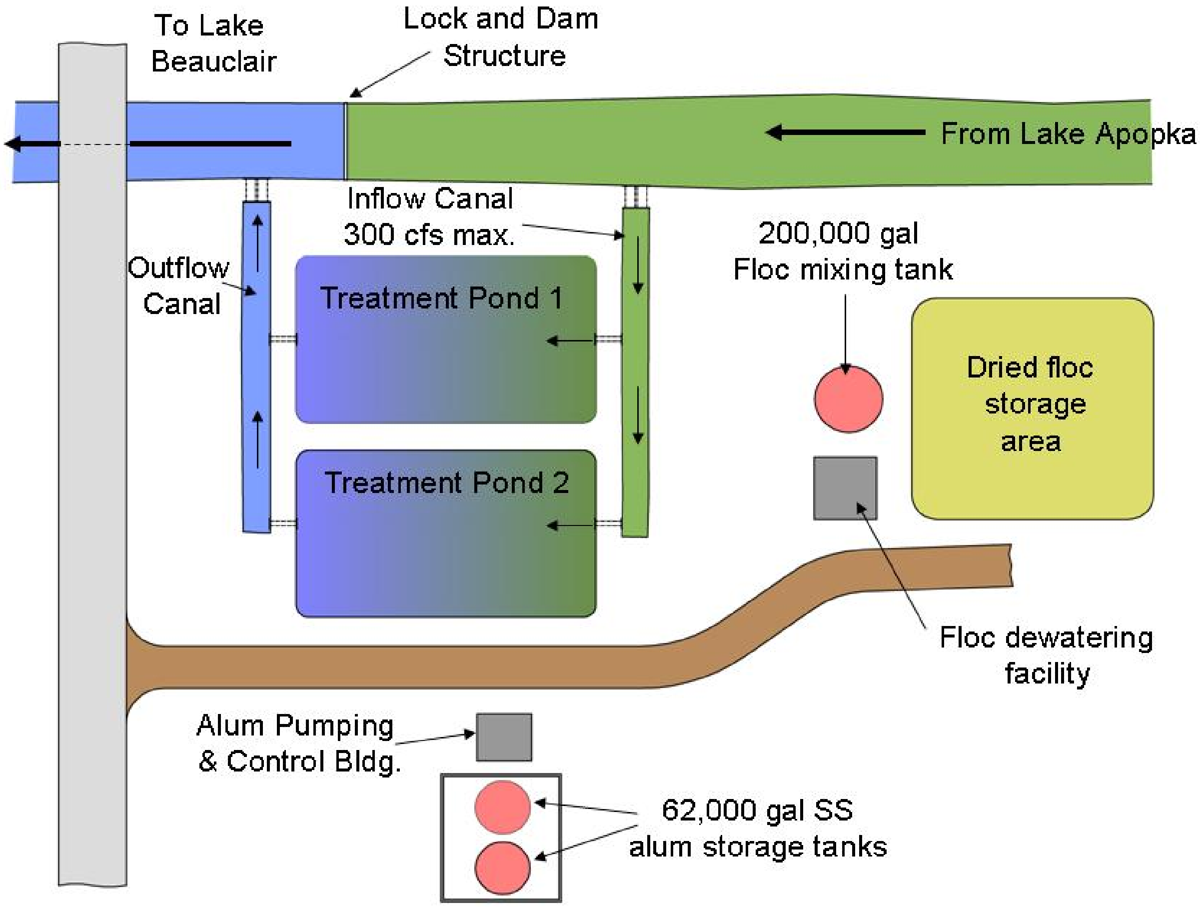

Figure 1. Schematic of Lake County NuRF Facility.

PERFORMANCE EFFICIENCY

Over the past 20 years, literally hundreds of laboratory jar tests have been performed to evaluate the effectiveness of alum for reducing pollutant concentrations in urban runoff. Typical alum doses required for treatment of urban runoff have ranged from 5-10 mg Al/liter. Although pollutant reductions have been observed at alum doses less than 5 mg Al/liter, floc formation and settling patterns are often too slow to be useful for treatment of urban runoff where floc collection is required.

A summary of typical removal efficiencies for alum treated urban runoff is given in Table 1. Mean removal efficiencies are listed for alum treatment of urban runoff at doses of 5, 7.5, and 10 mg Al/liter. Comparative removals are also provided for runoff settled for 24 hours without alum addition. In general, settling of alum floc generated by treatment of urban runoff is approximately 90% complete in 1-3 hours, with additional settling occurring over a period of 12-24 hours. Alum treatment of urban runoff has consistently achieved a 90% reduction in total phosphorus, 50-90% reduction in heavy metals, and >99% reduction in fecal coliform. Removal efficiencies typically increase slightly with increasing alum dose. In general, removal patterns and efficiencies for phosphorus species, turbidity, TSS, heavy metals, and coliform bacteria are predictable and consistent for virtually all types of stormwater runoff. However, alum treatment removal efficiencies for nitrogen can be highly variable. In general, alum treatment has only a minimal effect on concentrations of ammonia and virtually no impact on concentrations of NO_x in stormwater runoff. Removal of dissolved organic nitrogen species can also be highly variable, depending upon molecular size and structure of the organic compounds. The only nitrogen species which can be removed predictably is particulate nitrogen. As a result, removal efficiencies for total nitrogen are highly dependent upon the nitrogen species present, with higher removal efficiencies associated with runoff containing large amounts of particulate and organic nitrogen and lower removal efficiencies for runoff flows which contain primarily inorganic nitrogen species. Selection of the "optimum" dose often involves an economic evaluation of treatment costs vs. desired removal efficiencies.

In general, removal efficiencies achieved with alum stormwater treatment meet or exceed removal efficiencies obtained using dry retention or wet detention stormwater management systems. A comparison of treatment efficiencies for common stormwater management systems is given in Table 2 (Harper and Baker, 2007). Removal efficiencies achieved with alum treatment are similar to removal efficiencies achieved with dry retention and appear to exceed removal efficiencies which can be obtained using wet detention, wet detention with filtration, dry detention, or dry detention with filtration.

Alum stormwater treatment has been shown to provide highly competitive mass removal costs compared with traditional stormwater treatment techniques such as wet detention and wetland treatment. The smaller land area required for alum treatment, combined with high removal efficiencies, results in a lower life-cycle cost per mass of pollutant removed. A comparison of life-cycle costs per mass of pollutant removal for similar large-scale stormwater retrofit projects is given in Table 3. Life-cycle costs are calculated using the initial capital costs and 20 years of operation and maintenance. Based upon this analysis, the cost per mass removal for total phosphorus and total nitrogen by alum treatment is substantially less than mass removal costs for large regional wet detention systems.

TABLE 1

TYPICAL PERCENT REMOVAL EFFICIENCIES FOR ALUM TREATED STORMWATER RUNOFF

PARAMETER	SETTLED WITHOUT ALUM	ALUM DOSE (Dose in mg Al/liter)		
		5	7.5	10
Dissolved Organic Nitrogen	20	51	62	65
Particulate Nitrogen	57	88	94	96
Total Nitrogen	20*	65*	71*	73*
Dissolved Orthophosphorus	17	96	98	98
Particulate Phosphorus	61	82	94	95
Total Phosphorus	45	86	94	96
Turbidity	82	98	99	99
TSS	70	95	97	98
BOD	20	61	63	64
Total Coliform	37	80	94	99
Fecal Coliform	61	96	99	99

* Depending on types of nitrogen species present

TABLE 2

COMPARISON OF TREATMENT EFFICIENCIES FOR COMMON STORMWATER MANAGEMENT SYSTEMS

TYPE OF SYSTEM	ESTIMATED REMOVAL EFFICIENCIES (%)			
	TOTAL N	TOTAL P	TSS	BOD
Dry Retention (0.50-inch runoff)	40-80[1]	40-80	40-80	40-80
Wet Detention[2]	20-30	60-70	75-85	65-70
Wet Detention with Filtration	20-30	60	> 90	80
Dry Detention	0-30	0-40	60-80	0-50
Dry Detention with Filtration	0-30	0-40	60-90	0-50
Alum Treatment	40-70	> 90	> 95	60-75

1. Varies according to project characteristics and location
2. Based on 14-day wet season residence time

TABLE 3

COMPARISON OF LIFE-CYCLE COST PER MASS POLLUTANT REMOVED FOR SIMILAR STORMWATER RETROFIT PROJECTS

PROJECT	LIFE-CYCLE COSTS ($)	COST PER MASS REMOVED ($/kg)		
		TOTAL P	TOTAL N	TSS
Alum Treatment				
Largo Regional STF	2,044,780	5,061	1,293	79
Lake Maggiore STF	4,086,060	3,583	1,268	37
Gore Street Outfall STF	1,825,280	1,736	314	16
East Lake Outfall TF	1,223,600	2,707	334	21
Lake Howard	596,359	74	32	2.21
Wet Detention				
Melburne Blvd.	1,069,000	7,985	2,498	36
Clear Lake Ponds	1,091,600	10,496	4,166	30

FLOC PRODUCTION

After initial formation, alum floc consolidates rapidly for a period of approximately 6-8 days, compressing to approximately 5-10% of the initial floc volume. Additional gradual consolidation appears to occur over a period of approximately 30 days, after which sludge volumes appear to approach maximum consolidation (Harper, 1991).

Estimates of maximum anticipated sludge production, based upon the results of hundreds of laboratory tests involving coagulation of urban stormwater runoff with alum at various doses and a consolidation period of approximately 30 days, are given in Table 4 (Harper, 1991). At alum doses typically used for treatment of urban stormwater runoff, ranging from 5-10 mg Al/liter, sludge production is equivalent to approximately 0.16-0.28% of the treated runoff flow. Sludge production values listed in Table 4 reflect the combined mass generated by alum floc as well as solids originating from the stormwater sample.

Actual accumulation rates of alum floc have been monitored in waterbodies receiving alum treated inputs. In most cases, the observed field accumulation rates are substantially lower than would be expected based on the predicted accumulation rates summarized in Table 4. The reduced observed accumulation rates are thought to be a result of additional floc consolidation over time and incorporation of alum floc into the existing sediments.

TABLE 4

ANTICIPATED PRODUCTION OF ALUM SLUDGE FROM ALUM TREATMENT OF URBAN STORMWATER AT VARIOUS DOSES

ALUM DOSE (mg/l as Al)	SLUDGE PRODUCTION[1]	
	AS PERCENT OF TREATED FLOW	PER AC-FT OF RUNOFF TREATED
5	0.16	69.7 ft^3
7.5	0.20	87.1 ft^3
10	0.28	122 ft^3

1. Based on a minimum settling time of 30 days

FLOC COLLECTION AND DISPOSAL

Early alum stormwater treatment systems provided for floc settling directly in receiving waterbodies. Extensive laboratory testing was conducted by Harper (1991) to evaluate the long-term stability of phosphorus and heavy metals contained in alum floc generated as a result of alum stormwater treatment. These evaluations were conducted by collecting accumulated alum floc from the bottom of various receiving waterbodies and using an incubation apparatus to evaluate the influence of pH and redox potential on the stability of alum treated sediments. These experiments indicated that phosphorus and heavy metals combined into alum floc are extremely stable under a wide range of pH conditions and redox potentials ranging from highly oxidized to highly reduced. The stability of heavy metals within the sediments under post-treatment conditions was found to be substantially greater than the observed under pre-development conditions. As alum floc ages, the freshly precipitated $Al(OH)_3$ forms into a series of ringed structures which are extremely stable and which tightly bind phosphorus and heavy metals in a crystalline lattice network. These phosphorus and metal associations are inert to changes in pH and redox potential normally observed in a normal lake system. Introduction of alum floc into polluted sediments has been shown to reduce poor water concentrations for phosphorus and all evaluated heavy metals.

Although only beneficial aspects of alum floc accumulation have been observed to date, the Florida Department of Environmental Protection (FDEP) has determined that the floc generated by treatment of stormwater runoff must be collected and can no longer be discharged directly to State waters. This requirement is based primarily upon language contained in Chapter 403 of the Florida Administrative Code (FAC) which prohibits treatment of stormwater in “Waters of the State”. As a result, current alum treatment system designs emphasize collection and disposal of floc rather than allowing floc accumulation within surface water systems.

Several innovative designs have been developed for floc collection and disposal. Where possible, sump areas have been constructed to provide a basin for collection and accumulation of alum floc. The accumulated floc can then be pumped out of the sump area on a periodic basis, using either manual or automatic techniques. Most current treatment systems provide for automatic floc disposal into the sanitary sewer system at a slow controlled rate. Since alum floc is inert and has a consistency similar to that of water, acceptance of alum floc on a periodic basis poses no operational problem for wastewater treatment facilities. Many operators have reported that introduction of the alum floc improves the performance efficiency of their treatment system due to the residual uptake capacity within the alum floc for adsorption of additional phosphorus and heavy metals. Floc collection has also been achieved using fabric mesh which traps the floc.

A dedicated manually operated dredging system has recently been designed for use in alum treatment projects within Pinellas County. This unit consists of a manually operated portable dredge with a rotary cutter head that can be raised or lowered to desired depths within the pond. The dredge is powered by a 40-HP outboard motor. The operator controls both the movement of the dredge and the position of the cutter head within the floc layer. The dredge is capable of removing approximately 2-3 ft of floc material with each pass. The pumping system for the dredge has been specially designed to provide an output of approximately 300-400 gallons per minute (gpm) which is suitable for discharge into either a sanitary force main or gravity sanitary sewer. The dredged floc material typically contains between 1-3% solids.

During 2003, ERD evaluated the feasibility of utilizing a hydrodynamic separator (CDS Unit) to collect alum floc generated as a result of treatment of the Lettuce Creek tributary which discharges into Lake Okeechobee. To enhance the speed of the settling process, a relatively high polymer dose was added in addition to the alum. The polymer caused rapid floc formation with virtually complete settling in approximately 2-3 minutes, corresponding to the detention time available within the CDS unit. However, subsequent field testing indicated that the capture rate for the unit was relatively small, probably due to turbulent conditions within the unit which impacted the ability of the floc to settle out. This study concluded that hydrodynamic separators are not feasible alternatives for collection of alum floc.

A long linear treatment basin and settling area has recently been designed for the Lake Seminole alum treatment project in Pinellas County. A schematic of this treatment system is given in Figure 2. The treatment area consists of a linear trough, approximately 25.5 ft in width and 600 ft in length, with a water depth of approximately 17 ft. Water is pumped into this system at a constant rate of 10 cfs with an added alum dose of 7.5 mg/l. The generated floc settles onto the sloped bottom area of the system and accumulates into a small central sump area. The sump area contains 6-inch diameter perforated pipe which is divided into eight separate zones. Floc removal from the system occurs on a daily basis, with each of the eight zones pumped for approximately 21 minutes each at a flow rate of approximately 300 gpm into the adjacent sanitary lift station. This unit is the first alum system which is totally automated for the chemical treatment, floc collection, and disposal processes, although the operation of the system must still be monitored on a frequent basis.

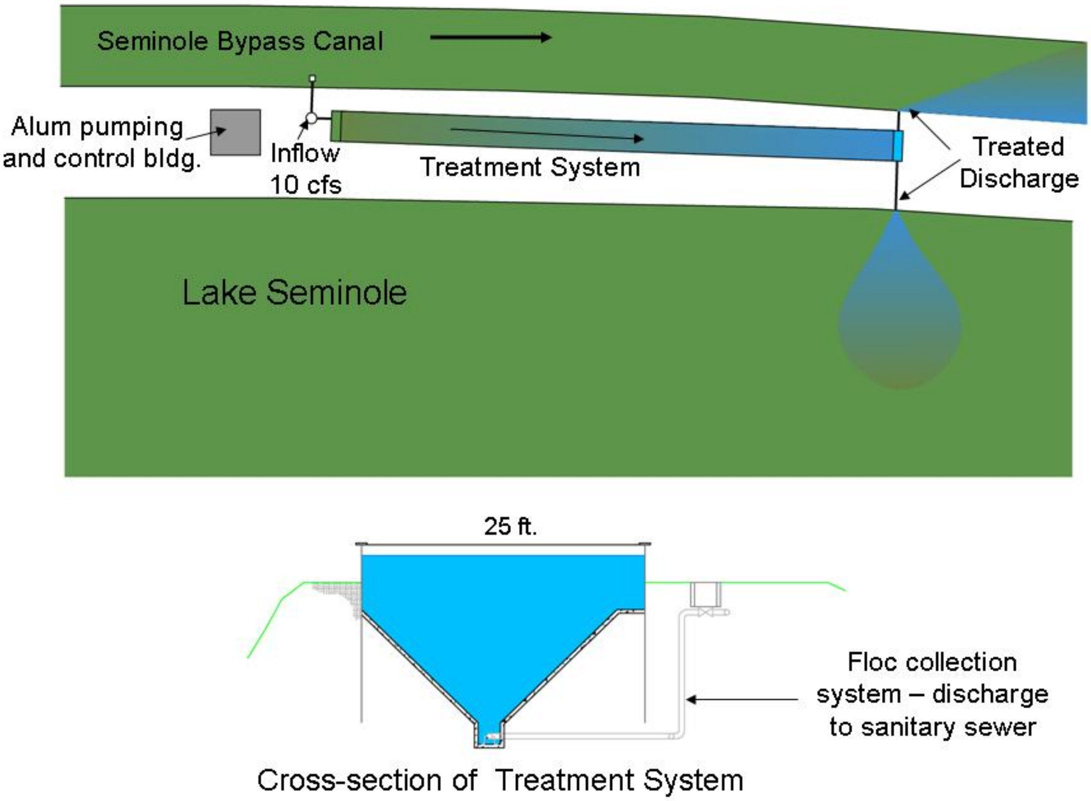

Figure 2. Schematic of Lake Seminole Bypass Canal Treatment System.

Several current alum treatment systems utilize on-site drying beds for floc dewatering. These drying beds are constructed similar to a wastewater sludge drying bed, with an underdrain system constructed beneath a permeable sand layer. The alum floc is deposited onto the drying area, and the leachate is returned to the settling pond. Drying characteristics for alum sludge are similar to a wastewater treatment plant sludge. A drying time of approximately 30 days is sufficient to dewater and dry the sludge, with a corresponding volume reduction of 80-90%.

A summary of the chemical characteristics of the dried alum residual from the NuRF pilot studies is given in Table 5. The alum sludge evaluated during this study was generated by chemical coagulation of thousands of gallons of water collected from the Apopka-Beauclair Canal. The generated floc was captured, placed onto a drying bed, and allowed to dewater. A photograph of the alum sludge during the dewatering process is given in Figure 3. After the sludge has dried, chemical characteristics of the sludge were evaluated and compared with Clean Soil Criteria, outlined in Chapter 62-777 FAC, to assist in identifying disposal options. As seen in Table 5, the measured chemical characteristics from the alum residual are substantially less than the applicable Clean Soil Criteria, based upon direct residential exposure which is the most restrictive soil criteria. Based upon this analysis, the dried alum residual easily meets the criteria for use as fill material for daily landfill cover.

TABLE 5

CHEMICAL CHARACTERISTICS OF DRIED ALUM RESIDUAL FROM THE NURF PILOT STUDIES[1]

PARAMETER	UNITS	VALUE	CLEAN SOIL CRITERIA[2] (Chap. 62-777 FAC)
Aluminum	µg/g	51,096	72,000
Antimony	µg/g	< 6.3	26
Barium	µg/g	< 21	110
Beryllium	µg/g	< 0.53	120
Cadmium	µg/g	0.5	75
Calcium	µg/g	1,564	None
Chromium	µg/g	65.0	210
Copper	µg/g	31.6	110
Iron	µg/g	764	23,000
Lead	µg/g	0.7	400
Magnesium	µg/g	96.8	None
Manganese	µg/g	12.3	1,600
Mercury	µg/g	< 0.091	3.4
Nickel	µg/g	2.3	110
Zinc	µg/g	50.6	23,000
NO_x	µg/g	0.773	120,000
Total N	µg/g	2,054	None
SRP	µg/g	< 1	None
Total P	µg/g	166	None
pH	s.u.	6.17	None

1. Residual sample air-dried and screened using an 0.855 mm sieve
2. Based on residential direct exposure criteria.

Figure 3. Alum Floc Drying Process.

CONCLUSIONS

Alum treatment of stormwater runoff has emerged as a viable and cost-effective alternative for providing stormwater retrofit in urban areas. Recent research in alum stormwater treatment indicate:

1. In general, removal efficiencies obtained with alum stormwater treatment are similar to removals obtained using a dry retention stormwater management facility.

2. Unit costs per mass of pollutant removal using alum treatment are less than mass removal costs for wet detention systems.

3. Several innovative designs have recently been developed for collection of alum floc in sump areas and containment areas, with floc disposal to sanitary sewer or adjacent drying beds.

4. Dried alum floc has no restrictions for use as fill material or cover.

5. Recent designs continue to automate the treatment process to improve overall efficiency and reduce costs.

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