ALUM TREATMENT OF STORMWATER RUNOFF - AN INNOVATIVE BMP FOR URBAN RUNOFF PROBLEMS

Harvey H. Harper, Ph.D., P.E. and Jeffrey L. Herr, P.E.
Environmental Research & Design, Inc.; Orlando, Florida

Eric H. Livingston
Florida Department of Environmental Protection; Tallahassee, Florida

Alum treatment of stormwater runoff originated in 1986 as part of a lake restoration project at Lake Ella in Tallahassee, Florida in 1986. This system provides treatment of stormwater runoff entering the lake by injecting liquid alum into major stormsewer lines on a flow-weighted basis during rain events. When added to runoff, alum forms non-toxic precipitates of $Al(OH)_3$ and $AlPO_4$ which combine with phosphorus, suspended solids and heavy metals, causing them to be rapidly removed from the treated water. The alum stormwater treatment system resulted in immediate and substantial improvements to water quality in Lake Ella which led to implementation of additional systems on other urban lakes. There are currently 23 alum stormwater treatment systems either operational or under construction in Florida and one experimental system in Seattle, Washington.

Alum treatment of stormwater runoff has consistently achieved a 90% reduction in total phosphorus, 50-70% reduction in total nitrogen, 50-90% reduction in heavy metals, and >99% reduction in fecal coliform. Ultimate water quality improvements in the receiving water body have been related to the percentage of total inputs treated by the system. Heavy metal and phosphorus associations with alum floc have been shown to be extremely stable over a wide range of pH and redox conditions.

In general, alum treatment of runoff is substantially less expensive than traditional treatment methods and often requires no additional land purchase. Recent designs have incorporated automatic floc collection and removal systems with disposal to drying beds or sanitary sewer.

Introduction

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:

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

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

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

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. Phosphorus removal or entrapment can occur by several mechanisms, depending on the solution pH. Inorganic phosphorus is also effectively removed by adsorption to the $Al(OH)_3$ floc. Removal of particulate phosphorus is most effective in the pH range of 6-8 where maximum floc occurs (Cooke and Kennedy, 1981). At higher pH values, OH^- begins to compete with phosphate ions for aluminum ions, and aluminum hydroxide-phosphate complexes begin to form. At lower pH values and higher inorganic phosphorus concentrations, the formation of aluminum phosphate ($AlPO_4$) is favored.

In 1985, a lake restoration project was initiated at Lake Ella, a shallow 13.3 ac hypereutrophic lake in Tallahassee, Florida, which receives untreated stormwater runoff from approximately 163 ac of highly impervious urban watershed areas. 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 no 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 end product. 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.

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 will not redissolve due to changes in redox potential or pH under conditions normally found in surface waterbodies. Over time, the freshly precipitated floc ages into even more stable complexes, eventually forming gibsite. The solubility of dissolved aluminum in the treated water is regulated entirely by chemical equilibrium. 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.

Since the Lake Ella system, alum stormwater treatment systems have been constructed in Florida for Lake Dot, Lake Rowena and Lake Lucerne in Orlando; Lake Osceola, Lake Virginia North and Lake Mizell in Winter Park; Lake Cannon in Polk County; Channel 2

Drainage Canal in Pinellas Park; Celebration Town Lake in Celebration; Lake Holden in Orange County; Lake Tuskawilla in Ocala; and five separate systems for Lake Maggiore in St. Petersburg. An experimental treatment facility has also been constructed in the Lake Sammamish watershed in Seattle, Washington. In addition to these projects which have been constructed and are currently operational, additional projects are currently under design in Winter Park, Orlando, Largo, Tampa and Clearwater. The first project to treat stormwater discharged to a brackish water became operational in January 1998 in the City of St. Petersburg, Florida.

Alum treatment of stormwater runoff has now been used as a viable stormwater treatment alternative in urban areas for over 10 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. A summary of current knowledge in these areas is given in the following sections.

System Configuration

Once alum has been identified as an option in a stormwater retrofit project, 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 extensive 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 determine floc strength and stability, required mixing intensity and duration, and determine design criteria for dedicated floc settling basins.

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. If a buffering agent, such as NaOH, is required to maintain desired pH levels, a separate metering system and storage tank will be necessary. The operation of each injection pump is regulated by a flow meter device attached to each incoming stormwater line to be treated. Measured flow from each stormwater flow meter is transformed into a 4-20 mA electronic signal which instructs each metering pump to inject alum according to the measured flow of runoff discharging through each individual stormsewer line. 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 and electronic controls, are typically housed in a central facility which can be constructed as an above-ground or below-ground structure. A 6,000 gallon alum storage tank is typically used for bulk alum storage. 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. Early designs for alum stormwater treatment systems utilized individual chemical metering pumps and stormsewer flow meters for each point of alum addition. However, in an effort to reduce overall system costs and complexity, current alum stormwater treatment systems often feed alum to multiple points using a single chemical metering pump and control valves.

Water Chemistry

In general, construction and operation of alum stormwater treatment systems has resulted in significant improvements in water quality for treated waterbodies. The degree of observed improvement in water quality is directly related to the percentage of annual hydraulic inputs treated by the alum stormwater treatment system. A comparison of pre- and post-modification water quality characteristics for three typical alum stormwater treatment systems, including Lake Ella and Lake Dot (which provide treatment for approximately 95-96% of the annual hydraulic inputs entering these lake systems), and Lake Osceola (which provides treatment for only 9% of the annual hydraulic inputs entering the lake system) is given in Table 1.

Table 1. Comparison of Pre- and Post-Modification Water Quality Characteristics for Typical Alum Stormwater Treatment Systems

PARAMETER	UNITS	LAKE ELLA		LAKE DOT		LAKE OSCEOLA	
		BEFORE (1974-85)	AFTER (1/88-5/90)	BEFORE (1986-88)	AFTER (3/89-8/91)	BEFORE (6/91-6/92)	AFTER (2/93-12/96)
# of Samples	--	15	11	5	15	12	46
pH	s.u.	7.41	6.43	7.27	7.17	8.22	7.63
Diss. O_2 (1 m)	mg/l	3.5	7.4	6.6	8.8	8.8	8.8
Total N	μg/l	1876	1417	1646	696	892	856
Total P	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
Diss. Al	μg/l	--	44	--	65	18	51
Florida TSI Value	--	98 (Hyper-eutrophic)	47 (Oligotrophic)	86 (Hyper-eutrophic)	42 (Oligotrophic)	61 (Eutrophic)	56 (Mesotrophic)
Lake Area	--	13.3 ac		5.9 ac		55.4 ac	
Watershed Area	--	57 ac		305 ac		153 ac	
Percent of Annual Hydraulic Inputs Treated	%	95		96		9	

In general, operation of the alum stormwater treatment systems resulted in a decline in pH within each of the three waterbodies, ranging from a reduction of approximately 1 unit in Lake Ella to 0.6 units in Lake Osceola. A pH reduction of only 0.1 unit was observed for the Lake Dot treatment system which injects alum along with sodium hydroxide to control pH levels within the lake. Significant improvements in dissolved oxygen were also observed in both Lake Ella and Lake Dot. Alum treatment of stormwater runoff resulted in a 78% reduction in total nitrogen concentrations in Lake Ella, with a 55% reduction in Lake Dot and a 4% reduction in Lake Osceola where only a small portion of the annual hydraulic inputs are treated. The majority of the total nitrogen removal observed is a result of reducing concentrations of dissolved organic nitrogen and particulate nitrogen, since alum is generally ineffective in reducing concentrations of inorganic nitrogen species, such as ammonia or NO_x. Alum stormwater treatment resulted in a substantial reduction in measured concentrations of orthophosphorus and total phosphorus in each of the three lake systems, with total removals of 89%, 93% and 30% for Lake Ella, Lake Dot and Lake Osceola, respectively. Alum stormwater treatment also reduced in-lake concentrations of BOD in each of the three lake systems, with a reduction of 93% in Lake Ella and 84% in Lake Dot.

Alum stormwater treatment appears to be extremely effective in reducing concentrations of chlorophyll-a in receiving waterbodies, with a reduction of 97% in Lake Ella, 89% in Lake Dot and 13% in Lake Osceola. Reductions in measured concentrations of chlorophyll-a occur as a result of enmeshment and precipitation of algal particles within the water column of the lake by alum floc as well as phosphorus limitation created by low levels of available phosphorus in the water column. Substantial increases in Secchi disk depth were observed in Lake Ella and Lake Dot, and to a lesser extent in Lake Osceola, with improvements of 340% in Lake Ella, 212% in Lake Dot and 9% in Lake Osceola. Based upon the Florida TSI Index (Brezonik, 1984), Lake Ella and Lake Dot have been converted from hypereutrophic to oligotrophic status, with a conversion from eutrophic to mesotrophic in Lake Osceola.

A graphical history of total phosphorus concentrations in Lake Lucerne, which was retrofitted with an alum stormwater treatment system in June 1993 which provides treatment for approximately 82% of the annual runoff inputs into the lake, is given in Figure 1. Prior to construction of the alum stormwater treatment system, total phosphorus concentrations in Lake Lucerne fluctuated widely, with a mean concentration of approximately 100 μg/l. Following start-up of the alum treatment system, total phosphorus concentrations began to decline steadily, reaching equilibrium concentrations of approximately 20-40 μg/l. A slight increase in total phosphorus concentrations is observed during the last half of 1995 when the system was off-line due to lightning damage. When system operation resumed in June 1996, total phosphorus concentrations returned to equilibrium values of approximately 20 μg/l.

In general, measured concentrations of heavy metals have been extremely low in value in all waterbodies retrofitted with alum stormwater treatment systems, with no violations of heavy metal standards. In addition, measured levels of dissolved aluminum have also remained low in each lake system. Mean dissolved aluminum concentrations for Lake Ella, Lake Dot and Lake Osceola have averaged 44 μg/l, 65 μg/l and 51 μg/l, respectively. Although there is no standard for dissolved aluminum in the State of Florida, the U.S. EPA has recommended a long-term average of 87 μg/l for protection of all species present in the

U.S. The solubility of dissolved aluminum is regulated almost exclusively by pH. As long as the pH of the treated water can be maintained in the range of 6.0-7.5 during the treatment process, dissolved aluminum concentrations will remain at minimal levels.

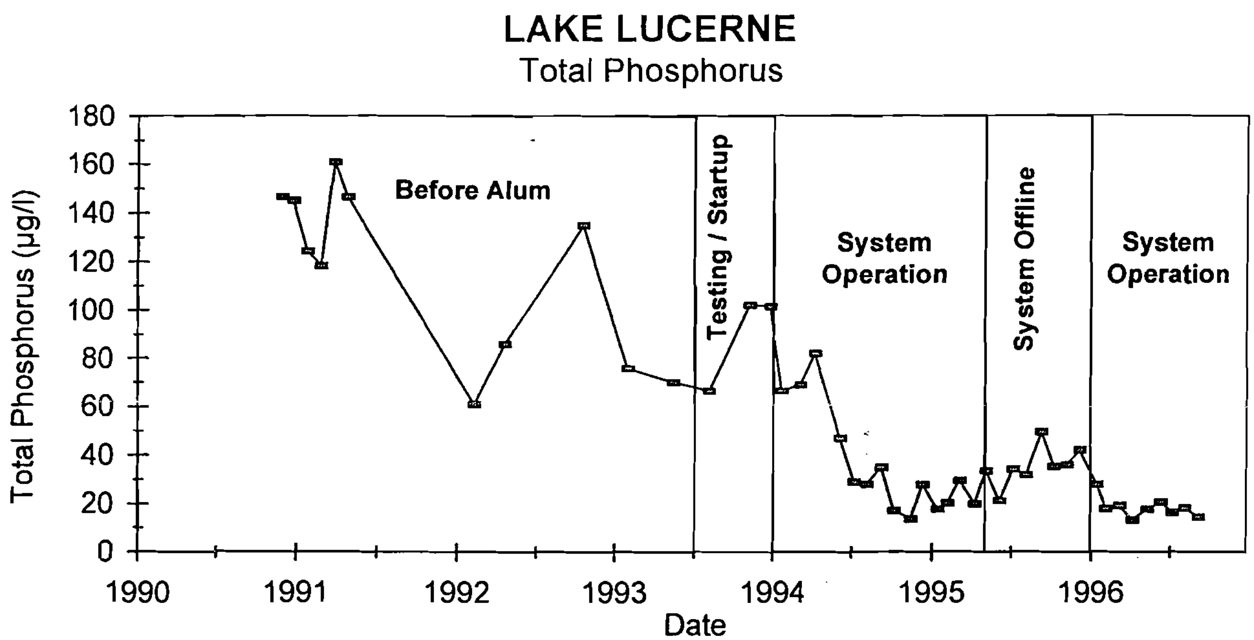

Figure 1. **Trends in Total Phosphorus Concentrations in Lake Lucerne Before and After Alum Treatment of Stormwater Runoff**

Floc Accumulation

Laboratory investigations have been conducted on stormwater runoff collected from a wide range of land uses typical of urban areas to quantify the amount of alum floc generated as a result of alum treatment of stormwater runoff at various treatment doses. After initial formation, alum floc appears to consolidate rapidly for a period of approximately 6-8 days, reaching approximately 20% of the initial floc volume. Additional consolidation appears to occur over a settling period of approximately 30 days, after which collected sludge volumes appear to approach maximum consolidation (Harper, 1990).

Estimates of maximum anticipated sludge production, based upon literally hundreds of laboratory tests involving coagulation of stormwater runoff with alum at various doses, and based upon a consolidation period of approximately 30 days, is given in Table 2. At alum doses typically used for treatment of stormwater runoff, ranging from 5-10 mg/l as Al, sludge production is equivalent to approximately 0.16-0.28% of the treated runoff flow. Sludge production values listed in Table 2 reflect the combined mass generated by alum floc as well as solids originating from the stormwater sample.

Table 2. Anticipated Production of Alum Sludge from Alum Treatment of Stormwater at Various Doses

ALUM DOSE (mg/l as Al)	SLUDGE PRODUCTION[1]	
	AS PERCENT OF TREATED FLOW	PER 10^6 GALLONS TREATED
5	0.16	214 ft^3
7.5	0.20	268 ft^3
10	0.28	374 ft^3

1. Based on a minimum settling time of 30 days

Field investigations have also been performed in lake systems receiving alum treated stormwater runoff to document the accumulation rate of alum floc within the sediments by collection and visual inspection of sediment core samples collected in clear acrylic tubes at selected monitoring sites in each lake. A comparison of observed and predicted floc accumulation rates in lake systems receiving stormwater treatment is given in Table 3. Each of the listed lakes has been receiving alum treatment for approximately five years or more. The primary predicted settling area for floc accumulation was determined by evaluating lake bottom topography and stormsewer inflow characteristics. Predicted floc accumulation rates are based upon the anticipated floc production rates summarized in Table 2.

Table 3. Comparison of Observed and Predicted Floc Accumulation Rates in Lake Systems with Alum Stormwater Treatment

LAKE	PREDICTED SETTLING AREA	PREDICTED ACCUMULATION RATE (cm/yr)	OBSERVED ACCUMULATION RATE
Lake Ella	50% of lake bottom	1 cm/yr	0.33 cm/yr
Lake Lucerne	areas 10 ft or deeper	3.3 cm/yr	none
Lake Osceola	50% of lake bottom	0.5 cm/yr	none

Annual floc production in Lake Ella was predicted to be approximately 1 cm/yr over 50% of the lake bottom. However, floc accumulation evaluations performed in 1990 indicate an observed accumulation rate of approximately 0.33 cm/yr, approximately one-third of the predicted accumulation rate. The reduced observed accumulation rate is thought to be a result of additional floc consolidation over time and incorporation of the alum floc into the existing sediments. The observed post-treatment floc accumulation rate in Lake Ella is similar to the pre-treatment sediment accumulation rate in Lake Ella resulting from the extremely high algal production prior to the lake restoration efforts in 1985. Sediment accumulation in Lake Lucerne is anticipated to occur in areas 10 ft or deeper, with a predicted accumulation of 3.3 cm/yr. However, no sediment accumulation was observed at any of the 10 fixed monitoring locations within the lake which have been monitored on approximately an annual basis since start-up of the alum treatment system. A similar conclusion has been reached in Lake Osceola which has no visible floc accumulation after approximately five years of alum stormwater treatment. Both Lake Lucerne and Lake Osceola appear to be incorporating alum floc into the existing sediments with no visible surface floc layer.

Construction and O&M Costs

A summary of construction and annual operation and maintenance (O&M) costs for existing alum stormwater treatment facilities, with treated watershed areas ranging from 64 ac to 1450 ac, is given in Table 4. Construction costs for alum stormwater treatment systems have ranged from $75,000 to $400,000, depending upon the number of outfalls to be retrofitted. In general, the capital cost of constructing alum stormwater treatment systems is independent of the watershed size since the capital cost for constructing a treatment system for a 100 ac watershed at one location is identical to the cost of constructing a system to treat 1000 ac at the same location, although annual O&M costs would increase. The average capital cost for existing alum stormwater treatment facilities is $245,998.

Table 4. Summary of Construction and O&M Costs for Existing Alum Stormwater Treatment Facilities

PROJECT	AREA TREATED (ac)	CONSTRUCTION COST/SYSTEM ($)	ESTIMATED ANNUAL O&M COST ($)	CONSTRUCTION COST PER AREA TREATED ($/ac)	ANNUAL O&M COST PER AREA TREATED ($/ac)
Lake Ella	158	200,400	--	1,268	--
Lake Dot	305	250,000	--	823	--
Lake Lucerne	272	400,000	16,000	1,472	59
Lake Osceola	153	300,000	6,500	1,959	43
Lake Cannon	490	135,000	13,100	276	27
Channel 2	84	180,000	--	2,144	--
Lake Virginia North	64	242,000	--	3,769	--
Celebration	158	300,000	25,000	1,898	158
Lake Holden	183	292,000	--	1,598	--
Lake Tuskawilla	311	242,000	19,627	777	63
Lake Rowena	538	75,000	--	139	--
Lake Mizell	74	300,000	15,389	4,049	208
Lake Maggiore (5)	1450	400,000	21,450	1,379	74
Webster Avenue	91	130,000	12,397	1,423	136
Lake Virginia South	437	288,000	--	659	--
Merritt Ridge	195	201,575	26,298	1,033	135
AVERAGES	310	$ 245,998	$ 17,307	$ 1,542	$ 100

Estimated O&M costs are also provided in Table 4 and include chemical, power, manpower for routine inspections, and equipment renewal and replacement costs. Operation and maintenance costs for existing alum stormwater treatment systems range from $5,500 to $26,298 per year. Construction costs and annual O&M costs are also included on a per acre treated basis for comparison with other stormwater treatment alternatives.

Comparison with Other Stormwater Treatment Alternatives

In general, removal efficiencies obtained with alum stormwater treatment are similar to removal efficiencies obtained using a dry retention or wet detention stormwater management facility. A comparison of treatment efficiencies for common stormwater management systems is given in Table 5 (Harper, 1995). Estimated removal efficiencies for alum treatment exceed removal efficiencies achieved in dry retention for total phosphorus and TSS, but removal efficiencies for total nitrogen and BOD appear to be slightly lower than those achieved in dry retention. In general, dry retention is considered to be the most effective common stormwater management technique in use today. Removal efficiencies achieved with alum treatment appear to exceed removal efficiencies which can be obtained using wet detention, wet detention with filtration, dry detention, or dry detention with filtration.

Table 5. 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)	80	80	80	80
Wet Detention	20-30	60-70	85	50-60
Wet Detention with Filtration	40	60	> 90	90
Dry Detention	10-20	20-40	60-80	30-50
Dry Detention with Filtration	0-20	0-20	60-90	0-55
Alum Treatment	50-70	> 90	> 95	60

Alum treatment of stormwater runoff also compares favorably with other stormwater treatment alternatives with respect to both initial capital construction costs and annual O&M costs. A comparison of costs for alum stormwater treatment and equivalent retention facilities is given in Table 6. Initial capital construction costs and annual O&M costs for three existing alum stormwater treatment facilities are compared with the estimated cost for construction of an equivalent retention facility for treatment of the first 0.5 in of runoff. Each of the equivalent retention facilities would require purchase of land in heavily urbanized areas which, if available at all, would be prohibitively expensive. The cost listed for the equivalent retention facilities include land costs only and do not include actual construction costs. Estimated annual O&M cost for retention pond maintenance, such as routine mowing, weed control and trash removal, is higher than the estimated O&M costs for the alum treatment systems which includes chemicals, weekly inspections, and parts and supplies.

Table 6. Comparison of Costs for Alum Stormwater Treatment and Equivalent Retention Facilities

LOCATION	AREA TREATED (ac)	ALUM TREATMENT SYSTEM		EQUIVALENT RETENTION FACILITY		
		CAPITAL COSTS ($)	ANNUAL O&M COSTS[1] ($)	LAND AREA REQUIRED[2] (ac)	LAND COST ($)	ANNUAL O&M COSTS[3] ($)
Lake Osceola	88	235,000	6,500	3.0	1,500,000[4]	9,000
Lake Lucerne	210	420,000	16,000	7.3	3,700,000[4]	21,900
Lake Cannon	490	135,000	13,100	17.0	850,000[5]	51,000

1. Includes chemical costs, weekly inspection, and $1000 for supplies and parts
2. Based on equivalent treatment of 1 inch of runoff and a 3 ft deep pond
3. Based on $3000/acre for O&M (Ref; FDOT)
4. Based on a land cost of $500,000/acre
5. Based on a land cost of $50,000/acre

Floc Collection and Disposal

Although virtually all existing alum stormwater treatment systems allow for floc settling directly in receiving waterbodies, and only beneficial aspects of alum floc accumulation have been observed to date, 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 collection and disposal of alum floc. 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, using either manual or automatic techniques, on a periodic basis. Several current treatment systems provide for automatic floc disposal into the sanitary sewer system at a slow controlled rate. Since alum floc is virtually 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. A schematic of a settling pond designed for the Lake Virginia system is given in Figure 2.

A recent design for collection of floc discharging from a submerged pipe in a lake system is also illustrated in Figure 2. The floc containment area consists of a fabric mesh with holes sized to allow water flow while trapping floc particles. The floc is then collected in the sump area in the bottom of the containment area and pumped on a periodic basis to the sanitary sewer system or adjacent drying bed. 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%. Dried alum sludge has chemical characteristics suitable for general land application or in agricultural sites, as outlined in Chapter 62-640 F.A.C.

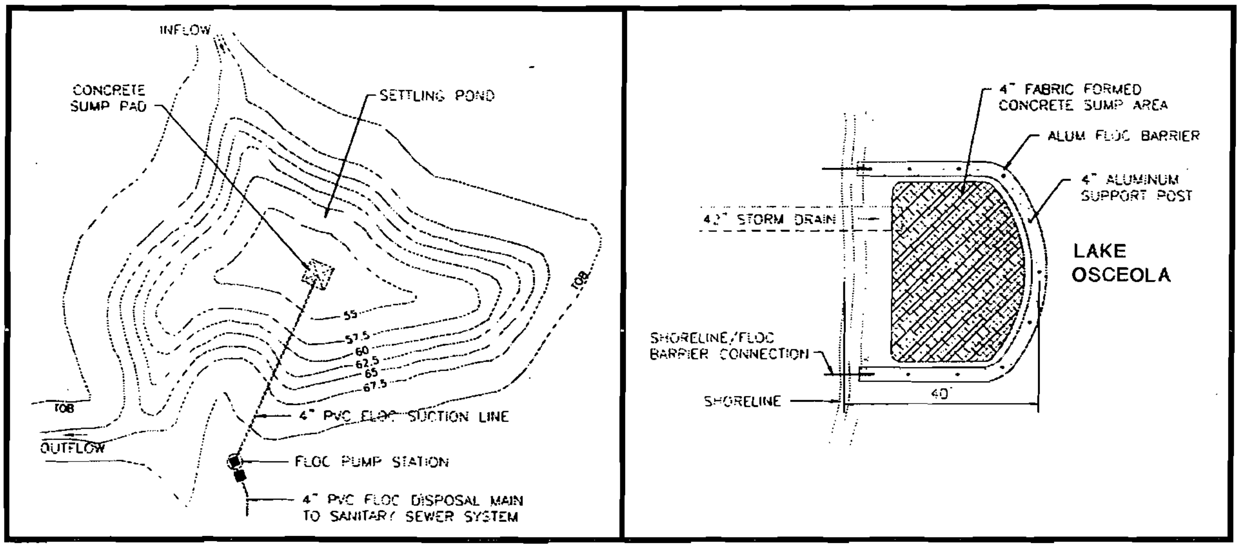

Figure 2. Typical schematics of floc collection and disposal systems

Conclusions

Alum treatment of stormwater runoff has emerged as a viable and cost-effective alternative for providing stormwater retrofit in urban areas. Based upon the first 10 years of experience with alum stormwater treatment, the following conclusions have been reached:

1. In lake system where a large percentage of the annual runoff inputs are retrofitted with an alum treatment system, alum treatment has consistently achieved a 90% reduction in total phosphorus, 50-70% reduction in total nitrogen, 50-90% reduction in heavy metals, and >99% reduction in fecal coliforms. However, ultimate water quality improvements in the receiving waterbodies are highly correlated with the percentage of total inputs treated by the system.

2. The observed accumulation rate of alum floc in the sediments of receiving waterbodies appears to be substantially lower than the predicted accumulation rate due to additional floc consolidation over time and incorporation of alum floc into the existing sediment.

3. Construction costs for alum stormwater treatment systems are largely independent of the watershed area to be treated and depend primarily upon the number of outfalls to be retrofitted.

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

5. Alum treatment of stormwater runoff is often substantially less expensive than other stormwater treatment alternatives with respect to both initial capital construction costs and annual O&M costs.

6. 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.

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