CHEMICAL COAGULATION OF STORMWATER RUNOFF: AN ECONOMICAL ALTERNATIVE FOR REDUCING NONPOINT SOURCE IMPACTS

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Abstract

Chemical coagulation of nonpoint source runoff originated in 1986 at Lake Ella in Tallahassee, Florida as part of a restoration project to improve water quality in the lake. An automatic chemical injection system was constructed to provide 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 deposited into the sediments of the lake, or in a dedicated settling area or pond, in a stable, inactive state. The alum stormwater treatment system at Lake Ella resulted in immediate and substantial improvements to water quality which led to implementation of additional systems on other urban lakes. There are currently more than 35 alum stormwater treatment systems either operational or under construction in Florida, Washington and Indiana.

Alum treatment of urban 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 are directly related to the proportion 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.

Alum coagulation has also been used for treatment of agricultural runoff in both pilot and full-scale systems. Consistent removals of 70-80% have been achieved for both orthophosphorus and total phosphorus. Simple continuous injection systems have also been used to improve the efficiency of wet detention ponds and improve surface water quality in small lakes. In general, alum coagulation 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:

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

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 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.

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 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.

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 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 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 30 additional alum stormwater treatment systems have been constructed. The majority of these systems are located in Florida, with additional systems in Seattle, Washington and LaPorte, Indiana.

Alum treatment of stormwater runoff has now been used as a viable stormwater treatment alternative in urban areas for over 15 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 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. 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 the chemical injection pump is regulated by a flow meter device attached to the incoming stormwater line to be treated. Measured flow from the stormwater flow meter is transformed into a 4-20 mA electronic signal which instructs the metering pump to inject alum according to the measured flow of runoff discharging through the 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.

Removal Efficiencies

Over the past 15 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.

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 with a 24-hour settling period. 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. For consistency, all alum jar tests are performed with a 24-hour settling period. Alum treatment of urban runoff has consistently achieved a 90% reduction in total phosphorus, 40-70% reduction in total nitrogen, 50-90% reduction in heavy metals, and >99% reduction in fecal coliform. Removal efficiencies typically increase slightly with increasing alum dose. Selection of the "optimum" dose often involves an economic evaluation of treatment costs vs. desired removal efficiencies.

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	67	88	94	96
Total Nitrogen	49	65	71	73
Dissolved Orthophosphorus	17	96	98	98
Particulate Phosphorus	71	82	94	95
Total Phosphorus	45	86	94	96
Turbidity	92	98	99	99
TSS	80	95	97	98
BOD	44	61	63	64
Total Coliform	37	80	94	99
Fecal Coliform	61	96	99	99

Alum treatment has also been evaluated for use in reducing nutrient concentrations in agricultural runoff. Harper (1987) performed an extensive study to evaluate the effectiveness of alum for reducing nutrient concentrations in agricultural runoff from the Central Florida area. The evaluated farm areas were utilized primarily for row crops which were grown in high organic muck and peat type soils. Runoff generated from these areas was found to contain high levels of color, with large portions of inorganic and organic nutrient forms. The dominant nitrogen species was found to be dissolved organic nitrogen, while the dominant phosphorus species was dissolved orthophosphorus.

Typical changes in water quality characteristics resulting from alum treatment of agricultural runoff are summarized in Table 2. In general, alum treatment resulted in slight reductions in pH and alkalinity in the treated water, with corresponding increases in specific conductivity. Inorganic nitrogen species were relatively unaffected by the treatment process, with the majority of total nitrogen removal occurring as a result of reduction in concentrations of organic nitrogen. Alum treatment was observed to be extremely effective in reducing concentrations of dissolved orthophosphorus with more than 90% removal achieved at alum doses in excess of 10 mg Al/liter. Alum treatment was also effective in reducing concentrations of TSS and BOD, with approximately 50% removal for these parameters at alum doses in excess of 10 mg Al/liter. In general, efficient removal of phosphorus species from agricultural runoff using alum required doses which were approximately two times greater than the doses necessary to substantially reduce nutrient concentrations in urban runoff.

TABLE 2

TYPICAL CHANGES IN WATER QUALITY CHARACTERISTICS RESULTING FROM ALUM TREATMENT OF AGRICULTURAL RUNOFF[1]

PARAMETER	UNITS	RAW WATER	ALUM TREATED (Dose in mg Al/liter)			
			5	10	15	20
pH	s.u.	7.24	6.88	6.59	6.40	6.10
Alkalinity	mg/l	186	153	128	102	80.6
Specific Conductivity	μmho/cm	589	600	609	619	627
NH_3-N	μg/l	1083	1101	1094	1081	1131
NO_x-N	μg/l	133	50	56	59	62
Organic Nitrogen	μg/l	3850	2438	2541	1775	1625
Total Nitrogen	μg/l	5066	3689	3689	2913	2816
Orthophosphorus	μg/l	666	244	100	24	11
Total Phosphorus	μg/l	853	696	642	257	80
TSS	mg/l	34.1	20.5	18.0	17.1	10.6
BOD	mg/l	5.3	3.9	3.1	2.4	2.1

1. Harper (1987)

Receiving 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 each alum stormwater treatment system. A comparison of pre- and post-modification water quality characteristics for three typical alum stormwater treatment systems which provide treatment for 95%, 43% and 9% of the annual hydraulic inputs to the receiving water body is given in Table 3.

TABLE 3

COMPARISON OF PRE- AND POST-MODIFICATION WATER QUALITY CHARACTERISTICS FOR TYPICAL ALUM STORMWATER TREATMENT SYSTEMS

PARAMETER	UNITS	LAKE ELLA		LAKE MIZELL		LAKE OSCEOLA	
		PRE (1974-85)	POST (1/88-5/90)	PRE (4/94-8/94)	POST (5/97-2/00)	PRE (6/91-6/92)	POST (2/93-2/00)
# of Samples	--	15	11	12	68	36	318
pH	s.u.	7.41	6.43	8.33	7.51	8.21	7.86
Diss. O_2 (1 m)	mg/l	3.5	7.4	9.3	8.5	8.9	8.9
Total N	μg/l	1876	417	1339	724	867	850
Total P	μg/l	232	26	37	20	35	25
BOD	mg/l	41	3.0	5.9	1.9	4.4	3.4
Chlorophyll-a	mg/m^3	180	5.1	31.7	14.5	24.9	21.7
Secchi Disk Depth	m	0.5	> 2.2	0.7	1.8	1.1	1.2
Diss. Al	μg/l	--	44	29	36	19	45
Florida TSI Value	--	98 (Hyper-eutrophic)	47 (Oligotrophic)	65 (Eutrophic)	48 (Oligotrophic)	58 (Meso-trophic)	56 (Meso-trophic)
Lake Area	--	13.3 ac		63.3 ac		55.4 ac	
Watershed Area	--	57 ac		219 ac		153 ac	
Percent of Annual Hydraulic Inputs Treated	%	95		43		9	

Floc Formation

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, 1990).

Estimates of maximum anticipated sludge production, based upon literally hundreds of laboratory tests involving coagulation of urban stormwater runoff with alum at various doses, and based upon a consolidation period of approximately 30 days, are given in Table 4 (Harper, 1990). 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.

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 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

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. In many lakes, the observed post-treatment floc accumulation rate is similar to the pre-treatment sediment accumulation rate resulting from the extremely high algal production prior to the lake restoration efforts.

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 5. Construction costs for alum stormwater treatment systems have ranged from $75,000 to $786,585, depending upon the number of outfalls to be retrofitted and piping modifications necessary to optimize the system. 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 $307,627.

TABLE 5

SUMMARY OF CONSTRUCTION AND O&M COSTS FOR EXISTING ALUM STORMWATER TREATMENT FACILITIES DESIGNED BY ERD

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	13,089	1,959	86
Lake Cannon	490	135,000	16,140	276	33
Channel 2	84	180,000	9,724	2,144	116
Lake Virginia North	64	242,000	11,577	3,769	181
Celebration	158	300,000	25,000	1,898	158
Lake Holden	183	292,000	23,584	1,598	129
Lake Tuskawilla	311	242,000	19,627	777	63
Lake Rowena	538	75,000	14,098	139	26
Lake Mizell	74	300,000	15,389	4,049	208
Lake Maggiore (5)	1450	400,000	21,450	1,379	74
Webster Avenue	91	154,000	12,397	1,692	136
Lake Virginia South	437	323,000	56,015	739	128
Merritt Ridge	195	416,805	26,298	2,137	135
Largo	1159	786,585	38,874	679	34
Clear Lake	63	110,000	8,731	1,746	139
Gore Street	752	600,000	41,276	798	55
Mirror Lake	144	360,000	15,044	2,500	104
Lake Howard	216	247,000	17,482	1,144	81
East Lake	1127	454,000	37,241	403	33
AVERAGES	330	$ 307,627	$ 21,952	$ 1,518	$ 99

Estimated O&M costs are also provided in Table 5 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 $8,731 to $38,874 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 6 (Harper, 1995). 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.

TABLE 6

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)	60-80	60-80	60-80	60-80
Wet Detention	20-30	60-70	85	50-60
Wet Detention with Filtration	20-30	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	40-70	> 90	> 95	60

Floc Collection and Disposal

Although most 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. Floc collection has also been achieved using fabric mesh which traps the floc.

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.

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 15 years of experience with alum stormwater treatment, the following conclusions have been reached:

1. In lake systems 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, 40-70% 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. 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.

References

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